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Control of Smoke Movement in Buildings: A Review

I. A. Benjamin, F. Fung and L. Roth

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U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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Institute for Applied Technology
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CONTROL OF SMOKE MOVEMENT IN BUILDINGS: A REVIEW

I. A. Benjamin, F. Fung and L. Roth

Abstract

A state-of-the-art review of efforts in smoke movement and smoke control is presented. Basic principles, experimental techniques and results, computer models, and smoke control methods which have been employed are presented. The paper covers all work in the area of smoke movement and smoke control but emphasizes the work of NBS.

Key words: Basic principles; computer calculations; computer modeling; experimental methods; smoke control methods; smoke movement; smoke simulation; state-of-the-art review.

1. INTRODUCTION

This paper briefly describes the literature in the field of dynamic smoke movement and control in building fires, reviews experiments which have been conducted in the area of dynamic smoke movement and control, reviews computer models which have been developed to predict smoke movement, and reviews experience in designing buildings using smoke control methods. This paper does not intend to be an annotated bibliography, but rather attempts to introduce the reader to the field of smoke control and acquaint him with the literature.

Because of the smoke hazard which can exist during building fires, methods of controlling the movement of smoke have been developed. These methods of control have been divided into two categories: active and passive. Active methods use the HVAC (Heating, Ventilating and Air Conditioning) system; passive methods use mechanical barriers or vent shafts to control smoke movement. The active control systems assume that the fire is "small" enough so that the smoke generation does not overwhelm the HVAC system; or that the energy output of the fire is small relative to the energy output of the HVAC system. This implies that the pressure differences generated by the HVAC system are much greater than the pressure differences generated by the fire. Tests have been made on both active and passive methods by both actual or simulated fire tests in buildings. Since such experimentation is very costly and time consuming, mathematical models have been developed to simulate smoke movement and control under real fire situations; and in a few cases the results of these models have been compared to the results of experimental tests.

Major contributors to the design of smoke control methods and to mathematical modeling and experimental testing of these methods are: the Building Research Institute, Ministry of Construction, Tokyo, Japan; the National Bureau of Standards, Washington, D.C., USA; the Fire Research Station, Borehamwood, Hertfordshire, England; and the National Research Council of Canada located in Ottawa. The Commonwealth Experimental Building Station of Australia; National Department of Civil Protection in France; Brooklyn Polytechnic Institute Brooklyn, N.Y., USA; Battelle Memorial Institute, Columbus, Ohio, USA; and Georgia Institute of Technology, Atlanta, Georgia, USA, have also made contributions to smoke control methods. This paper is a summary of the contributions of these selected sources, with more detailed comments on the work of the National Bureau of Standards.

2. EXPERIMENTS TO STUDY SMOKE CONTROL SYSTEMS

2.1. National Research Council, Canada (NRC) Experiments

In one set of experiments [1][1] the effectiveness of stair shaft pressurization systems was tested. The pressurization was accomplished by means of external fans which were connected to the stair shaft by aluminum ducts. Plastic tubes 1/4 inch in diameter were strung vertically in the stair shaft from the top — terminating at several levels so that the ends of the tube could serve as pressure taps to measure loss within the shaft. The difference in pressures between each pressure tap and the top of the stair shaft was measured with a pressure meter (diaphram type with silicon piezo-resistive gage). The tests were conducted with two outdoor temperatures 2 °C (35 °F) and 10 °C (50 °F).

Experiments similar to those in reference [1] measured the air leakage of stair shafts and elevator shafts constructed with different types of materials [2]. The results showed that the leakage values for elevator shaft walls constructed of masonry units were a great deal higher than those of cast-in-place concrete. However, for stair shafts which were constructed of masonry and were plastered the air leakage rates were similar to those of the elevator shafts constructed of cast-in-place concrete. They also showed that the internal resistance to flow within a stair shaft was considerably more than that of an elevator shaft.

[1] Numbers in brackets refer to the literature references listed at the end of this paper.

Similar experiments measured the air leakage through the exterior walls of tall buildings [3]. The exterior walls of the buildings tested allowed relatively high air leakage rates, similar to laboratory tests on unplastered brick.

As discussed in Appendix A, pressures can build up in a fire room from the expansion of gas at elevated temperatures, forcing smoke into adjacent areas in the building. One way to avoid this pressure build-up is to vent the fire area by means of a dampered smoke shaft. In the process of venting, the shaft dampers are exposed to high temperature; and for the shaft to be effective the dampers must not allow smoke to leak to other floor areas. A total of six 2-hour fire tests [4] were performed in the NRC wall furnace to ascertain the amount of leakage through the dampers of smoke shafts. Each test involved between three and five dampers. Leakage tests were performed on the dampers both before and after the fire tests. The results indicated that rapid and substantial temperature rise is not likely to give increased leakage, and that curtain dampers, in general, gave less leakage increase due to fire test than other types.

In another set of experiments [5] pressure measurements on a 17-story building were taken, using one of the stairwells as a smoke shaft. The smoke shaft behavior of the stairwell was achieved by opening a vent at the top of the stairwell. Pressure difference readings between key floors were obtained both before and during smoke shaft simulation. Measurements were made with windows in the building closed and open. The results indicated that the smoke shaft was effective when the windows were closed, but not effective when the windows were open.

2.2. Building Research Institute, Japan (BRI)

BRI reported an actual full-scale fire test [6] measuring quantities such as temperature (by thermocouples), smoke concentration, O_2, CO_2, and CO in a five-story building (Welfare Ministry Building). In this test the burn-room was located on the second floor. The maximum fire room temperature was 1300 °C (2372 °F) and the average fire room temperature was 650 °C (1202 °F). The outside temperature was 14.4 °C (57.9 °F) and the wind velocity was 2.5 m/s (.75 ft/s).

The reasons for the test were: (a) to try and correlate real fire test data with that data generated from the Japanese computer model (which will be discussed in section 3); (b) to study the effectiveness of a smoke control method of supplying the stairwells with fresh air to prevent the movement of smoke into the stairwells from the ground floor; and (c) to analyze the combustion behavior in the Sennishi Building Fire by studying a test building (Welfare Ministry Building).

The experiment showed that the results generated by the theoretical model agreed very satisfactorily with the results generated by the field test on this building, and that the smoke control method was very effective, provided that there was a large resistance to airflow between the stairwell and corridor due to a physical barrier.

Simulated smoke tests were also performed using smoke candles to study the effectiveness of blowing air into the stairwells at the ground floor [7]. The results showed that with the burn-room windows open, and the pressurization system on, the output from the burn-room into the stairwell was suppressed.

Two tests were performed in the Training Tower, Tokyo Fire Department, Shibuya, Tokyo. This was a large fire-resistive eleven-story building with a basement. The burn-room was located on the fourth floor. Tests were performed by blowing air into the stairwell with various combination of opening and/or shutting of doors on the first floor and windows of the fourth, seventh and eleventh floors. The results were that smoke movement could not be suppressed even by forced air if the window to the burn-room was closed. When the burn-room windows were open, however, this smoke movement could be suppressed.

A real fire test was performed in ex-U.S. Force's "Ofi Camp," Kitaku, Tokyo. This was a fire resistive building, with five stories above the ground, a basement and a penthouse. The burn-room was located on the second floor. Air was forced into the stair shaft by a fan located on the first floor. The tests were performed for variable quantities of forced air rates and for a variety of openings of windows and doors. The average burn-room temperature was 700 °C. The results were that the stairwell pressurization prevented the movement of smoke into the stairwell.

2.3. Commonwealth Experimental Building Station, Australia

Simulated fire tests were conducted with and without smoke control [8,9]. The purpose of the experiments was to test a multi-story office building for smoke movement; and to determine the performance, under early fire conditions, of a smoke control system. The office building consists of fifteen office floors above the ground floor, a lower ground floor, and upper and lower basements opening onto a car park. Six elevator shafts are continued from the lower basement to the fifteenth floor and there are three elevators opening into a separate lobby serving floors from the ground to the sixth level only. The simulated fire floor was located on the fifth and tenth floors. The building air temperature was around 21 °C (70 °F) at the time of test. Pressure measurements were coupled with the tracing of smoke movement through the dispersion of warm artificial smoke. The smoke was generated by entraining heated droplets of paraffin oil in a stream of carbon dioxide. The pressure measurements were obtained using differential gages. Smoke concentration measurements were obtained using optical density smoke meters with 0.5 meter light paths. These experiments showed that smoke movement occurred quickly; and that smoke control procedures should be implemented early. The experiments also showed that the smoke control procedure, discussed in section 5, was adequate to prevent smoke movement.

2.4. Joint Fire Research Station (FRS), (formerly JFRO)

The FRS conducted simulated smoke tests using standard smoke candles [10]. These tests were conducted at the Pearl Assurance House. Each floor of the building had open window areas of 2-1/2 percent of the floor area for ventilation. The tests measured airflow pressure differentials to determine the effectiveness of a pressurization system for the stairwells and stairwell lobbies. The system prevented the smoke from entering the office space even if the stairwell doors were open. The external weather conditions did not affect the pressurization system in any way.

2.5. Brooklyn Polytechnic Institute (BPI)

BPI conducted both simulated fire tests, using smoke candles, and real fire tests in a building [11,12]. The office building, located at 30 Church Street in downtown Manhattan, was twenty-two stories. Both smoke and heat were generated by four fires set at different locations on the seventh and tenth floors. Maximum fire temperatures recorded were 928 °C - 984 °C (1500 - 1600 °F); and the maximum pressure differential was 37.5 Pascals[2] (.15 inch Water Gage

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[2] 1 Pascal = 1 N/m^2

(W.G.)). The smoke concentration was measured by the attenuation of light. Also during the tests building pressure differentials were measured by using pitot static tubes. The tests evaluated a stairwell pressurization system which will be discussed in detail in section 5. The pressurization system was found to clear the stairwell of smoke both in the simulated and real fire situations.

2.6. Georgia Tech, Atlanta, Georgia, USA

A series of smoke tests for simulated and real fires were conducted in the Henry Grady Hotel, Atlanta, Georgia [13] to test out a proposed smoke control system for the City of Atlanta. The Henry Grady Hotel was: a 550-room fire-resistive building constructed in 1929, a fourteen-story structure of reinforced concrete; stairwells were 98 square feet in cross-sectional area and enclosed a volume of 15,000 cubic feet. The three hotel elevators were contained in a single shaft of 120 square feet in cross-sectional area. In the simulated tests, smoke was produced by an army oil smoke generator which uses a pulse jet engine and fog oil to produce smoke. The resulting smoke movement was monitored by optical density smoke meters. The maximum fire temperature was about 1832 °F (1000 °C). The test showed that the proposed smoke control system was adequate, consisting of a 12000 cfm blower, capable of maintaining an overpressure of 15 in. W.G. in the stairwell.

2.7. National Bureau of Standards

Tests have been performed on five Federal office and laboratory buildings [14-17], an apartment building [18], and six VA hospitals [19-22].

In all of these buildings, SF_6 was used as a tracer with the HVAC system in normal and smoke control modes, for a variety of simulated burn-room locations. Tests were also performed to determine the results of opening various stairwell doors on the effectiveness of the smoke control mode. The simulated burn room temperature, where the SF_6 is released, was in the range of 27 °C (80 °F) to 30 °C (85 °F). The burn-room concentration of SF_6 ranged from around 80 to 170 ppb. The range of outside temperatures during the tests was from -7 °C (20 °F) to around 28 °C (80 °F). The inside building temperatures ranged from 22 °C (72 °F) to 26 °C (79 °F).

In the Seattle and Chicago Federal Buildings systematic pressurization is employed for smoke control. In this method the HVAC system of the fire floor is put on exhaust while the HVAC system of all other floors is put on supply. In these two buildings in addition to the SF_6 concentration measurements, a moderate number of pressure measurements and some meteorological (e.g. temperature and wind speed and direction) data were obtained.

The Roanoke GSA Building is a 15-story office building, employing a smoke control mode which will be discussed in detail in section 5. Extensive pressure measurements and meteorological data were obtained on this building. It was found through these tests that the smoke control system was inadequate. NBS proposed another smoke system, which SF_6 testing and pressure measurements indicated would be effective in controlling smoke.

The Rouse Wates Building is a twelve-story apartment building located in St. Louis, Missouri. This building employs a stairwell pressurization smoke control system with a supply at the top of the stairwell. In addition to the SF_6 concentration measurements, a limited amount of pressure and meteorological data were obtained for this building.

The San Diego VA hospital is a modern six-story structure with a 2.4-meter (8-foot) high interstitial space between each floor. The building consists of four identical wings connected to a symmetrical core. The smoke control for this building was to horizontally pressurize the building so that smoke would not move horizontally from the fire affected part to a non-fire affected part. In this building extensive pressure measurements were made and a moderate amount of meteorological data was taken.

SF_6 tests and a sparse number of pressure and meteorological measurements were performed on two buildings at the NASA Goddard Space Flight Center, buildings 22 and 23, which are four-story office buildings. The tests showed that the existing smoke control mode of exhausting the burn floor only, while all other floors were normal, was not adequate. It was suggested (but not tested) that pressurized stairwells be installed as a smoke control method.

SF_6 tests were also performed on the San Antonio VA hospital to determine smoke movement. This building has a total of seven floors above grade. This building did not have a smoke control system. The results of the tests showed that the interstitial space served as a smoke absorbing void in reducing smoke infiltration. It was suggested that a smoke removal system be implemented in the interstitial spaces of this building.

SF_6 tests and pressure measurements were also performed on the Hines VA hospital. This building has 15 floors and a penthouse above grade level. Also the first and second floors were connected to another building, at grade level, by a corridor through which air moved due to stack effect. This building also has no smoke control system. Potentially hazardous areas of high smoke concentration were established for various fire locations. A smoke control system, has been proposed for this building and follow-up tests are planned when this system is put into operation.

3. THEORETICAL TECHNIQUES TO STUDY SMOKE MOVEMENT AND SMOKE CONTROL IN BUILDINGS

3.1. NBS Computer Model

This model has been developed by Integrated Systems, Inc. under contract to NBS. A detailed description is given of this model since it attempts to integrate many of the features of the other existing models.

3.1.1. Assumptions

The base for the NBS model is described here. Because of the complexity of the smoke simulation model many simplifying assumptions are necessary and used in the existing models to keep the problem tractable. The model employs the basic principles of smoke movement which are discussed in Appendix A.

1. Smoke is assumed to move in the same manner as air. Thus smoke movement between compartments depends on the pressure gradients existing between these compartments.

2. It is assumed that the fire is small. In the case of smoke control, only low energy fires, or the incipient stage of a developing fire is considered. For this case the output energy of the smoke control system (see page 1) is large relative to the fire energy.

3. The pressure forces are in steady-state.

4. Diffusion is considered instantaneous within a given compartment, so that the concentration at any given time within the compartment is uniform. The effect of this assumption is to impose a conservative approach to the build-up of smoke in a given space.

5. The temperatures for the internal parts of the building including the fire areas are known.

In the mathematical model three types of equations are needed: (1) equations describing the movement of the fluid (mass balance and momentum); (2) equations of state, which is the relationship between pressure, temperature, and density of the fluids; and (3) the species conservation equation, which describes the smoke concentration build-up.

3.1.2. Mass Flows

The mass flow rate equilibrium equation for the simulation of the steady-state air movement in a building space is:

$$F_{1j} + F_{2j} + \ldots F_{ij} + \ldots + F_{nj} = 0 \qquad (1)$$

where F_{ij} is the mass flow rate of air between the i-th and j-th building spaces.

This equation is solved for each corridor and compartment on each floor, for all shaft openings, for each supply duct network, for each return air duct network, and for each Air Handling Unit (AHU). The system of equations that must be solved in each case is completely dependent on the building system modeled by the program user. The mass flow rate for different openings sometimes referred to as the orifice equation (and which is a combination of mass flow and momentum equation) is as follows.

$$F = k_{\rho}^{\ x} \nu^{1-2x} \Delta P^{x} \qquad (2)$$

where K is determined as a function of the type of opening, the effective area, and the appropriate flow coefficient for the above types of openings. A moderate opening is defined as having an area the order of 0.01 m^2 (.1 ft^2) to .1 m^2 (1 ft^2). Openings with areas larger than this are classified as large openings, while those having smaller areas are classified as small openings.

x is 1/2 for the large and moderate openings and 1 for the very small or crack-type opening.

F is the mass flow rate (kg/s)

ρ is the density of air on the inlet side (kg/m^3)

ΔP is the pressure difference (kg/m^2)

μ is the viscosity of air on the inlet side of the opening.

External wind leakage can be a significant factor in the effectiveness of the smoke control system and, under certain conditions, can defeat the use of an HVAC system in controlling pressures within a building. Consequently, program capability was provided to define varying conditions operating on the external walls of the simulated building. Ten external wind states, depending on the wind direction were included in the design of the program. Each of these states was then defined by a wind speed normal to the wall, varying with height and at a given temperature. The velocity includes the pressure coefficient, which appears in other models, as will presently be discussed. Temperature is held constant for each wind state. The velocity is given by

$$V = f(h_i, T) \tag{3}$$

where V is the velocity (in meters per second)

T is the temperature in K

$f(h_i, T)$ is a tabular function

h_i is the height in meters at the i-th point.

Excluding an exhaust fan or intake blower interfacing directly with the outside air, all of the airflow in or out of the simulated building is determined as a function of the pressure difference and the degree of leakage in the walls. Consequently, the pressure due to the wind at any given floor level and on any given external wall must be determined.

The dynamic pressure due to the wind was defined as

$$P_d = 1/2 \ \rho \ V^2 \tag{4}$$

where P_d is the dynamic wind pressure (N/m^2)

ρ is the density of the outside air at the given height and temperature (kg/m^3)

V is the wind speed at the given height on the given external wall (meters per second).

3.1.3. Pressure Relationships

Critical to a meaningful simulation is the representation of the airflow behavior within an open shaft, such as a stairwell, elevator shaft, or plumbing chase. Two basic situations are usually encountered with such shafts: (a) a non-pressurized shaft which is coupled for air movement purposes by leakage passages, and (b) a pressurized shaft with specific and designed flow openings as well as leakage openings.

In a non-pressurized shaft the pressure is selected at a most probable location of the largest flow in the shaft.

In a pressurized shaft, i.e., where an inlet blower exists and/or a pressurized condition exists, another relationship was introduced to include the effects of the blower or fan pressurization. An equation (duct equation) was introduced to provide a means of determining the vertical pressure distribution within a pressurized shaft, i.e.,

$$\Delta P_{IO} = \frac{.00020393\ \bar{T}\ F_O^{2} |\Delta h|\ f}{(\bar{A})^{5/2} \bar{P}_{IO}} \tag{5}$$

ΔP_{IO} = is the pressure loss between the fan inlet to the shaft and the major outlet (N/m^2)

$\bar{T}$ = is the average temperature between the shaft's inlet and outlet (K)

Δh = is the vertical distance between the shaft's inlet and outlet (m). (In the case of the stairwell, a correction factor is included.)

$\bar{A}$ = is the average area in the shaft between the inlet and the outlet (m^2)

$\bar{P}_{IO}$ = is the average pressure in the shaft between the major inlet and the major outlet (N/m^2)

f is the friction factor (which is a function of Reynolds Number)

F_O is the mass flow rate at the shaft outlet (kg/min)

The duct loss equation is solved iteratively as an implicit function where

$$F_O = \phi(P_O, P_{ext}) \tag{6a}$$

$$\bar{P}_{IO} = \psi(P_O, P_I) \tag{6b}$$

P_O is the pressure at the outlet

P_{ext} is the pressure on the external side of the outlet

P_I is the pressure in the shaft at the inlet.

The duct loss was assumed to occur between the major inlet point and the major outlet point, where either one could be physically above or below the other. The distance over which function loss occurs was assumed to be the distance between these two locations, except in the case of a stairway. In the case of a stairwell, a lengthened channel was assumed due to the energy losses of a stairwell, and the vertical distance between the defined inlet and outlet was multiplied by a correction factor.

The loss in pressure was included in the continuity condition. A linear relationship was used between the inlet and the outlet to provide the vertical distribution of the pressure loss. If a shaft extends beyond an inlet or outlet a stagnant condition is assumed, with the pressure determined from the inlet or outlet pressures, respectively.

3.1.4. Blower Functions

Initially, an attempt was made to represent a fan or blower as a function of typical fan or blower characteristics and the air state at either the inlet or the outlet. However, the conditions were too complex. As a result, two methods of specifying a fan or blower, both of a simple form, were utilized.

The first method allows a user to specify a blower rotational speed (RPM), horsepower, and an outlet area. From tabular data representing a family of blowers, throughput is determined, i.e., static discharge pressure and volume flow rate at standard conditions.

The second method allows a user to specify the static discharge pressure and the volume flow rate under standard conditions.

In either case, the volume flow rate is converted to mass flow rate; i.e.,

$$Q_B = F_B \rho_S \tag{7}$$

Q_B is the mass flow rate output of the blower/fan (kg/min)

F_B is the specified volume flow rate output of the blower/fan (m^3/min)

ρ_S is the density of air under standard conditions (kg/m^3)

The mass flow rate from a specified blower enters the equilibrium equations coupled at the blower, except in the case of blowers, effectively as a boundary condition, i.e., the mass flow rate for that component is fixed and not allowed to vary as a function of the iterative processes.

The given static discharge pressure is of particular importance in the case of pressurized shafts and enters the solution via the duct loss equation in the continuity relationship. In other cases, where the flow only enters the equilibrium equation, the given static pressure is not directly used.

3.1.5. Air Properties

Air density was calculated at each point in the program as a function of the temperature and pressure of the building space involved in the calculation; i.e., at a constant height,

$$\rho = \frac{.3012\ P}{T}$$

ρ is density (kg/m^3)

P is the pressure (N/m^2)

T is the temperature (K)

The air within an open shaft was treated as a continuous medium and the pressures were determined as a function of the controlling flow and the height. The density became appropriately variable as a function of height. The viscosity of air is a function of temperature and linear segmented curve fit was made over the range of anticipated temperatures.

3.1.6. Solution Procedures

The method of solution chosen for all corridors and compartments on all floors, all shafts, each duct supply and return network, and for each air handling unit (AHU) was a nested iterative solution. The matrix which is generated is nonlinear. Initial values for the pressures for each space are chosen based on the nominal interior state and external ambient condition. When the pressures are chosen, and the temperatures are specified, the densities are known. Thus, the flows can be determined through the orifice equation. These results are substituted into the equilibrium equation. If the right-hand side of the equation is not zero the pressure is incremented and the above process is repeated. When the zero value is reached, the orifice state and continuity equations are solved for the next space. This process goes on until all the pressures in all spaces have been solved. Figure 1 is a diagram of this process.

The second step of solving for the smoke concentrations if the mass flow rates are known can be obtained by the species conservation equation as follows:

$$\rho_i \, V_i \, \frac{dC_i}{dt} = \sum_{i=1}^{N} W_{ji} \, C_i \tag{8}$$

where W_{ji} is the flow rate from space j into space i. (When this is negative C_j is replaced by C_i.)

ρ_i is air density

V_i is the compartmental volume

t is the time.

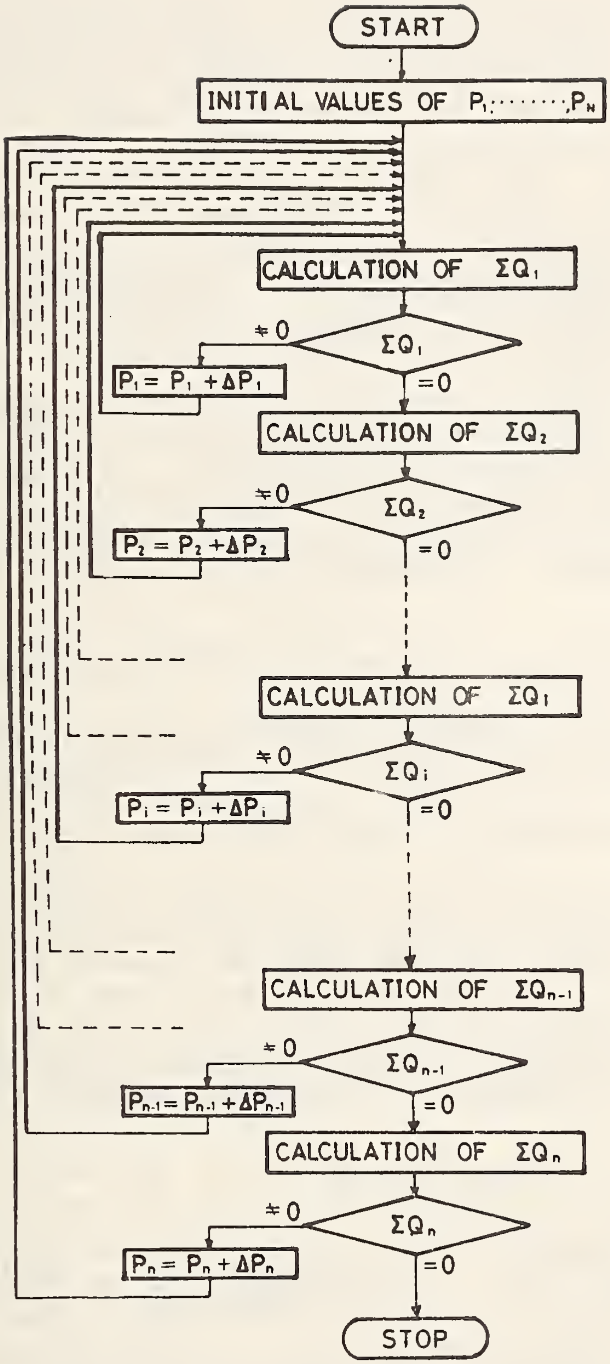

Figure 1. General procedure for calculating mass balance equations in a building including multiple compartments.

At the present time the smoke concentration program is limited to the movement of smoke between a corridor and a shaft and between corridors by a floor to floor leakage term. This program is being modified to remove this limitation. Presently there is no means of predicting lateral movement or to account for all of the various spaces and paths available from the air movement program, or that exist in a real building. This places a significant burden on the user to preselect the shafts which are to be used by the smoke concentration program. This implies that the user must guess, in advance of the air movement simulation, which shafts will be significant. If the user selects the wrong set, he will get erroneous and misleading results.

Although all characteristics of all building systems cannot be specifically represented by the capability of the computer program, the functional representation of almost all characteristics can be modeled by simulation of the available characteristics. Reviews of the NBS smoke movement computer model program are reported in [23-27].

3.1.7. Comparison of Computer Models and Field Studies

To determine if the simulation realistically represents the pressure differentials and smoke concentrations measured by SF_6 tests, five of the buildings discussed in section 3 were simulated by the movement and smoke concentration programs.

The San Diego VA hospital [28], Hines VA hospital [29], NASA Goddard Buildings [30], and the Seattle Federal Building [31], were parametrically modeled and the model was calibrated against field acquired pressure and/or trace gas data collected with the HVAC system in various modes. In most cases the computer model agreed with the experimental tests.

3.2. NRC, Canada

The computer model used at NRC is the forerunner of the one now being used at NBS [32]. The assumptions in this model are basically the same as for the NBS model. The differences between the two methods are: (a) the NBS model is more general in its capability to handle different building configurations, (b) the NBS model includes friction in shafts (c) the NBS model solves for the absolute pressure levels whereas the NRC model yields pressure differences, and (d) the solution technique for the NRC model is to solve iteratively a linearized matrix of the equilibrium equations whereas the NBS method solves a nonlinear equation system iteratively.

3.3. Battelle

Battelle Memorial Institute [33] also used a computer model similar to the NRC computer model. However, the Battelle model was designed to model only the stack effect and is of a much more limited nature than the NRC model.

3.4. BRI, Japan

BRI considered both steady and unsteady models for an air movement program. In the steady situation, they considered two types of programs, a simplified steady-state and a precise steady-state model. The simplified steady-state is a method for solving the mass balance equations only for sources where the major flows are found.

In the precise steady-state model there are two ways of modeling thermal states: methods A and B. Method A specifies the temperatures throughout the building. Method B specifies all the building temperatures except the temperatures in the corridor adjacent to the burn-room. In this corridor, a two-layered flow of smoke above air is considered. The degree of stratification depends on the Reynolds number and Richardson number [34,35]. This situation partially removes the restriction that the air and smoke in all spaces are completely mixed.

If method A is used, the precise steady-state program is comparable to that at NBS, except for minor variations such as the wind pressure expression and the type of orifice equation which is used in the corridor adjacent to the burn-room.

If method B is used, a two-layered flow in which smoke above air is considered, the temperature of the smoke layer is found to decay exponentially with horizontal position (but not time) from the burn-room. These methods intend to solve the problem of the steady-state, or quasi steady, movement of smoke and air in a building as a whole, by computing the quantity of smoke and air flowing through each opening or flow path. The localized flows in specific rooms are neglected in this treatment.

In the unsteady situation the problem of changing building space temperatures and external building temperatures is considered. The burning rate of the fire compartment varies according to the following relationships

$$\bar{R} = 350 \times t \text{ (Kcal/min)}; \quad 0 \leq t \leq 10 \text{ (min)} \qquad (9a)$$

$$\bar{R} = 3500 \text{ (Kcal/min)}; \quad t > 10 \text{ (min)} \qquad (9b)$$

where t is the time.

An energy equation is used to describe the temperature profile.

A discussion of the above Japanese models can be found in [36-38].

3.5. FRS, Computer Model

The Evers and Waterhouse computation method for smoke movement in high rise buildings [39] is very similar to the precise steady-state model of the BRI, using method B [36]. The differences between the two models are as follows: (a) the FRS solve their equations for pressure differences rather than for absolute pressures; (b) the method of solution used by the FRS is the same as that used by NRC; and (c) the FRS allow their program to operate in either of two modes; deterministic or stochastic. In the deterministic mode, the input variables are specified. This mode calculates smoke movement as a result of a particular type of fire under specified environmental conditions. In the stochastic mode, which is used to calculate building risk levels, the stochastic variables are sampled at random from specified statistical distributions using a Monte Carlo technique for each pass.

The following are the stochastic parameters of the model:

1. Location of the fire
2. Temperature of the fire
3. Smoke concentration in the fire compartment
4. Ambient air temperature inside the building
5. Ambient air temperature outside the building
6. Wind speed
7. Wind direction
8. Area of each door opening
9. Area of each window opening
10. Time at which the door of the fire compartment burns down
11. Time at which the window of the fire compartment breaks

The following variables are also considered:

1. Size of cracks around doors
2. Size of cracks around windows
3. Reliability of the ventilation system.

3.6. Brooklyn Polytechnic Institute, Computer Model

The BPI model [40] idealizes the stair shaft as a duct in which the flow is quasi one dimensional. A momentum equation is written expressing the pressure change with height as: a function of the area change of the shaft, the temperature change in the shaft, the mass flow change in the shaft (e.g., due to leakage), the frictional drag in the shaft, and the hydrostatic effect. The exact expression of these functional relationships involves constants which are determined by model scale experiments.

4. DESIGN METHODS OF SMOKE CONTROL

Although the passive methods are briefly mentioned in 4.1, the primary purpose of this paper is to discuss the active methods. There are many methods of smoke control. These methods include the passive methods of top or bottom venting, and use of smoke shafts for evacuation of smoke, and the active methods which use the HVAC system for various types of active smoke control.

4.1. Passive Methods of Smoke Control

The passive smoke control methods of top or bottom venting of a shaft, and use of non-pressurized smoke shafts are the older smoke control methods. These methods are particularly sensitive to environmental changes. They are not subject to adjustment and control as are the active methods. Top venting raises the level of the neutral plane of the shaft. The optimum top vent area is the minimum area that raises the position of the neutral plane to the top of the shaft, so that flow from every building floor is into the shaft. Top venting can assist in the evacuation of smoke which has leaked into a shaft from the fire floor and can keep it from going into other floors. Since top venting of a shaft causes the shaft to become filled with smoke it is highly desirable that a specially dedicated shaft be provided for venting. Thus, stair shafts and elevator shafts should not be top vented.

Bottom venting of a shaft lowers the level of the neutral plane of the shaft. The optimum bottom vent size is the minimum area which lowers the neutral plane of the vent to the first floor. Bottom venting prevents smoke from entering the shaft. Thus, bottom vented shafts can be used for evacuation in the event of a fire. The theoretical concepts for top and bottom venting as methods of smoke control are set forth in NRC publications [41-43] and are based on their theoretical computer model, and on experimentation.

The smoke shaft is a top vented shaft dedicated to smoke removal, which has openings to all the building floors. These openings are controlled by dampers. When the damper on the fire floor is opened smoke moves out of the fire floor into the shaft because of top venting [5].

Sometimes a smoke proof tower is used to prevent stairwell contamination [5,44,45]. This smoke tower consists of a vestibule between each story and the stairwell, with an opening either directly to the outside or to a smoke shaft in one of the vestibule walls. This design can be improved if the vestibule is pressurized. Also the efficiency of smoke removal of a smokeproof tower can be increased by heating the air in the tower with a heater [45].

Inflatable smoke shutters are used to contain smoke movement [46-48]. These shutters are composed of fire resistant material and are normally folded in nonfire conditions. In the event of a fire, these shutters are released and can block the movement of smoke through a passageway.

4.2. Active Methods of Smoke Control

Smoke control by the HVAC system is an active means of smoke control. Smoke control by the HVAC system may be by building pressurization, including systematic horizontal and vertical pressurization, by pressurization of corridors, or by pressurization of stair shafts or smoke shafts.

4.2.1. Pressurized Building Method

The building HVAC system is operated to supply enough air to pressurize all floors above the outside atmospheric pressure [49-51]. Because of leakage into the stairwell and elevator shafts, these shafts are also pressurized above the external building pressure. In the winter-time, because of the stack effect the inside to outside pressure difference of the building increases from bottom to top of the building.

According to estimates by Tamura, McGuire, and Wilson [50] 90 m^3/min (3000 cfm) of air per building story were needed when the outside temperature was 24 °C (75 °F) and the building temperature was 21 °C (70 °F). The authors also suggest an added flow of 9.0 m^3/min per typical stairwell door into the stairwell to make up for leakage. These studies were done on a 20-story model building with 120 by 120 ft floor plan. These NRC estimates are now incorporated into the Canadian National Building Code.

In the absency of an adverse wind or stack effect smoke control can be improved if the fire floor can be vented to the outside, by means of an opening in the building (e.g. broken window) or to a smoke shaft. This creates a lower pressure in the fire floor relative to the other floors and to the shafts of the building and smoke is contained on the fire floor.

NBS has been studying various modes of building pressurization as a method of smoke control. One method of systematic pressurization [14,15,52] consists of dividing the building vertically into horizontal zones to be served by separate air handling systems with each zone containing several floors. In the event of a fire, the HVAC system is switched to a smoke control mode: the fire zone is exhausted and the nonfire zones are supplied with air. This situation creates a positive pressure in the fire-free zones in reference to the fire zone; and prevents smoke movement from the fire zone into the fire-free zones. The optimum number of floors in each zone is found when there is enough pressure difference created by the HVAC system across the stairwell doors to counteract the flow of smoke from the fire floor, but at the same time the pressure difference is not large enough to prevent opening the stairwell doors.

A practical design approach in systematic pressurization is the variable zoning approach [52]. The amount of flow to each zone is proportional to the number of floors in the zone. In the variable zoning approach the supply to each zone can be varied so that the zones requiring the largest amount of flow include the most floors. Thus, in a leaky building, in which the stack effect is very important, and the neutral plane is at midheight the zones incorporating the most floors will be the top and bottom zones. The systematic pressurization technique was studied in the field on both the Chicago Federal Building and Seattle Federal Building.

A zoned systematic method of smoke control, with no horizontal separation, was able to prevent smoke from infiltrating through either stairwells or elevator shafts under both summer and winter conditions in the Seattle Federal Building [14,15]. In addition to confining smoke to the floor of origin, the system was able to effectively reduce the smoke concentration to below 1% of the burn-room concentration, except in the immediate simulated fire area; even with as much as 15 minutes of delay in switching from the normal mode to the smoke control mode.

In an airtight building such as the Chicago Federal Building [14], in which the pressure due to the stack effect was almost negligible, since the outside temperature was 6 °C to 10 °C (42 °F to 50 °F), the force across the stairwell door was about 25 Pa (0.1 in. W.G.), with a maximum recorded pressure of 50 Pa (0.2 in. W.G.). Such pressure calls for an additional force of 40 Newtons (9 lbs) to open the stairwell door. This is the additional force required over and above that needed to counteract the door closer.

Another example of systematic pressurization was studied in a 13-story GSA building in Roanoke, Virginia. The tower portion consists of floors 2 - 13. The planned smoke control mode is as follows: each floor is divided by HVAC zones (no physical barrier exists) into an east side and a west side. If a fire occurs on a floor on the east side, this side is exhausted, and the west side of the fire floor is put on supply; also the east side of the floors above and below are put on supply. All return fans on the east side of the building are put on half speed because of concern over the fiberglass ductwork of the HVAC system collapsing. The HVAC system operates normally in all other parts of the building. If a fire occurs on the west side, the smoke control procedure is the reverse of the one just discussed.

This type of smoke control mode was found inadequate because pressure gradients could not be established on the fire floor to prevent smoke movement, since no physical barrier exists between east side and west side. Also, pressurizing only one side of one floor both above and below did not prevent smoke infiltration into the shafts. For example, with a simulated fire in the east wing of the 4th floor, the 4th floor corridor had 6.3 Pa (.025 in. W.G.) positive pressure differential in the east stairwell and the west wing had 5.0 Pa (0.02 in. W.G.) pressure differential in the west stairwell. The investigation indicated that the best method of smoke control for this building would be to pressurize all floors above and below the fire floor and to exhaust the entire fire floor.

In reference [20] horizontal pressurization as applied to the San Diego VA Hospital is discussed. For this situation the building being studied was divided into four wings enclosing a central core. In the situation of a fire in one of the wings, the affected wing is exhausted and the non-affected wings are pressurized. Thus, a positive pressure gradient is maintained from the nonaffected wings to the affected wing. Pressure differences generated in this situation are on the order of 7.5 Pa (0.03 in. W.G.).

4.2.2. Stairwell Pressurization

Some systems have been designed to pressurize stairwells only, and not the total building. This procedure will keep the stairwells smoke free but not the building itself. Table 1 taken from [53] gives a comparison of the requirements for stairwell pressurization in various countries. As can be seen from the table, the requirements vary considerably between countries. Some countries have considered stairwell pressurization as an adequate smoke control solution and many different methods of stairwell pressurization have been developed.

One experimental design, studied by NBS and tested in a 12-story building in St. Louis, Mo., had a stairwell pressurized by providing a mechanical air supply (fan) at the top of the shaft with 280 m^3/min (10,000 cfm) plus 2.8 m/min (100 cfm) for each door [18]. The stair shaft had a vent at street level. The stairwell opening is directly to the outside. The area of the vent opening is 1.84 m^2, (20 sq ft^2).

With the pressurization system on for a fire in the second floor, under moderate temperatures (outside around 16 °C (60 °F) and inside at 24 °C (75 °F)) the SF_6 concentration in the stairwell at 15 minutes after the start of the test was below 0.1% of the SF_6 concentration in the burn-room. When the pressurization was off the measured concentration at 15 minutes in the stairwell ranged from 4 to 70% of the burn-room concentration. The maximum force needed to open the stairwell doors with the pressurization was around 19.6 Newtons (43 lbs). This occurred on the eleventh floor, near the blower outlet. This large force is a disadvantage for the single outlet pressurization system.

The BRI method of stairwell pressurization is to pressurize with an air supply at the bottom of the stairwell [6]. A self-closing door is used between the fire floor and the shaft. For the five-story Welfare Ministry Building, supplying 1000 m^3/min (33300 cfm) into the stairwell, smoke in the stairwell was removed in 1-1/2 minutes.

Table 1. Comparison of Pressurization Procedures in Various Countries

Country and Code	Mechanical Ventilation Requirements
AUSTRALIA N.S.W. Code	Pressurize Stairways, Ramp, or Passageway to 50 Pascals (0.2 inch Water Gage); Air Velocity of 1 m/s (200 ft/min) through open door, design for 10% open.
CANADA National Building Code of Canada	Pressurize whole building or Stairways and Elevator shafts. No figures for excess pressure levels given but air supplies needed defined in detail.
USA San Diego and Los Angeles	Stair shaft pressurized to 12.5 Pa (0.05 in. W.G.) with 1.2 m^3/s (2500 cfm) extraction at top of stair shaft. Lobbies at a reduced pressure of 25 Pa (0.10 in. W.G.) below minimum stair pressure with an exhaust of 2500 cfm from each lobby. Air supply to lobbies not specified.
New York City Building Code	Stair shaft pressurized to 12.5 Pa (0.05 in. W.G.) at the fire floor with a minimum of 5 Pa (0.02 in. W.G.) at all other floors. (Max. door opening force 11.4 kg (25 lbs) at door knob.
Uniform Building Code of USA	Stair shaft pressurized to 12.5 Pa (0.05 in. W.G.) with a 1.2 m^3/s (2500 cfm) extraction at top of stair shaft. Lobbies have extraction and air supply to give 1 air change per minute with extract at least 150% of air supply. Lobbies shall be at least 25 Pa (0.10 in. W.G.) pressure below stair shaft.
BELGIUM N.B.N. 713.011	Stair shaft pressurized to 50 Pa (0.20 in. W.G.); other conditions not specified yet, although an unspecified minimum air velocity through an open door is mentioned.
FRANCE Directive of 1967	Stairwell brought up to a positive pressure, large extraction from lobbies, and pressure in lobbies is lower than in the stairwell but higher than in the neighboring corridor or accommodation spaces.
UNITED KINGDOM Code now in draft	Stairwell and lobbies pressurized to value of up to 50 Pa (0.20 in. W.G.) depending on building height. Pressure in lobby equal to or slightly less than that in stairwell. No extraction from either stair or lobby. Positive measures to ensure adequate air leakage from accommodation spaces at building perimeter.

Methods of stairwell pressurization are also suggested by NRC [1,40,54,55]. Experimental tests and theoretical studies were conducted on buildings with the air supply at both the top and bottom of the shaft. It was found that with the stairwell doors to both the fire floor and ground floor open, a supply rate based on a rate of uniform pressurization of 25 Pa (0.1 in. W.G.) at all levels maintained the stairwells smoke free. When more stairwell doors were open, there was increased possibility of stairwell contamination with smoke.

With air injection into the bottom, there was a substantial loss of supply air through the open exit door at the ground floor. When air was injected at the top, there was a high leakage rate into the upper floors; and in addition an increased pressure gradient across the upper floor stairwell doors. Both Tamura [1] and Fung [18] concluded that the best stairwell pressurization method would be a more uniform pressurization method in which air supply is injected at several levels. This uniform pressurization scheme was studied by Shaw and Tamura [56]. Air injection occurred at every fifth floor starting from the top, since multiple injection is more effective than single injection for providing an uniform air supply for dilution in the event smoke penetrates the shaft. A further step, used by Shaw and Tamura for uniform pressurization, was to provide a top vent.

BPI experimental work [11] pressurized stairwells by injecting air at the bottom of the stairwell by a fan located in the bottom stairwell doorway and exhausting the air through a fan in the roof vent, or by injecting air into the roof vent through a fan and exhausting the air out a bottom stairwell door. They also studied stairwell pressurization by injecting air at a maximum velocity of 900 m/min (3000 ft/min) at the top and bottom of a stair shaft. Although they did not obtain uniform stairwell pressure profiles, the report suggests that a routine pressure of 5 Pa (0.02 in. W.G.) with respect to the floor space should be maintained throughout the stair shaft, except at the fire floor where a positive pressure of 12.5 Pa (0.05 in. W.G.) should be maintained with respect to the floor space. To accomplish this profile, they suggest the possibility of injecting the air at multiple levels in the shaft and recommended that a maximum velocity of 600 m/min (2000 ft/min) flow through a single open stairwell door and a maximum door opening force of 11.4 kg (25 lbs).

Erdelyi [57] has used a system of uniform injection and uniform exhaust of a stairwell. The injection rates and exhaust rates are respectively suggested at 11.2 m^3/min (400 cfm) and 7.7 m^3/min (275 cfm). The location of the intake fans are placed at random points on the windward side of the building so as to minimize smoke contamination by the intake system. The exhaust intakes are located as close as possible to the stairwell entrance door so as to remove as early as possible any contamination that would enter the stairwell upon opening this door.

Butcher [10,53] in Great Britain has proposed that in addition to uniform pressurization across the stairwell, which in England is 25 to 50 Pa [0.1 to 0.2 in. W.G.], the stairwells should also be protected by pressurized lobbies or vestibules. The pressure in the lobbies should be equal to or slightly less than the stairwell. This pressure should, however, be a minimum of 25 Pa (0.1 in. W.G.) above that in the accomodation. If the stairwell pressure is too large (i.e., 100 Pa (0.4 in. W.G.)) then difficulties might arise in opening stairwell doors. With this pressurization system air flows out of the stairwell, through the lobbies, along the corridor to the fire area, and out of the building at the external wall.

The FRC uniform stairwell pressurization technique requires supply duct openings at every floor level of the stairwell [10,53]. The air for the lobby and stairwell pressurization should be drawn from a point where there is no smoke, e.g. near the ground. Also independent pressurization systems for the stairwell and lobby are needed.

4.2.3. National Department of Civil Protection Method

The French use a dilution system, in which air is introduced into and smoke is extracted from corridor lobbies or staircases [58,59] to maintain a crawling height safe level in the corridors. Also smoke and air are extracted from the fire compartment. The system does not establish a pressure gradient to control smoke movement. The only physical barrier between the lobby and horizontal corridor is a smoke door. The system requires a balance between the supply and exhaust rate; and there is a danger that if the extraction rate is greater than the supply rate a negative pressure gradient from stair shaft to floor space would be established, causing smoke to move into the stair shaft.

4.2.4. Commonwealth Experimental Building Station Smoke Control Method

The Australian code of smoke control is as follows [8]: in the event of a fire in which smoke does not penetrate into the supply or return air ducts of the HVAC system, pressurization of fire escape exits and fire isolated shafts is started; if the smoke penetrates into the return air system, the fire isolated shafts are pressurized, the return air system is exhausted to the outside with only clean outside air delivered as supply air. If smoke penetrates into the supply air system, the supply fan and pressurizing fan are shut down and the outside air fan dampers are closed. When clean air is again available, supply and stairwell pressurization are reversed. One feature which is not required, but is recommended in the code is automatic closure of the damper controlling the supply air to the fire floor, continued exhaust from the fire floor and supply and exhaust of all other floors.

5. SUMMARY AND RECOMMENDATIONS

5.1. A considerable number of buildings have been field tested to study smoke movement. From a review of the literature it appears that the simplest and most meaningful experimental test method for measuring smoke movement is the SF_6 test, used in conjunction with pressure measurements. These tests can be performed in an occupied building during working hours and are completely unnoticed by the people who work in the building.

5.2. The steady-state computer methods of the BRI and FRC model a steady-state pressure profile, with a mathematically obtained temperature profile, in the corridor adjacent to the burn-room. The BRI unsteady air movement model is designed to model unsteady pressure and temperature profiles in the corridor adjacent to the burn-room.

The NBS method can model a larger number of building variables than the other methods. However, the smoke concentration program cannot simulate lateral movement or account for all various spaces and paths that exist in a building. This places a significant burden upon a user since he must preselect the vertical shafts which are to be used by the smoke concentration program.

A defect of all models is that instantaneous mixing is assumed in a compartment, except in the corridor adjacent to the burn-room in the British method and steady-state method B of the Japanese. In a large fire this mixing has a large effect on the building temperature and pressure profiles and, therefore, on smoke movement. Further, no provision is made for the transport due to turbulence from the point of entrance of the smoke into a given space to the point of passing into another space. The NBS model is now being further developed to handle some of these limitations. The assumption of instantaneous mixing of smoke and air is a worst possible case and requires the HVAC system to work harder than is necessary to remove the smoke. This necessitates more fuel consumption and higher operating cost of the HVAC system in the smoke control mode.

5.3. A considerable number of field tests have been conducted by NBS to study the qualitative aspects of smoke control; to provide input into the NBS model and to calibrate the model for use on existing buildings. With the model calibrated for an existing building parametric studies of smoke movement can be done on the computer.

5.4. If smoke is to be controlled in high-rise buildings, to protect the building occupants without complete evacuation of the building, then some type of building pressurization approach should be used. The variable zoned method provides a comprehensive approach to a pressurized building smoke control systems.

5.5. If smoke is to be controlled in high-rise buildings so that evacuation of the building occupants takes place by means of the stairwells, then a method of uniform stairwell pressurization should be used. The stairwell pressure should be 25 to 50 Pa (0.1 to 0.2 in. W.G.) above the pressure in the floor space. Also, the stairwell should not be vented, since compensation for the leakage requires a pressure build-up in certain levels.

5.6 For a building which is divided by a physical barrier into horizontal sections a method of horizontal pressurization may be employed to control smoke movement. By using this method both evacuation of the nonfire wings of the building and property loss are reduced.

5.7 There is considerable diversity today in the approaches used by various countries to achieve smoke control. The techniques and the technology are new; and much expense will be required before optimum solutions can be postulated.

APPENDIX A. BASIC PRINCIPLES OF SMOKE MOVEMENT

One of the basic assumptions in the analysis of smoke movement is that smoke moves with the air along pressure gradients. As indicated by Fung [18], pressure forces can originate by, (a) restriction of volume expansion, (b) by buoyancy forces, including the stack effect, (c) by the effect of wind velocity, and (d) by the pressure differences imposed by the air handling systems.

A.1. Pressure Differences Due to Buoyancy Forces

In references [18] and [20] are detailed discussions of (a), (b), and (c), as cited above, including derivation of formulas from basic principles and comparison of orders of magnitude. The buoyancy force between air at ambient temperature and air containing smoke at higher than ambient temperatures can be expressed as

$$\Delta P_B = 3600 \left(\frac{1}{T_o} - \frac{1}{T}\right) H \tag{A1}$$

where ΔP_B is the pressure difference due to the buoyancy force (Pascals)

H is the heated air column height (meters)

T is the temperature of the smoke column (K) at height (H)

T_o is the ambient air temperature (K)

For a fully developed fire, with a gas temperature reaching about 870 °C (1600 °F) in a room of about 3.1 m (10 ft), the pressure difference in the room due to the buoyancy force i 25 Pascals (0.1 in. W.G.).

Another type of buoyancy force involved in smoke movement in buildings is caused by stack effect. This force is generated by differences in densities due to the difference in temperature between air inside and outside of a building. The pressure difference due to the stack effect can be written as

$$\Delta P = 3600 \left(\frac{1}{T_o} - \frac{1}{T}\right) h \tag{A2}$$

where ΔP is the pressure difference due to the stack effect (Pascals)

h is the height (meters) above or below the neutral plane of the building (the position where $\Delta P = 0$)

T is the inside building temperature

T_o is the outside building temperature

The form of equation (A2) is identical to that of (A1): the difference is in the meaning of the height term. Equation (A2) indicates that for a 31-meter (100-foot) tall building with the neutral plane at mid-height and a 39.2 °C (70 °F) temperature differential, a stack effect or pressure difference of 25 Pascals (0.1 in. W.G.) would exist.

In the winter time the building temperature is higher than the outside temperature. Below the neutral plane at this time of the year the pressure outside the building is higher than inside, and the flow in the lower floors moves from outside the building to inside. Above the neutral plane of the building the reverse condition occurs. The position of the neutral plane is determined by the condition that the mass flow into the building below the neutral plane is equal to the mass flow out of the building above the neutral plane. In the summertime, the flow directions are the reverse of the winter time.

In addition to the stack effect which may occur in a building, a local buoyancy effect may occur on the fire floor, in the event of window breakage [60,61] or open doors to the burn-room. Outside air would enter a door opening through the bottom and exit through the top. For a door opening 2 meters (6 feet) high (with a neutral plane at mid-height) and with a burn room temperature of 871 °C (1600 °F) the pressure difference given by equation (A2) is 4.1 Pascals (0.02 in. W.G.).

A.2. Pressure Differences Due to Restriction of Volume Expansion

The volume output from a fire depends on the ratio of the absolute fire temperature to absolute ambient temperature. If the fire temperature reaches 1151 K (2059 °R) and the ambient room temperature is 294 K (529 °R), the effect of the temperature increase can represent a four-fold expansion of gas at room temperature. If there is no outflow from the burn-room the pressure will increase four-fold. If there is volume outflow from a fire the average pressure due to the outflow is given [18]:

$$2.5 \times 10^{-1} \left(\frac{\overset{\circ}{R}}{T_o A}\right)^2 T \leq P \leq 1.0 \left(\frac{\overset{\circ}{R}}{T_o A}\right)^2 T \qquad \text{(A3)}$$

where ΔP is the pressure difference in Pascals

T is the burn-room temperature (K)

T_o is the ambient room temperature (K)

A is the area of the opening in m^2

$\overset{\circ}{R}$ is the burning rate in kg/min.

The inequality represents a range of air to fuel ratios which occur in different fires. The above shows that the pressure difference across the outlet of a burn-room is directly proportional to the absolute temperature and the square of the burning rate, and inversely proportional to the square of the burn-room outflow area.

In a fully developed room fire, with a burning rate of 4.55 kg/min (10 lb/min) and the upper air temperature at 870 °C (1600 °F), a 1.84 m^2 (20-ft^2) doorway opening will have a pressure difference of 0.037 Pascals (0.00015 in. W.G.) to .147 Pascals (0.0006 in. W.G.): A 0.018 m^2 (2 ft^2) small window opening can have a pressure difference of 3.7 Pascals (0.015 in. W.G.) to 14.7 Pascals (0.06 in. W.G.) across the window opening.

A.3. Pressure Difference Due to Wind Velocity and Wind Direction

Because of viscosity the wind velocity profile on the windward side of the building is of a boundary layer type [61]. The outside wind velocity will produce a pressure gradient, which is positive from outside the building to inside the building on the windward side, and the reverse on the leeward side. This sets up a horizontal movement throughout the building. The magnitude of this movement depends on the flow paths into and within the building, the wind speed, and wind direction. The wind speed and direction are variable. In references [60] and [61] statistical data for wind properties are available.

The wind pressure gradient can be calculated according to the following formula [2]

$$\Delta P = \frac{V^2}{20.16T} \qquad \text{(A4)}$$

where V is the velocity (meters per minute)

T is the temperature (K)

ΔP is the pressure difference (Pascals)

For example if there is a 396 m/min (1320 ft/min) wind and the temperature is 273 K (459 °R) the wind pressure generated is 25 Pascals (0.1 in. W.G.). Thus, it appears that when the height of the fire is small and the burn-room door is open, the order of magnitude of the pressure difference due to the stack effect (both local and global) and wind pressure are much larger than the pressure difference due to volume output of the fire and the buoyant force between the smoke and ambient air [5,6,7,18,39,4].

Other authors have discussed the buoyant forces including the stack effect and overpressure due to fire [60,61]. For further discussion of these factors the reader is referred to these papers.

A.4. Pressure Differences Caused by Air Handling Systems

So far we have discussed natural buoyancy and fire induced pressure effects. These forces cause smoke to move throughout a building during a fire, through cracks, openings and vertical shafts. With the HVAC system turned off, smoke can also move through the duct system by stack action and buoyancy pressures, to infiltrate the remainder of the building [50,62]. If the HVAC system is in operation, smoke will be taken into the return air duct system and move throughout the building under the system pressure, [50,60, 62].

The HVAC system can either move smoke throughout the building or be used to control smoke movement. By creating areas where the pressure is greater than the buoyancy and stack pressures discussed previously, the smoke can be kept out. By creating areas of low or negative pressure smoke can be made to exhaust. Various arrangements of controls for smoke movement are discussed in references [17,61]. The subsequent sections in this report will discuss both field tests and analytical procedures used to measure and predict the pressure developed by various control systems.

Building leakage may play a very significant part in the pressure gradients affecting smoke movement in leaky buildings [14]. In tightly constructed buildings, the air handling system more than compensates for the possible leakage of air into and out of a building due to the stack effect. In other words, these buildings can be considered air tight with the makeup flow generated by the air handling system. Although there is no perfectly airtight building, one can compensate for small amounts of leakage with the makeup air supply from the air handling system. With a leaky building, the HVAC system may require supplementary capacity to make up for the air leakage.

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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.)*

A state-of-the-art review of efforts in smoke movement and smoke control is presented. Basic principles, experimental techniques and results, computer models, and smoke control methods which have been employed are presented. The paper covers all work in the area of smoke movement and smoke control but emphasizes the work of NBS.

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)* Basic principles; computer calculations; computer modeling; experimental methods; smoke control methods; smoke movement; smoke simulation; state-of-the-art review.

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Much time and effort during this first Quarter of FY 77 has been devoted to the coordination of electrode/insulator tests in various MHD facilities. This involved close collaboration with a number of MHD-contractors and sub contractors with respect to the procurement of materials, the design of electrode/insula tor assemblies, as well as the planning and information of actual running conditions. NBS is participating in a number of test series: the U-02 experiments, the ANL/Reynolds screening tests for U-25 electrodes, the recently initiated accelerated program of elec trode testing in the MIT rig, as well as the AVCO program on materials for slagging con ditions. A considerable number of tested electrode assemblies were received by NBS; these are being analyzed and evaluated using optical microscopy, x-ray diffraction and SEM techniques. Valuable information was obtained concerning the durability of various electrode materials and the possible causes of degradation. Two major problems address during this reporting period were: a. The fabrication of relatively thin layers (1-4mm) of spinel, zirconia and chromite by means of arc plasma spraying and, b. The joining of ceramics to metal-alloy leadouts. Because of the heavy emphasis on Materials Testing a Characterization (Task K), work in other areas was somewhat reduced. Progress on other tasks included: 1. Viscosity was determined of some slag (Illinois #6) obtained from t UTSI MHD-channel. 2. Additional data were obtained relevant to the interaction of seed and slag. 3. A thorough investigation was made of reaction layers on Corhart X-317 Cera mics exposed to flyash and seed in the test rig of the Fluidyne Eng. Corp. 4. A number of new and modified spinels were prepared and electrical conductivities of these materi were measured.

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*)

AVCO; electrode/insulator; magnetohydrodynamics; U-02

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