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R. E. BARRETT
Member ASHRAE

D. W. LOCKLIN
Member ASHRAE

Computer Analysis of Stack Effect in High-Rise Buildings

Stack effect is the phenomenon observed in cold weather when a tall building acts like a chimney, with air entering openings on lower floors, flowing upward through the building, and leaving through openings in upper floors. Stack effect results from the difference in density between the warm inside air and a like column of cold outside air, and often it creates undesirable pressure differentials and air flows. This paper presents an approach, with an example, for predicting the magnitude of potential problems so they may be minimized during building design.

PROBLEMS CAUSED BY STACK EFFECT

In zero-deg weather, an 800-ft building can develop a stack effect with pressure differentials totaling 2.0 in. of water along the air flow paths. High winds can contribute a similar component sometimes greater than 1.0 in. of water, so that the total stack effect may exceed 3 in. of water (or approximately 15 lbs per ft^2).

Stack effect can cause functional problems in building operation and nuisance problems for the building occupants. These problems can be categorized as follows:

1. Problems due to unwanted and uncontrolled air flows:
   a. Objectionable drafts and wind noise may be present in the vicinity of doors and elevators.
   b. Infiltration, exfiltration, and thermal loads may differ significantly from design values in local areas.
   c. In the event of a fire in the lower floors, smoke may enter stairways and elevator shafts and spread to upper floors.
   d. Moisture gained in the building may cause condensation and freezing problems as it exfiltrates from upper floors.
2. Problems due to pressure differentials per se:
   a. Leaf doors may be difficult or impossible to open manually, and elevator doors may be jammed against their rails (creating a safety hazard in an emergency evacuation).
   b. Pressure differentials across doors, windows, and interior walls may exceed design loads.
   c. The operating point of HVAC-system fans may shift where stack-effect pressures are superimposed on system design pressures.

Some of these problems can be reduced by relatively minor modifications to the building. An example is the use of revolving doors or two-door vestibules in critical areas where excessive forces are required to open single doors. Interrupting doors in stairways may also assist in controlling flows and pressure differentials. Altering the HVAC-system fan

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R. E. Barrett is a Research Engineer and D.W. Locklin is Associate Chief, Thermal Systems Research Division, Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio.
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selection and control to pressurize the building by providing a surplus of supply air over exhaust air is particularly effective for reducing pressure differentials across entrance doors at the street level; this is feasible in buildings with reasonably tight wall and window construction. Determination of exactly what modifications will reduce problems in a particular building requires a thorough knowledge of how the building will function under various operating conditions.

Tamura and Wilson have presented a generalized computer model[1] for studying important construction characteristics, including wall and internal leakage resistances, as they influence pressure differentials resulting from stack effect and HVAC-system operation. Measurements on Canadian buildings[2,3] verify their modeling technique and provide useful background for evaluating resistances of typical construction from a stack-effect viewpoint.

The approach to stack-effect analysis outlined in this paper represents a similar application of theory, but it is directed toward detailed predictions of pressure differentials and air flow for a specific building design so that alternative designs can be evaluated in advance of construction.

Specific Information Obtainable from Stack-Effect Analysis

A study of the type described makes possible the following predictions:

1. Pressure in all spaces examined
2. Pressure differentials across doors (establishing forces necessary to open doors)
3. Pressure differentials across exterior walls and windows, plus certain critical interior walls
4. Infiltration and exfiltration through exterior walls
5. Air flow quantities through all flow paths examined (including HVAC-system in off-design conditions).

These predictions can be examined to identify potential problems in specific parts of the building. Appropriate design modifications can then be suggested and evaluated in subsequent analyses.

ANALYSIS OF STACK EFFECT

The method of analysis outlined here involves determining the air flows for all possible paths through exterior walls and within the building. Air flows and pressures at all locations in the building are interdependent, so a change in any location can affect the overall pressure and flow balance in all parts of the building.

For analysis it is convenient to divide a building into multi-story zones based on the design of both the building and the HVAC-system. Air flows into and out of these zones are calculated by iterative techniques until balance is achieved. If air flows for individual floors are needed, these values can then be predicted on the basis of the zone results.

Example Building

Fig. 1 is a sketch of the 75-floor building used here to illustrate the method of analysis. This hypothetical building is typical of modern office buildings having curtain-wall construction. Zones 1, 3, 4, 7, and 8 are occupied zones, with all the floors of any one zone linked together by HVAC-system ducting. Zones 2, 5, and 10 are HVAC equipment floors serving the various portions of the building. Zone 6 is an elevator-transfer sky lobby, and Zone 9 is a restaurant near the top. The below-grade zone is a garage. It is assumed that there is free passage of air both vertically and horizontally within each zone through the HVAC-system ducts.

Fig. 2 shows some of the air-flow paths considered in the analysis. The basic paths are as follows:

1. From outside to zones (through walls, entrance doors, and HVAC-system fans)
2. From outside to stairways (through smoke holes)
3. From outside to elevator machine rooms (through supply fans and exhaust fans)
4. From zones to elevator shafts, stairways, and machine rooms (through doors)
5. From elevators to machine rooms (through smoke and cable holes)
6. From stairways to other stairways (through interrupting doors).

Computer Technique

Once the building is divided into zones and the

ıracteristics of all air-flow paths have been estab-
ned, the stack-effect air-flow quantities and pres-
·e differentials can be evaluated. The first step in
: solution is to assume pressures in each unique
ilding space based on linear predictions plus
ıgment. (The example building is divided into a
:al of 37 unique spaces comprising 7 occupied
nes, 13 elevator shafts, 1 stairway, 3 equipment
›ors, and 13 elevator-machine rooms.)

Pressures at each point in the building are ex-
essed as absolute pressures. Therefore, all air-
›w calculations are based on the difference be-
'een two absolute pressures, thus avoiding the con-
sion over signs which can result when air-flow
ılculations are based on relative pressure differen-
als. Final results can still be expressed as relative
:essure differentials by subtracting absolute pres-
ıres, and the direction becomes evident.

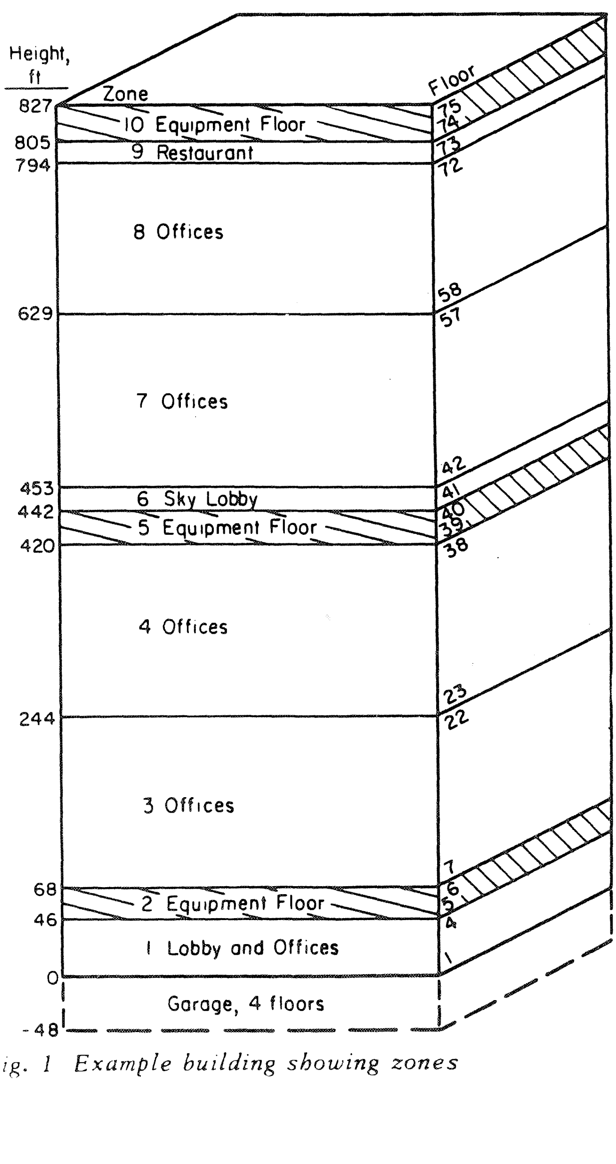

Fig. 1 Example building showing zones

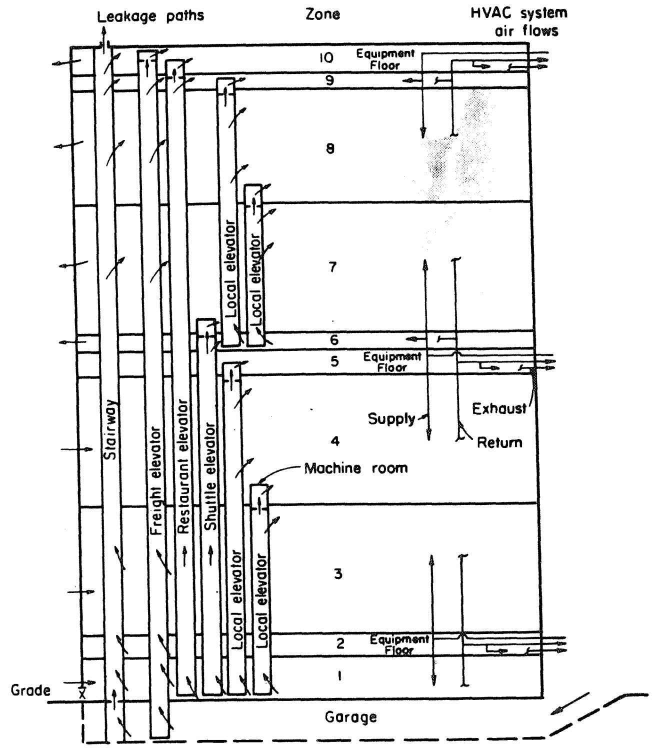

Fig. 2 Typical air-flow paths in example building

The computer is programmed to:

1. Calculate flows using conventional orifice flow equations (approximately 150 paths in the example)
   a. from outside to every space
   b. from each space to every other interconnected space
   c. through HVAC fans, adjusted for off-design pressure differentials
2. Sum up the total of all flows into and out of each space (net flow)
3. If the net flow for any space does not equal zero, calculate a new pressure for that space
4. Repeat steps 1-3 for all spaces simultaneously until net flow for each space is near zero.

Fig. 3 is a generalized logic diagram for the program, which was run on a CDC-6400 digital computer. To arrive at an acceptable solution for each condition examined, 150 iterations were used.

The programming of the iteration procedure includes changing pressures by relatively large increments during the first few iterations and gradually reducing the size of the increments as the iteration progresses. This program enables the computer to quickly correct major unbalanced conditions and reach approximate values, but also allows the small refinements necessary to obtain accurate final results.

DETAILS OF EXAMPLE BUILDING

Building characteristics for the example were selected as being typical of current design practice in high-rise buildings. In addition to the general configuration shown in Figs. 1 and 2, detailed assumptions are as follows.

Building Characteristics, Along Air-Flow Paths

1. Wall leakage for various cases: zero, 0.06, 0.20, and 0.60 cfm/ft^2 at 0.30 in. of water pressure differential
2. Walls of equipment floors of same tightness as other walls
3. Below-grade garage area at same pressure as outside

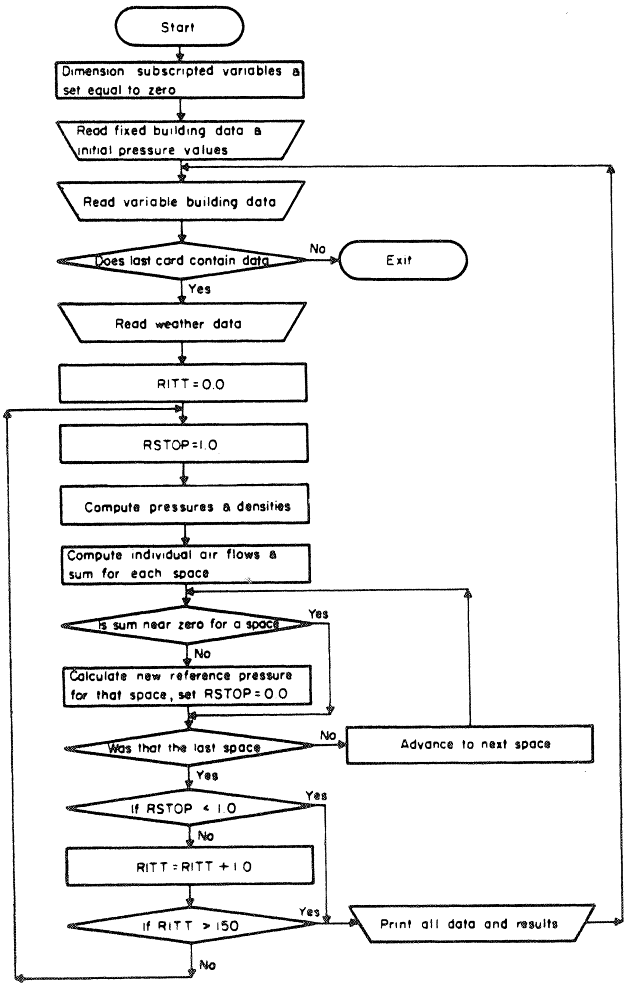

Fig. 3 Generalized logic diagram of stack-effect computer program

4. Revolving entrance doors, plus leaf entrance doors with vestibules.
5. Infiltration through entrance doors in agreement with data in ASHRAE HANDBOOK OF FUNDAMENTALS[4]
6. Single doors at stairways on all floors and at elevator-machine rooms
7. Leakage area for interior doors: 0.2 ft^2 per door
8. Elevator door peripheral crack area
   Shuttle and freight – door open: 8 ft^2 per door
   – door closed: 1 ft^2 per door
   Local – door open: 10 ft^2 per door
   – door closed: 0.7 ft^2 per door
9. Elevator smoke and cable holes: 2 ft^2 per elevator
10. Stairways: 2 from below grade to Floor 75, with interrupting doors between garage and Floor 1
11. Stairway smoke holes: 1.0 ft^2 per stairway
12. Flow coefficient for all leakage calculations: 0.9

Occupant Traffic Rates and Elevator Usage

1. Occupants entering or leaving building at rate of 8500 per hour
2. Elevator door position, % of time
   Shuttle elevators – door open at Floor 1 – 25%
   – all doors closed – 50%
   – door open at Floor 41 – 25%
   Local elevators – door open at Floor 1 or Floor 41 – 20%
   – all doors closed – 30%
   – door open at occupancy levels – 50%
3. All stairway doors remain closed

HVAC-System Characteristics (See Fig. 4 for schematic)

Occupied zones, sky lobby, and restaurant

1. Supply fans
   Periphery zones: Induction system, fan ΔP = 10.0 in. of water
   Interior zones: Single-duct reheat system; fan ΔP = 6.0 in. of water
2. Return fan ΔP = 2.0 in. of water
3. Exhaust fan ΔP = 1.2 in. of water
4. Supply air: 0.75 cfm per ft^2 gross floor area
5. Return air: 0.62 cfm per ft^2 gross floor area
6. Exhaust air: 0.05 cfm per ft^2 gross floor area

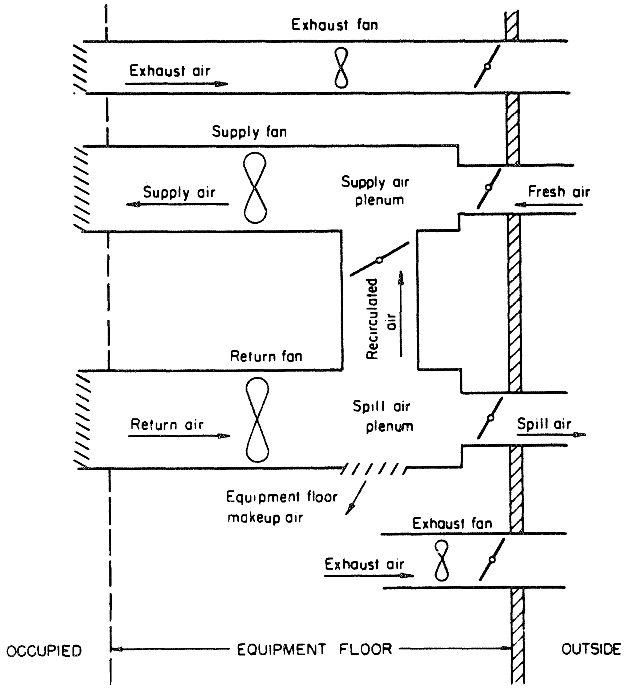

Fig. 4 Schematic of HVAC system

Equipment floors

1. Grills in spill-air plenums permit a volume of air to enter equipment floors equal to 80% of equipment-floor exhaust air at design condition
2. Exhaust air: 1.0 cfm per ft^2 gross floor area

Elevator – machine rooms

1. Supply and exhaust air: 11 cfm per ft^2 gross floor area
2. Supply fan ΔP = 4.0 in. of water
3. Exhaust fan ΔP = 1.2 in. of water

General operating data

1. HVAC system balanced on mild day
2. Fan characteristics typical of conventional fans
3. Spill air plenum operates at 0.25 in. of water above outside air pressure
4. Supply air plenum operates at 0.25 in. of water below outside air pressure

Fig. 5 shows how stack effect influences the operation of HVAC-system fans. Fans normally operate at the design point, where the head developed by the fan equals the system pressure losses due to ducts, dampers, and distribution units. Stack-effect pressure differentials must be added to system pressure losses to obtain the operating point under stack-effect conditions. At the top of the building, stack-effect decreases supply-air flow and increases return and exhaust-air flow. The reverse is true near the bottom of the building.

Wind Effects

Fig. 6 shows how the wind component effect can be generated. Wind tunnel tests[5] and measurements on buildings[6] have shown that the low pressures on 3 sides of a building during a high-velocity wind can more than offset the ram pressure on the windward side and, thus, generate a net suction on the exterior walls on a given level. Also, wind velocity at the top of a tall building usually is greater than wind velocity at ground level. This tends to depressurize the building at the top and induce an upward flow of air within the building. Air enters near the ground where the lower velocity wind produces a much lower net suction. Therefore, the wind contributes an airflow component similar to stack-effect.

It is assumed in this analysis that the net suction at any elevation in the building due to wind is directly proportional to the elevation. Other net suction-to-elevation relationships could be used. In the following discussion the term stack-effect is taken to include the wind component unless otherwise specified.

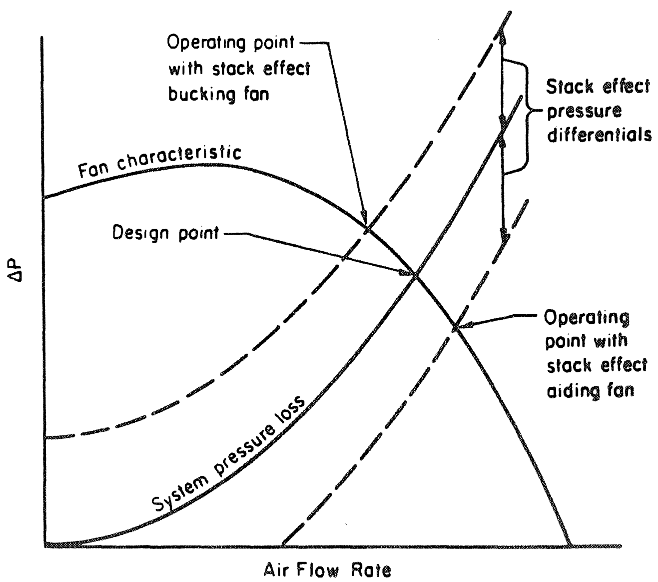

Fig. 5 Stack-effect influence on HVAC-system operation

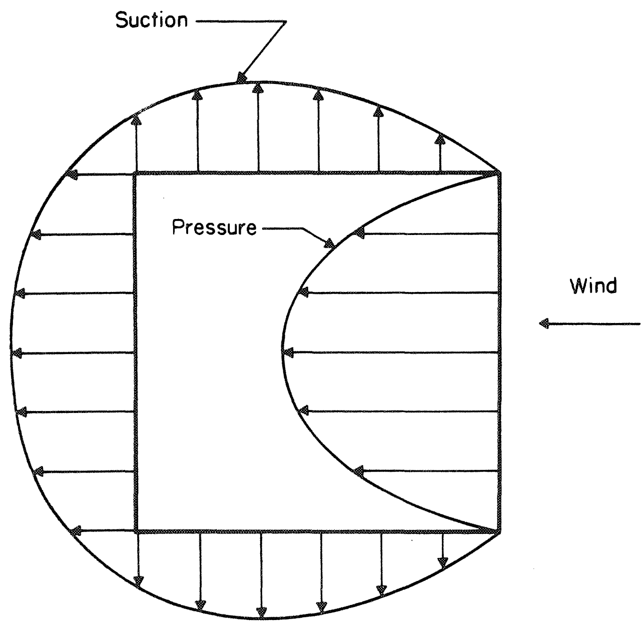

Fig. 6 Illustration of wind effect producing a net suction on a building

Two aspects of wind not included in this analysis are: (1) local flow across the building resulting from wind pressure on one side and suction on another side and (2) directional influence of wind on HVAC-system operation. In addition, flow resistance within zones and wall friction of air flowing in shafts are neglected as being insignificant compared with other resistances.

RESULTS OF ANALYSIS FOR EXAMPLE BUILDING

The three principal variables included in the example are: exterior-wall tightness, outdoor temperature, and wind velocity.

Cases Considered

Table 1 defines the quantities assigned to the variables for the individual cases discussed in this analysis. Case I is considered to be the balance condition on a mild day when stack-effect is not present; HVAC-system air flows are generally designed and balanced for this condition. Case II is for the same wall tightness, but on a cold, moderately windy day when stack-effect is severe. This is considered to be the basic winter case for this analysis. Results of the solution for Case II are discussed in detail, with air flows and pressures compared to those of Case I.

Cases III through VI are for the same wall tightness as Cases I and II, but outdoor temperature and wind are varied. Cases VII through IX represent the same environmental conditions as Case II, but wall tightness is varied.

The wind level in Cases II, IV, and VII through IX is moderate, producing a net suction at the top of the building of approximately 0.6 in. of water. For Case VI, the suction due to wind is doubled to simulate a severe condition.

TABLE 1

WALL TIGHTNESS AND ENVIRONMENTAL FACTORS FOR CASES EXAMINED

CASE	WALL LEAKAGE, CFM/FT²*	OUTSIDE TEMP, F**	WIND-EFFECT COMPONENT, IN. WATER
I Balance Condition	0.20	75	0
II Basic Winter Case	0.20	0	0.6
III Summer Condition	0.20	100	0
IV Balance + Wind	0.20	75	0.6
V No Wind	0.20	0	0
VI Severe Wind	0.20	0	1.2
VII Tight Wall	0.00	0	0.6
VIII NAAMM Std. Wall	0.06	0	0.6
IX Loose Wall	0.60	0	0.6

*At 0.30 in. of water pressure differential

**Inside temperature 75 F in all cases

Four values of wall tightness were considered in example:

(a) perfectly tight wall with zero leakage;

(b) leakage of 0.06 cfm/ft^2, based on the NAAMM standard for curtain-wall construction[7];

(c) leakage of 0.60 cfm/ft^2, based on leakage rate measurements on three Canadian buildings of curtain-wall construction[3]; and

(d) leakage of 0.20 cfm/ft^2, intermediate between (b) and (c), as might be expected of modern, fixed-window, curtain-wall buildings after several years' service.

nparison of Balanced Condition and Basic Winter se

;. 7 shows the design HVAC-system air flows for se I, the mild-weather condition for which the air ıdling system is balanced. These air-flow rates presented as a basis for comparison of HVAC-stem air flows calculated for other conditions. ;. 7 gives a simplified view of the air flows for building; flows into and out of all elevators and irway shafts and elevator-machine rooms are ıped to represent one composite shaft. All shafts treated as one to simplify the presentation of ults, even though the numerical values are based the computer analysis in which all flow paths are ısidered separately. The net flow into or out of y zone may not be quite equal to zero because the nber of computer iterations is arbitrarily limited, : the net unbalanced flows are small if compared th total flow through the zones (generally less ın 3%).

The values shown on Fig. 7 for the HVAC-system r flows are the supply, return, and exhaust flows ıtering and leaving the zones (as shown in Fig. 4); ese are not values for the fresh-air and spill-air ıantities entering and leaving the building. Wall ıd door-leakage values are also shown for both the :terior wall and the shaft boundaries. Examination the net flows for the occupied zones reveals a net ıpply-air flow into these zones through the HVAC-stem, as expected. This net supply-air flow tends pressurize the building slightly.

Results of the analysis for Case I indicate that r flows are in the directions shown by the arrows. his is the preferred flow pattern: from occupied

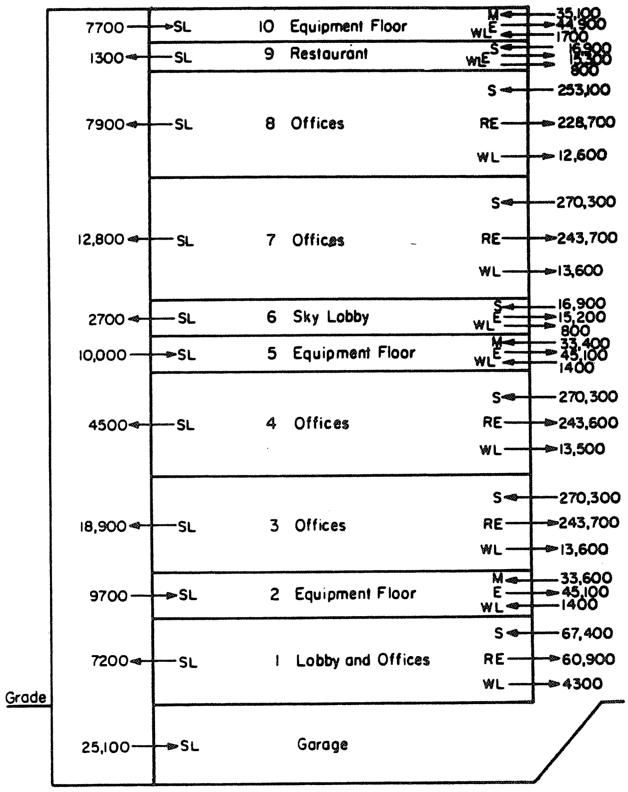

Fig. 7 Air flows for Case I, balanced condition

zones, to shafts, to equipment floors and garage, thus keeping any equipment odors from reaching occupied areas. Exterior wall leakage is slightly less than 1000 cfm per floor for all floors, except Floor 1 where entrance doors provide a larger leakage area.

Fig. 8 shows the air flows for Case II, the basic winter case, through the HVAC-system and various leakage paths. Comparison of Fig. 8 and Fig. 7 reveals the quantitative influence of stack-effect in altering the HVAC-system air flow and leakage air flow over those for the balance conditions.

Fig. 8 shows that the stack-effect air flows occur as predicted by theory: from outside into lower zones, into the shafts, up the shafts, into the upper zones, and to the outside. Because of the flow from the Zone 2 equipment floor to the shafts, equipment odors from this floor can enter occupied areas in the upper portion of the building.

Table 2 compares the HVAC-system air flows for Cases I and II. It can be seen that stack-effect causes an increase in air supplied to the lower zones and a decrease in air supplied to the upper zones. The reverse occurs in the lower zones.

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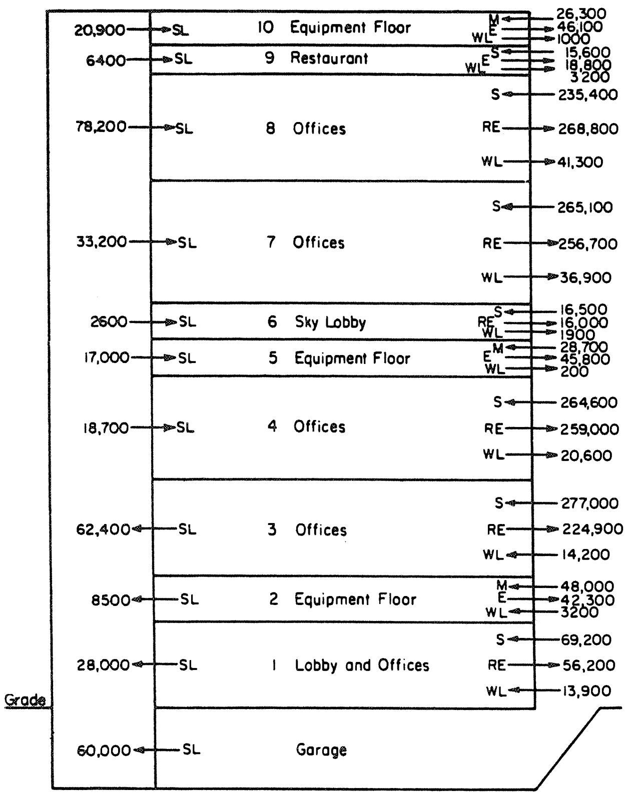

Fig. 8 Air flows for Case II, basic winter case (zero F and moderate wind)

The net-flow predictions in Table 2 show that stack-effect reverses the direction of the net HVAC-system air flow for some zones. For example, Zone 8 is designed for a net air supply of 24,400 cfm but operates with a net return (including exhaust) of 33,400 cfm for Case II conditions.

Stack-effect does not produce as large a shift in air-flow quantities for the air-supply fans as it does for the return and exhaust fans because the pressure heads for the supply fans are 6 and 10 in. of water, while the design pressure heads for the return and exhaust fans are 3.0 and 1.2 in. of water, respectively. Altering the zone-to-outside pressure differential by a fixed amount does not have as much effect on high-pressure fans as it does on low-pressure fans. Comparing Cases I and II for Zone 8, the 1.3 in. of water pressure differential caused by stack-effect decreases supply air only 7.0% while it increases return and exhaust air by 17.5%.

No conditions were revealed where there would be reverse flow in the fans as would occur if stack-effect pressure differential exceeded the fan head. However, this would be possible if low-pressure supply fans were used in tall buildings.

Fig. 9 shows the pressure differentials across the exterior walls and across the freight elevator doors at various elevations for Case II. Reference level for the elevation is grade level. This illustrates how stack-effect pressurizes the occupied zones above atmospheric pressure on the upper floors. Pressure differentials across exterior walls are slightly over 1.7 in. of water at the top of the building and the neutral point is located at about Floor 18, significantly below the mid-height.

The almost continuous gradient for the pressures in occupied zones indicates that, because internal-leakage areas are greater than exterior wall leakage areas, the occupied zones act as essentially one large zone. The shaft pressures become adjusted to about the same pressure gradient and, therefore, pressure differentials between shafts and occupied zones are small.

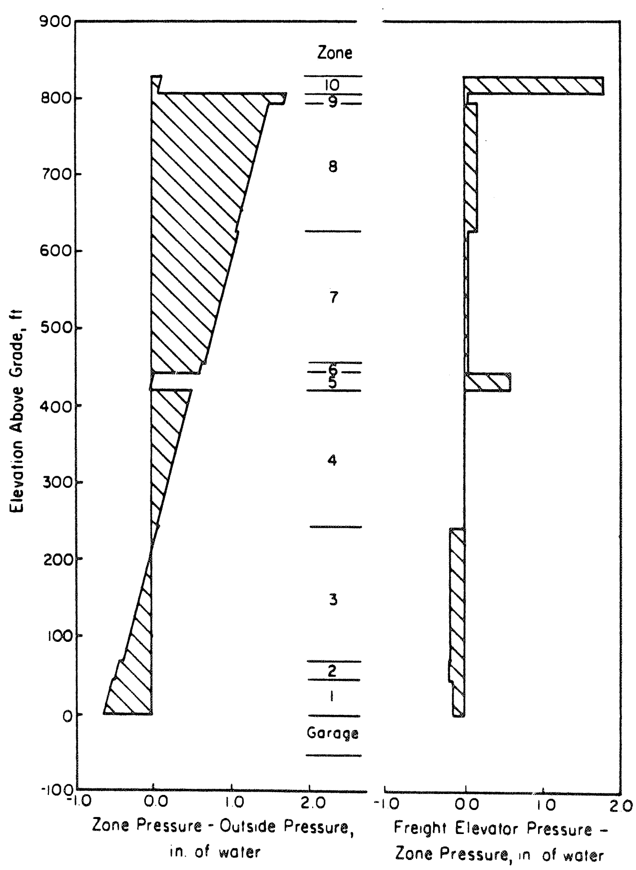

Fig. 9 Zone-to-outside and freight elevator-to-zone pressure differentials, Case II

TABLE 2

COMPARISON OF HVAC-SYSTEM PERFORMANCE FOR
CASE I BALANCE CONDITION AND CASE II BASIC WINTER CASE

ZONE	AIR SUPPLIED TO ZONE			AIR REMOVED FROM ZONE			NET FLOW INTO (+) OR FROM (−) ZONE	
	CASE I, CFM	CASE II, CFM	CHANGE, %	CASE I, CFM	CASE II, CFM	CHANGE, %	CASE I, CFM	CASE II, CFM
1	67,400	69,200	+2.7	60,900	56,200	−7.7	+6,500	+13,000
2	33,600	48,000	+42.9	45,100	42,300	−6.2	−11,500	+5,700
3	270,300	277,000	+2.5	243,700	224,900	−7.7	+26,600	+52,100
4	270,300	264,600	−2.1	243,600	257,900	+5.9	+26,700	+6,700
5	33,400	28,700	−14.1	45,100	45,800	+1.6	−11,700	−17,100
6	16,900	16,500	−2.4	15,200	16,000	+5.3	+1,700	+500
7	270,300	265,100	−1.9	243,700	256,700	+5.3	+26,600	+8,400
8	253,100	235,400	−7.0	228,700	268,800	+17.5	+24,400	−33,400
9	16,900	15,600	−7.7	15,300	18,800	+22.9	+1,600	−3,200
10	35,100	26,300	−25.1	44,900	46,100	+2.7	−9,800	−19,800

Because the air supply for equipment floors is introduced from a grill in the spill-air plenum, as shown in Fig. 4, the pressure in equipment floors cannot rise much above atmospheric pressure. Therefore, pressure differentials across exterior walls of equipment floors in the upper portion of the building are small, but pressure differentials between equipment floors and shafts are of considerable magnitude.

Specific Problems Revealed in the Case II Analysis

Two specific problems which can be evaluated from the analysis are the difficulty of opening doors and noise resulting from air flowing through cracks around doors.

Human engineering factors must be considered in accessing the door opening problems. Several simple tests were conducted to relate pressure differentials on doors, forces required to open leaf doors, and strength capabilities of typical building occupants. Forces were measured for three 3 × 7-ft doors for pressure differentials of 0.3 to 0.6 in. of water. The initial force normally exerted to open leaf doors, defined as the opening force, was about 10 lb. greater than half the total pressure force on the door. Weight and size of the door and mechanical door closers would influence the opening force, but the tests provided some basis for evaluation. These tests also indicated that an average adult can exert an opening force of about 40 to 45 lbs when attempting to pull a door which is difficult to open. Results of these limited tests suggest the maximum tolerable opening forces for doors used by occupants, although some people would not be able to exert a force of this magnitude.

Fig. 10 shows the relationship between required opening force and pressure differential for a 20-ft^2

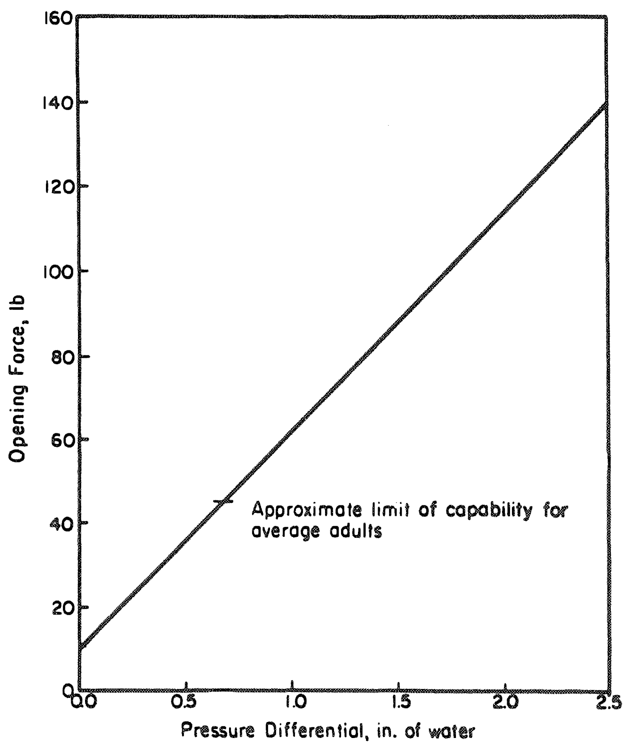

Fig. 10 Opening force on 20 ft^2 leaf doors

TABLE 3

PRESSURE DIFFERENTIALS ACROSS CRITICAL LEAF AND ELEVATOR DOORS, CASE II

DOORS AND ZONES	PRESSURE DIFFERENTIAL, IN. OF WATER	FORCE ON DOOR, LBS	OPENING FORCE, LBS
Stairway doors			
Zone 10	1.75	182	101
Zone 5	0.55	57	39
Stairway interrupting door at grade level	0.87	91	55
Elevator machine room doors			
Zone 10	1.75	182	101
Zone 1	0.63	66	43
Zone 5	0.60	62	41
Entrance doors			
Zone 1	0.57	59	40
Freight-elevator doors			
Zone 10	1.80	176	--
Zone 5	0.60	59	--
Garage-elevator doors			
Zone 1	0.63	62	--

door. A pressure differential of 0.60 in. of water on a door requires an opening force of 42 lbs, about the limit for average adults.

Observations of noise caused by air flowing through cracks around several styles of leaf doors reveal a wide range of pressure differentials required to generate noise. For doors located in a quiet environment, noise may be objectionable at a differential of only 0.05 in. of water. However, noise is not perceptible from some doors until the pressure differential reaches about 0.3 in. of water.

The analysis reveals several specific locations where problems such as excessive pressure differentials will occur for Case II.

Table 3 lists several door locations where presure differentials make opening or closing difficult. All stairway locations having excessive pressure differentials are on equipment floors; therefore, only maintenance personnel are expected to use these doors. Nevertheless, opening forces of about 100 lbs would make doors impossible to operate and would create a safety hazard. The highest pressure differential for stairway doors for Case II (apart from those listed) is 0.21 in. of water, which requires a 21-lb opening force.

Other locations of high pressure differentials are at elevator-machine-room doors opening into Zones 5, 10, and Zone 1 (from the garage elevators). Again, only maintenance personnel are affected. Elevator-machine-room doors not listed require 18 lbs or less opening force.

Entrance doors at Floor 1 would be somewhat difficult to open if only single doors were used, because an opening force of 40 lbs is required.

Table 3 also shows where pressure differentials cause high side thrust on elevator doors. The highest force, 176 lbs, occurs at the Zone 10 equipment floor. Forces on elevator doors not listed do not exceed 17 lbs.

The most severe door problems would arise at the equipment floors, as a result of their being at a lower pressure than the rest of the building. Such a condition could be overcome by providing a positive source of supply air to serve the equipment floors; however, this could create a potential for forcing equipment fumes and odors into occupied portions of the building, unless a pressure-sensitive control were used.

Results of the analysis for Case II show that forces on internal doors normally used by occupants will not be severe.

Effect of Environmental Conditions

Table 4 summarizes the results obtained for the analysis of 6 cases for constant wall tightness at different environmental conditions in order of increasing stack-effect. Cases I and II are included to provide a basis for comparison. It can be seen from Table 4 that both low outside temperatures and winds can produce stack-effect air flows which cause the building to operate at off-balance conditions. The moderate wind of Case IV produces some stack-effect, but does not produce as great an effect as the low temperature of Case V. Nevertheless, stack-effect problems can occur on mild, windy days as evidenced by the fact that the doors between the stairway and Zone 10 would be difficult for an average adult to open.

Reverse stack effect in summer is shown in Case III where the outside temperature is 100 F with no wind. In this case, air tends to enter the building at the top, flow down the shafts, and leave at the lower floors. This air-flow pattern could carry equipment odors into the first-floor lobby area.

Effect of Wall Leakage

Table 5 summarizes results of the analysis for 4 cases with different wall tightness for constant environmental conditions of low temperature and moderate wind. Case II is included for comparison purposes.

Results for Cases VII and VIII are almost identical, showing that a wall having the NAAMM standard leakage of 0.06 cfm/ft^2 performs essentially as a tight wall. The loose wall Cases II and IX show much greater stack-effect air flows than Cases VII and VIII.

Because the sum of the pressure differentials along the air flow path is dependent only on the indoor-outdoor temperature difference and wind, it is not affected by changes of wall tightness. Increasing wall leakage does alter the pressure distribution within the building such that some pressure differentials actually decrease. Two examples are the presure differentials between the freight elevator and Zone 10 and between the stairway and Zone 10. These pressure differential decreases occurred because the looser wall of Cases II and IX permitted so much air to flow through Zone 8 that the flow through Zone 10 was decreased, even though the total stack-effect was increased. This somewhat unexpected result demonstrates the difficulty of visualizing what changes in air flows and pressure differentials will occur as a result of changes in building construction. A study of the type described here can provide answers to these questions.

CONCLUSIONS AND DISCUSSION

Application of Technique

The method of analysis outlined in this paper is useful in identifying the nature and location of problems created by stack effect in a particular building. Further, the magnitude of these problems can be predicted, and the effectiveness of corrective means can be assessed prior to building construction.

It should be emphasized that the overall pressure potential caused by stack-effect cannot be altered by design; however, the distribution of pressure differentials and the magnitude of air flows can be controlled by building design and HVAC-system design. Also, shifts in local heating and cooling loads can be handled by equipment and control selection.

Better Information Needed on Building Components

The validity of predictions derived from this type of analysis depends on advance knowledge of flow resistances of building components along the air-flow paths. Wall and window-leakage characteristics are of special importance; thus, more information is needed on the as-constructed performance of various designs. Additional information is also needed on the flow resistance or effective crack areas of leaf doors and elevator doors as installed.

Occupant Safety

Safety aspects of building performance may also be evaluated with this technique. For example, pressure differentials across doors used in emergency evacuation will be affected by stack-effect and by HVAC shutdown during a power blackout. During an emergency evacuation with heavy occupant traffic, interrupting doors in stairwells and doors from occupied zones would likely be continuously open, changing the entire balance of pressure and flows. Extremely high air velocities up the stairwells could result. Movement of smoke from the location of a fire can also be predicted for various conditions by this technique.

Results of this type of computer analysis to predict and control problems of stack-effect can be generalized to some extent for typical buildings, but more importantly, the technique offers the opportunity for the specific and detailed preliminary analysis that is justified in the design of major buildings.

TABLE 4

COMPARISON OF RESULTS FOR SEVERAL ENVIRONMENTAL CONDITIONS FOR SAME WALL TIGHTNESS*

CASES	III	I	IV	V	II	VI
	SUMMER	BALANCE	BALANCE + WIND	WINTER, NO WIND	BASIC WINTER	SEVERE WIND
Outside temperature, F	100	75	75	0	0	0
Wind component of stack effect, in. of water	0	0	0.6	0	0.6	1.2
RESULTS						
Location of neutral point, floor	47	N.A.**	N.A.**	15	18	22
Upward air flow in composite shaft at Floor 23, cfm	−72,100	−8,700	26,400	130,400	158,900	189,800
Typical HVAC-system flows, cfm						
Zone 3: air supplied	267,800	270,300	271,200	274,800	277,000	278,700
air removed	250,200	243,700	241,300	231,200	224,900	219,500
Zone 8: air supplied	256,900	253,100	248,100	238,200	235,400	232,100
air removed	218,200	228,700	241,200	263,100	268,800	275,100
Zone 9: air supplied	17,200	16,900	16,600	15,800	15,600	15,400
air removed	14,300	15,300	16,300	18,200	18,800	19,200
Typical leakage flows, cfm						
Composite shaft to garage	46,700	25,100	−10,100	−48,500	−60,000	−69,100
Composite shaft to Zone 2	13,400	9,700	8,100	−3,900	−8,500	−11,800
Zone 3 to composite shaft	−6,000	18,900	16,900	55,400	62,400	77,200
Zone 8 to composite shaft	48,200	7,900	−21,000	−62,200	−78,200	−89,800
Zone 9 to composite shaft	3,700	1,300	−1,500	−5,100	−6,400	−7,200
Zone 1 to outside	8,500	4,300	900	−11,200	−13,900	−15,800
Zone 8 to outside	−13,400	12,600	25,200	38,700	41,300	44,200
Typical pressure differentials, in. of water						
Outside – Zone 1	−0.36	−0.12	−0.02	0.35	0.57	0.76
2	0.05	0.09	0.11	0.33	0.44	0.51
3	−0.26	−0.12	−0.12	0.02	0.14	0.22
8	0.14	−0.12	−0.50	−1.17	−1.33	−1.53
9	0.25	−0.12	−0.57	−1.45	−1.73	−2.03
10	0.28	0.12	0.05	−0.03	−0.04	−0.06
Shuttle Elevator – Zone 1	0.01	0.00	0.00	−0.06	−0.10	−0.14
6	−0.03	0.00	0.01	0.05	0.08	0.12
Restaurant elevator – Zone 1	0.03	0.00	−0.01	−0.11	−0.17	−0.23
6	−0.01	0.00	0.00	0.01	0.01	0.03
9	−0.01	0.00	0.00	0.02	0.03	0.03
Freight elevator – Zone 1	−0.01	0.00	0.01	−0.09	−0.14	−0.19
5	0.16	0.21	0.35	0.57	0.60	0.66
10	−0.01	0.24	0.63	1.50	1.80	2.11
Garage elevator – Zone 1	−0.33	−0.10	0.01	0.41	0.63	0.82
Local elevator – Zone 1	0.13	0.00	−0.01	−0.09	−0.13	−0.18
Stairway interrupting door	0.40	0.11	0.03	0.58	0.87	1.16
Stairway – Zone 1	0.03	0.00	−0.02	−0.13	−0.19	−0.26
3	0.02	−0.01	−0.02	−0.13	−0.19	−0.28
5	0.17	0.20	0.34	0.54	0.55	0.58
8	−0.04	−0.01	0.00	0.07	0.12	0.16
9	−0.01	0.00	−0.01	0.00	0.01	0.00
10	0.01	0.24	0.63	1.47	1.75	2.04
Machine room – Zone 1	−0.32	−0.10	0.01	0.41	0.63	0.82
5	0.15	0.21	0.35	0.58	0.60	0.66
10	0.05	0.24	0.63	1.47	1.75	2.06

*Wall leakage: 0.20 cfm/ft² at 0.30 in. of water pressure differential

**N.A.: Neutral point is not applicable when stack-effect air flow patterns do not occur

TABLE 5

COMPARISON OF RESULTS FOR SEVERAL WALL TIGHTNESS CONDITIONS FOR THE SAME ENVIRONMENT CONDITIONS*

CASES	VII	VIII	II	IX
Wall Leakage, cfm/ft²	0.00	0.06	0.20	0.60
RESULTS				
Location of neutral point, floor	12	12	18	24
Upward air flows in composite shaft at Floor 23, cfm	120,000	113,500	158,900	228,800
Typical HVAC-system flows, cfm				
Zone 3: air supplied	274,400	274,200	277,000	277,500
air removed	232,300	232,900	224,900	223,100
Zone 8: air supplied	230,500	230,700	235,400	240,500
air removed	277,800	277,500	268,800	258,400
Zone 9: air supplied	15,300	15,300	15,600	15,900
air removed	19,200	19,200	18,800	18,200
Typical leakage flows, cfm				
Composite shaft to garage	−49,200	−48,400	−60,000	−65,900
Composite shaft to Zone 2	400	−1,000	−8,500	−13,900
Zone 3 to composite shaft	49,200	44,000	62,400	107,200
Zone 8 to composite shaft	−47,900	−56,300	−78,200	−116,800
Zone 9 to composite shaft	−3,800	−4,600	−6,400	−10,500
Zone 1 to outside	−6,700	−7,900	−13,900	−26,900
Zone 8 to outside	0	14,100	41,300	102,200
Typical pressure differentials, in. of water				
Outside – Zone 1	0.34	0.33	0.57	0.66
2	0.30	0.30	0.44	0.41
3	−0.08	−0.10	0.14	0.19
8	−1.73	−1.71	−1.33	−0.90
9	−2.06	−2.06	−1.73	−1.42
10	−0.08	−0.08	−0.04	−0.02
Shuttle elevator – Zone 1	−0.05	−0.06	−0.10	−0.21
6	0.03	0.04	0.08	0.20
Restaurant elevator – Zone 1	−0.08	−0.09	−0.17	−0.34
6	0.00	0.00	0.01	0.07
9	0.01	0.02	0.03	0.08
Freight elevator – Zone 1	−0.06	−0.08	−0.14	−0.27
5	0.85	0.85	0.60	0.40
10	2.06	2.06	1.80	1.60
Garage elevator – Zone 1	0.43	0.42	0.63	0.70
Local elevator – Zone 1	−0.06	−0.08	−0.13	−0.25
Stairway interrupting door	0.58	0.58	0.87	1.14
Stairway – Zone 1	−0.11	−0.12	−0.19	−0.37
3	−0.11	−0.13	−0.19	−0.42
5	0.81	0.81	0.55	0.29
8	0.03	0.05	0.12	0.28
9	−0.02	−0.01	0.01	0.04
10	2.02	2.02	1.75	1.49
Machine room – Zone 1	0.43	0.42	0.63	0.70
5	0.85	0.85	0.60	0.42
10	2.01	2.01	0.75	1.57

*Environment conditions: zero F outside temperature and 0.6 in. of water wind component of stack effect

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REFERENCES

1. G. T. Tamura and A. G. Wilson, Building Pressures Caused by Chimney Action and Mechanical Ventilation, ASHRAE TRANS., Vol. 73, Pt. II, 1967, pp II. 2.1-9.
2. G. T. Tamura and A. G. Wilson, Pressure Differences for a Nine-Story Building as a Result of Chimney Effect and Ventilation System Operation, ASHRAE TRANS., Vol. 72, Pt. I, 1966, p 180.
3. G. T. Tamura and A. G. Wilson, Pressure Differences Caused by Chimney Effect in Three High Buildings, ASHRAE TRANS., Vol. 73, Pt. II, 1967, pp II.1.1-10.
4. ASHRAE HANDBOOK OF FUNDAMENTALS, 1967, pp 411-414.
5. N. Chien, Y. Feng, and H. Wang, Pressure Distribution on Models of Three-Dimensional Buildings Exposed to Moving Air, Master of Science Thesis, State University of Iowa, June 1948.
6. G. T. Tamura and A. G. Wilson, Pressure Differences Caused by Wind on Two Tall Buildings, ASHRAE TRANS., Vol. 74, Pt. II, 1968
7. Metal Curtain Wall Manual, National Association of Architectural Metal Manufacturers, 1960, pp 4-9 and BA-2.4.

DISCUSSION

G. T. TAMURA (Ottawa, Canada): The authors are to be commended for their contribution to the understanding of the mechanism of stack action in buildings and the various problems associated with it. We are much involved in the investigation of stack effect in buildings from several points of view. It is, therefore, gratifying to us to see a contribution made in this field.

We have also conducted a computer analysis of stack effect in tall buildings. As noted, our model was a generalized one compared to the specific model used in this paper. The treatment of combined effect of wind and stack and the simulation of the HVAC system in the model used in the computer analysis are of particular interest in us.

The first question relates to the manner in which the data on elevators under the sub-heading of Occupant Traffic Rates and Elevator Usage were used in the computer analysis. The second question concerns the treatment of wind effect in the analysis. The paper states that the net suction due to wind was assumed to be directly proportional to the elevation. The question is whether the variation in the pressure around the building caused by wind was also taken into account in the analysis.

ALWIN B. NEWTON (York, Pa.): This paper adds significantly to literature relating to stack effect in tall buildings. It is noted that the computer program developed permits the analysis of extremes of winter and summer conditions as well as the so-called "Balance" condition. The authors are to be congratulated on their results.

I would like to ask the reason for considering 75 deg outside as the balance condition at which HVAC-systems are generally designed and balanced. My own experience suggests that the stack effects within the duct systems serving large numbers of floors, and having different temperatures of air therein, may dictate some other "Balance" condition.

The present widely accepted practice of supplying warmer air in the high pressure ducts of an induction system in warm weather, and cool air in cold weather, creates other pressure differences between the ducts and the building ambient pressures. These differences vary in sense from summer to winter. When this occurs, frequent and little understood adjustments must be made to keep the system in balance as to air delivery. Are these effects to be considered for further study? If so, the building-to-outside pressure differentials at the fan inlets under extreme temperature, and wind velocity conditions, may need further analysis.

It is stated that the computer program recognizes absolute pressures at each point in the building. I would like to suggest that the authors consider the replotting of Fig. 9 in terms of absolute pressure as the horizontal scale rather than pressure difference. The slopes of the external pressure gradients and their reversal from summer to winter then come into focus and may be more readily compared to the relatively constant building pressure gradient. Absolute pressures in vertical ducts and their pressure gradients, as they pass through a large number of floors and experience different delivery temperatures, are easily displayed in such a plotting. They then show the pressures available for delivery at each outlet. They will be far from constant in most systems.

I would urge that more work of this analytical nature be done with the aim of making it easier to analyze and adjust systems for any given building.

I would also point out that the assumption that the ducts leak enough so that duct pressures agree with local ambient building pressures is not correct. Certainly in high pressure systems used with induction units, no such leakage could be tolerated. Therefore, the pressure gradients between building and ducts becomes very important in adjusting a system initially and in maintaining its adjustment thereafter.

MR. BARRETT: In reply to Mr. Tamura's first comment, the data on elevator door positions were used in conjunction with the data of elevator door peripheral crack areas (opened and closed) to determine the average elevator door leakage areas over a period of time. Because the analysis was made for the steady-state condition and not for an instantaneous condition, time average leakage areas were required.

In answer to Mr. Tamura's second question pertaining to consideration of variation in wind pressure around the building; it was stated in the paper that this aspect was not included in the analysis. Local variations in wind pressures around the building would not be a factor unless internal walls were included in the analysis.

Although, for this analysis, it was assumed that the net suction due to wind effect was directly proportional to elevation, other relationships could be used with only minor changes in the program. For the analysis of stack effect in a particular building, a curve could be fit to wind tunnel data.

In answer to the first of Mr. Newton's several questions, 75 F was used as the outside temperature for the balance condition because, with the inside and outside temperatures being equal, no stack effect component would exist to influence the operation of the HVAC system. If temperature differences existing within the building were included in an analysis, such as between air in HVAC ducts and air in the rooms, it might be necessary to consider other balance conditions.

I agree with Mr. Newton that a complete analysis of a proposed building would include the wind pressure at fan inlets and exhausts as a variable. This would probably require wind tunnel tests to generate the input data. This factor was not included in the analysis used in this paper because we were primarily concerned with presenting the general technique and were not conducting a complete design analysis.

Plotting results in terms of absolute pressures is helpful in visualizing the physical situation and was done by the authors, but it is difficult to show small pressure differences, 0.1 or 0.2 in. of water, on a scale of 10 to 20 in. of water in small illustrations. Therefore, for clarity in the paper, we presented results in terms of relative pressure. We recommend that absolute pressures be used for any analysis of this type because they greatly simplify the computations.

As to Mr. Newton's final comment, it was not necessary to assume that the duct and room pressures were equal at all points due to leakage. In fact, it was assumed that the ducts were airtight and that a pressure existed in the ducts at the fans sufficient to overcome the pressure losses due to duct friction and the air discharge device. Fig. 5 illustrates this. As a result, a positive pressure would exist at every point in the ducts.