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Test and Evaluation of the Smoke Control Capabilities of the San Diego Veterans Administration Hospital

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Center for Fire Research
Institute for Applied Technology
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Final Report

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TEST AND EVALUATION OF THE SMOKE CONTROL CAPABILITIES OF THE SAN DIEGO VETERANS ADMINISTRATION HOSPITAL

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Abstract

A study was made by the National Bureau of Standards to evaluate the smoke control capabilities of the San Diego Veterans Administration Hospital. A unique feature of the hospital is the presence of independent air-handling units for each floor and each wing. This feature allows the air-handling units to be manipulated for smoke control following the systematic pressurization concept. Systematic pressurization is a means of smoke control whereby a building is divided into either vertical or horizontal compartmented zones such that the air-handling systems are designed to exhaust the immediate fire zone and pressurize the adjacent surrounding zones upon detection of smoke. An experimental technique of smoke simulation and smoke movement measurement was used for the study. The effectiveness of the systematic pressurization smoke control concept is demonstrated by the simulated smoke concentration profiles and pressure measurements.

An extensive series of experiments designed to evaluate the above smoke control concepts were performed by the NBS in cooperation with the VA. Two types of experiments were performed with the building air-handling system operating in normal and various smoke control modes. First, simulated smoke infiltration measurements were obtained by using the sulfur-hexafluoride smoke simulation technique. Second, pressure measurements were obtained across elevator doors, and doors leading from the building central core to each wing. Both SF_6 concentrations and pressure measurements are key indicators of smoke movement in this evaluation. Six basic air-handling test configurations were established and pressure difference data was collected at fifteen locations on each floor measured. At least two floors and more generally three floors were measured for each mode. Each of the six configurations tested are summarized in table 7, and the measured data are summarized in table 8. A total of six smoke simulation experiments were conducted. The results and test conditions for each test are tabulated in tables 1 to 6 inclusively. It is concluded that air-handling systems in the San Diego VA Hospital can be effective in controlling smoke movement if the proper vertical and horizontal systematic pressurization concept as described in this report is applied. This is illustrated in figures 7, 8, 11, and 12.

A computer smoke movement simulation analysis is also presented. Computer calculations compared favorably with field data. Parametric analysis was also performed on smoke control modes for varying environmental and leakage conditions to further study the smoke control uses of the air-handling system and to demonstrate the capability of the computer simulation program.

Key words: Air-handling units; building pressure profile; computer simulation; elevator shaft pressure profiles; parametric analysis; simulated smoke concentration; smoke control; smoke movement; smoke simulation; systematic pressurization.

1. INTRODUCTION

In a high-rise building where total evacuation time from a building is excessive, or when evacuation is impractical or impossible, such as in a health care facility, a system is needed to provide for smoke-free travel routes to an area of refuge and to maintain refuge areas free from the migration of smoke. The system for control of smoke is needed primarily for occupant protection, although it could very well aid the firefighter. It is recommended that smoke control systems not be merely passive systems, such as those involving simple closing of dampers, or the automatic shut-down of air-handling system fans upon the detection of smoke in the return air system. What is needed are active systems to overcome the natural fluid motion of smoke in tall buildings where the air is buoyant and expanding at elevated fire temperatures, where the air is subject to movement due to conditions external to the building, such as stack effect and wind conditions.

Fluid motion in general, including air or smoke, is caused by the action of natural and mechanical forces. In a fire the two motivation forces that cause smoke movement are the buoyancy forces and the pressure forces. Buoyancy forces in a fire are caused by density changes in air due to heating. The relative difference in density then sets up a convective flow in a gravitational field. Pressure forces can originate in a number of ways, e.g., (1) by restriction of volume expansion, (2) by the exterior-interior temperature differences, (3) by the effect of wind velocity and direction, and (4) by the pressure differences maintained by the air-handling systems. For example, the well known stack effect in a high-rise building [1-5][1] is caused by the difference in hydrostatic pressure due to two air columns (one inside the building and the other outside) at different temperatures. For a detailed discussion of these forces, including derivation of formulas from basic principles and a comparison of the order of magnitudes, one may refer to reference [6].

Various forms of stairwell, core, and corridor mechanical pressurization and exhaust schemes have appeared in the last couple of years [6-18].

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[1] Bracketed numbers refer to the references listed in Section 5 at the end of this paper.

The purpose of these systems is twofold: (1) to vent, or exhaust the fire area of smoke and (2) to pressurize adjacent and remote areas of the building to prevent smoke migration to and through the various exit travel routes (such as corridors, stairs and elevator shafts) and to the various refuge areas designated throughout a tall building. These systems need to overcome the various buoyancy forces and volume outflow from a fire, as well as external forces such as stack action and wind.

Mechanical methods of smoke control, such as the use of the building's air-handling system and the use of special fan and damper arrangements, are mainly for smoke or early phase fire control when the fire does not involve the air-handling equipment directly. For this reason, the buildings's air-handling system, adapted for smoke control, is considered as an adjunct to, but not a replacement of a manual smoke and fire venting system, as traditionally used by firefighters, to handle high temperatures in the immediate fire area. These smoke control systems are envisioned as operating best for the early phase of a fire or in sprinklered buildings where the fire, if not extinguished, at least is temperature controlled to the extent that a mechanical, air-handling system may be expected to sustain reliable operation.

The San Diego Veterans Administration (VA) Hospital is a modern, sixstory structure with a 2.4-meter-high (8-foot) interstitial space between each floor as shown in figure 1, the elevation sketch. Looking at a typical floor, the building consists of four identical wings connected to a central core in a symmetrical fashion as shown in figure 2. For a more complete description on the construction features of the San Diego VA Hospital one may refer to reference [19]. A unique feature of this building is that each floor of each wing has its own 100 percent outside air system that can be controlled separately. A brief description of the air-handling system is contained in Appendix A of this report. In view of this special capability, the National Bureau of Standards (NBS) suggested that the airhandling units be programmed for automatic horizontal and vertical smoke control.

A typical horizontal smoke control mode would have the fire wing under 100% exhaust and the other three wings of the affected floor under 100% supply. As the smoke hazard becomes progressively worse additional floors can be put into horizontal smoke control mode. This way smoke may be prevented from leaving the affected wing.

In addition should smoke make its way into the central core an automatic vertical smoke control mode would go into operation such that the affected floor will be under 100% exhaust and the floors immediately above and below the affected floor will be under 100% supply. Should the smoke hazard get progressively worse additional floors above and below the affected floor can be put on 100% exhaust. Since it is far more convenient to conduct horizontal evacuation in a hospital involving invalid patients than vertical evacuation it is recommended that whenever applicable the horizontal smoke control mode should be initiated first.

2. TEST METHODS

An extensive series of experiments designed to evaluate the above smoke control concepts were performed by the NBS in cooperation with the VA. Two types of experiments were performed with the building air-handling system operating in normal and various smoke control modes. First, simulated smoke infiltration measurements were obtained by using the sulfur-hexafluoride smoke simulation technique [6]. Second, pressure measurements were obtained across elevator doors, and doors leading from the building central core to each wing. Both SF_6 concentrations and pressure measurements are key indicators of smoke movement in this evaluation.

2.1. Smoke Simulation Experiments

The smoke simulation experiments consist of the following salient features. Smoke was simulated by a net airflow out of a designated "burn-room" (locations of various burn-rooms used are indicated in figures 3 to 5). The air was mixed with a predetermined amount of sulfur-hexafluoride tracer gas[2] and heated to a temperature approximately 3 to 4 °C (4 to 6 °F) above the corridor temperature. The range of reference concentrations of the SF_6 tracer gas[3] in the air from the burn-room was of the order of 150 parts per billion (ppb), which was the maximum reference concentration for each experiment. Six smoke movement simulations were conducted. Detailed conditions for each test are listed along with measurements for that test in tables 2 to 7 and are explained in section 3.

Prior to the beginning of each experiment the burn-room air was preheated to a temperature of approximately 27 °C (80 °F) by an electric heater with a capacity of 1,650 watts. A window box-type fan at the bottom of the doorway was used to draw the preheated air from the burn-room and blow it into the corridor. A cardboard mask was installed in the hall doorway, in the same vertical plane as the fan, to allow air from the burn-room only to be channeled through the fan. The measured air-flow through the fan was approximately 15 cubic meters per minute (500 cfm). This may typically represent a fire with a 2-pound per minute burning rate. For a detailed comparison of the above simulation parameters in relation to the volume outflow, energy and burning rate in a real fire one may refer to the derivation and discussions in reference [6].

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[2] SF_6 was chosen as a tracer gas because of its electron capture property for detection, as well as being odorless, colorless, harmless and stable.

[3] Occupational Safety and Hazard Administration (OSHA) concentration limits of SF_6 is 1000 ppm as set forth in the Federal Register, Volume 36, No. 157, August 13, 1971.

At the beginning of each test, a standard, lecture-size bottle[4] of SF_6 gas, located inside the burn-room behind the fan, was turned on to continuously deliver a predetermined amount of SF_6 to the burn-room air. The movement of the SF_6 throughout the building was then traced by sampling at different building locations and the results are tabulated in tables 2 to 7. The samples were collected by using individual 20 cubic centimeter syringes.

The air and SF_6 specimens taken at the several sampling locations, were analyzed by use of a portable gas chromatograph having an electron capture cell fitted with a 300 mc of radiation source. The response of the instrument to SF_6 is exponential and the usable range is between 1 and 1,000 ppb. If dilution of samples is necessary, syringes of various sizes can be used.

Flow rates of the simulated smoke from the burn-room were determined from velocity measurements made with a thermoanemometer having a low range of 30 to 150 meters per minute (100-500 feet per minute (fpm)), and a high range from 150 to 360 meters per minute (500 to 1,200 fpm). Average velocities were obtained by making a traverse of nine points in front of the fan or other openings.

2.2. Pressure Monitor Experiments

From the six basic air-handling tests described in table 1, pressure difference data were collected at fifteen locations on each floor measured. On at least two floors and more generally three floors, measurements were taken for each test. The measured data are summarized in table 8.

The sampling locations are illustrated in figure 6. At every location pressure differences were measured across a closed door with a magnehelic pressure gage of 2.5 to 125 Pascal (0.01 to 0.5-inch-H_2O) pressure range. Sample locations 4, 7, 10 and 13 were taken across the inner corridor doors which are normally open, providing one continuously open and connected corridor throughout each floor. Sample locations 5, 8, and 14 were taken across external doors opening on to the outside decks of the inner ring. Sample locations 6, 9, 12 and 15 were taken across external doors opening onto the outside decks at the outer perimeter of the building. Location 9 was directly exposed to the prevailing west wind which was usually at a velocity of about 17.6 kilometers per hour (11 mph).

3. RESULTS AND DISCUSSION

3.1. Smoke Simulation Experiments

A total of six smoke simulation experiments was conducted. The results and test conditions for each test are tabulated in tables 2 to 7 inclusively. The highlights of the experiments are as follows:

[4]Cylinder dimension: 5.08 cm x 38.10 cm. Contains: 1·1 kg of SF_6 in liquid form under $22{\cdot}06 \times 10^5$ Pascals pressure at 20 °C.

1. Smoke Simulation Test No. 1 (table 2, figure 3) — In this case the HVAC system was in a normal mode. The simulated burn-room was on the third floor. As shown by the graphs in figure 7 infiltration of SF_6 was extensive throughout the entire third floor. In 20 minutes the SF_6 concentration at third floor central core (the elevator lobby) was as high as 18% of burn-room concentration. (In the following all concentration measurements in parts per billion were normalized by the burn-room concentration to yield percentage concentrations.) The concentration at the central core measured to 34% at one hour. Horizontal SF_6 infiltration of other wings on the third floor was also extensive as shown by the concentration growth of the third floor East and West wings in figure 7. Note that above the fire floor, at the fourth floor, a gradual increase in SF_6 contamination was also detected.

2. Smoke Simulation Test No. 2 (figure 3) — In this case the HVAC system was in a control mode, as follows:

   (1) The south wing of the third floor was placed on exhaust only and the burn-room was located in this wing.

   (2) The East, West and North wings of the third floor were placed on supply only.

   (3) The third floor interstitial exhaust fans were turned off except for the South wing.

   (4) The balance of the building operated in a normal mode.

Results in table 3 clearly showed the effectiveness of the horizontal systematic pressurization smoke control concept. The only SF_6 measurements detected outside of the third floor South wing (the location of the burn-room) were in the interstitial space immediately over the burn-room. No trace of SF_6 was detected in the other wings of the third floor, nor was SF_6 detected on the fourth or sixth floors.

3. Smoke Simulation Test No. 3 — In this case the simulated burn-room was located in the central core on the second floor (figure 4). The second floor interstitial fans were off and the balance of the building remained in a normal HVAC mode. The SF_6 concentration in central core (see figure 8) rose rapidly to 56.3% in 20 minutes. In both the West and North wing, the SF_6 concentrations, as shown in figure 8, rose rapidly also (solid lines).

4. Smoke Simulation Test No. 4 — In this case the simulated burn-room was located on the second floor in the central core as shown in figure 4 (same as test 3). The second floor was placed on exhaust only, the third floor was placed on supply only, the third floor interstitial fans were turned off, and the balance of the building remained in a normal mode.

Results of this test are also plotted as dotted lines in figure 8 and are summarized in table 5. The difference between the smoke control mode and normal mode is very pronounced. Not only was there no SF_6 detectable away from the fire floor during smoke control mode operation, but the total contamination on the fire floor was also substantially reduced in all wings except the South wing during the vertical smoke control mode. The higher concentration of SF_6 showing up in the second floor South wing appears to be a result of air-handling system inbalance resulting in greater exhaust on the South side.

5. Smoke Simulation Test No. 5 — This was a smoke decay study of the third floor South wing interstitial space. The test conditions and burn-room conditions for this test are listed in table 6. At time zero release of SF_6 was discontinued, after an initial concentration level as tabulated in table 6 was reached. At that time the interstitial fan was turned on and the decay of the initial concentration was monitored.

   Results of this study are tabulated in table 6. The SF_6 concentration decay in the South wing (where the burn-room is located) is plotted in figure 9. Note in the plot, the data points after taking their logarithm value follow a linear decrease. This indicates that the decay behaved essentially exponentially as expected, and at half-an-hour the concentration in the South wing has dropped at 1.3% of the original concentration.

6. Smoke Simulation Test No. 6 — This case was a test to evaluate the exhaust fan in the third floor interstitial space. The SF_6 was released directly in the interstitial space and the HVAC system was in the normal mode. The interstitial exhaust fan was on.

   Results of this test are tabulated in table 7. The SF_6 release and sampling stations in relation to the exhaust duct location are shown in figure 5. It appears from this test that the exhaust fan in the interstitial space was able to channel the SF_6 gas straight through without contaminating the interstitial space.

3.2. Pressure Monitor Experiments

The pressure tests were conducted under the temperature and wind conditions listed in table 8. Since the indoor and outdoor temperature differences were small we did not expect much pressure difference due to the stack effect. Appendix B shows a derivation of the stack effect. For reference, figure 10 presents the pressure difference due to stack effect as a function of height and outdoor temperature. Note in figure 10 that the neutral plane is assumed to be at mid-height.

The pressure test configurations are summarized in table 1 and the results in table 9. Since only a small stack effect was expected, as discussed before, it can be concluded that the typical measured pressure difference in Test No. 1 of 2.5 Pascals (.01 inches H_2O) was probably attributable to the air-handling system. Also, as there is no definite recognizable pattern it can be conjectured that the measured pressure distribution was due to the balance of the air-handling units.

In the subsequent tests, when the air-handling units were put into smoke control modes by unbalancing the system, definite pressure patterns then emerged. These are illustrated by figures 11 and 12. In figure 11 data is taken from test 5, location 3, figure 6 which is the freight elevator shaft. It can be seen that the directions of the measured difference indicates that the flow was from the second and fourth floor into the elevator shaft. On the third floor (fire floor), flow direction was out of the shaft. This flow achieves the purpose of vertical systematic pressurization, which is to prevent flow of smoke from infiltrating the second and fourth floor. For reference, the pressure difference due to stack effect for a typical San Diego winter is plotted for comparison.

In figure 12, data are taken from test 2, second floor locations 4, 7, 10 and 13; figure 6. It can be seen that the measured pressure differences indicated that all flow was towards the South wing. This achieves the purpose of horizontal systematic pressurization, which is to keep the smoke from leaving the South wing through the core and thus infiltrating the other wings or the other floors.

Pressure test numbers 3a through 3e were essentially a repeat of test 2 except certain doors were opened to investigate the possibility of defeating the preferred pressure pattern set up by the horizontal systematic pressurization. The variations from the basic test 2 configuration (see fig. 6) are detailed as follows:

Case 3a Inner corridor doors to the West wing closed and West wing external door open (location 9) on the 3rd floor.

Case 3b Same as 3a except East wing (location 15) instead of West wing.

Case 3c Same as 3a except North wing (location 6) instead of West wing.

Case 3d Same as 3a except South wing (location 12) instead of West wing.

Case 3e All inner corridor doors and external doors closed. See note on figure 6.

Since there was a prevailing Westerly wind of approximately 18 kmph (11 mph), test 3 gave a good opportunity to see if significant wind pressure can defeat the horizontal systematic pressurization concept. In Appendix C a derivation was shown for the relationship of the maximum pressure induced by wind. The relationships were then plotted in figure 13 on semi-log paper. From this plot we see that a wind of 18 kmph (11 mph) can induce a maximum pressure of approximately 17.5 Pascals (0.7

inches H_2O), which is a significant pressure in relation to the measured operating pressures of the horizontal smoke control mode in test 2. However, the results of test 3, as tabulated in table 9, clearly indicated that the westerly wind did not affect the preferred smoke control pressure pattern as established by the air-handling system.

3.3. Computer Analysis of Smoke Movement

3.3.1. The Computer Program

The objective of a smoke control system is to provide dependable smoke control to reduce the hazard to life from smoke movement at a minimum cost. In order to evaluate the effectiveness of any smoke control system we need to know the reduction in smoke levels in the various designated refugee areas and escape paths of a high-rise building, as a function of time during a fire. As a first step in obtaining this quantitative concentration information we have initiated this series of smoke simulation experiments by using the SF_6 tracer gas technique. But large-scale experiments like these are time consuming and expensive and thus are necessarily limited in scope. Large-scale field experiments of this type also are subject to the limitations of a given design, the prevalent weather conditions, and the exisiting building operations. Thus, a more comprehensive study of smoke control design for a given building can best be accomplished by computer modeling.

The task of creating a general computer smoke movement program valid for today's buildings is a difficult one. First, the known physical laws are complex; second, the buildings can be complicated, and the smoke paths can be numerous and hidden. The main motivation forces that cause smoke movement in a high-rise building has been discussed in the Introduction section of this report. These include, buoyancy and expansion forces due to a fire, pressure forces due to wind, stack effect and the heating-ventilating system. Based on the above smoke movement principles, a computer program can be written to simulate rooms and corridors connected by leakage paths. A mass balance is then performed on this system with the flow governed by a generalized orifice flow equation which is temperature compensated. This system of simultaneous equations, characterizing the building as a complex airflow network, is then solved by a nested iterative approach. Given the calculated rates and directions of airflow in a building, it is then possible to determine the smoke concentration distribution as a function of time and relative to the burn-room concentration.

3.3.2. The Assumptions

Because of the complexity of the problem, many simplifying assumptions were necessary to keep the calculation tractable. The principal assumptions are as follows:

1. We are dealing with a small fire, so that the energy output by the HVAC system is large relative to fire size. A consequence of this is that, except in the immediate neighborhood of the burn-room and its connecting corridor, the smoke has essentially been cooled to the same temperature as its surrounding air. Consequently, at distances from the fire we can calculate smoke movement according to conditions of normal ventilation flows.

2. The flow calculations are based on a steady-state fire condition.

3. Distribution is considered instantaneous within a given compartment, such that the concentration at any given time within that compartment is uniform.

Some of these assumptions can be relaxed and the calculations improved as we gain more experience in applying the program. At the present stage of development the program represents our present state of knowledge about important contributing factors affecting the movement of smoke.

3.3.3. Building Configuration Properties

The primary problem identified with earlier published air movement programs was the lack of a realistic modeling ability for the spatial configurations of buildings and the components, and the arrangement of the HVAC system. The current computer program design which was developed and is now being utilized, has the capability of simulating:

1. Up to 100 floors;

2. A single corridor on each floor;

3. Up to 10 compartments which can be related to zones, suites, or specific spaces on each floor;

4. Up to 25 HVAC systems, each composed of:

    a. An air-handling unit (AHU) (blower/fan) which delivers air to the supply duct network,

    b. A supply duct network,

    c. A return air duct network or plenum,

    d. An outside air supply shaft or duct to the AHU inlet,

    e. A return air coupling to the AHU inlet to supply recycled air,

    f. A means to provide any mixture of outside air (OA) or return air (RA), from 100% OA to 100% RA, to the AHU,

    g. A ventilation shaft or duct to exhaust return air not recycled, and

    h. An exhaust fan for the ventilation shafts.

5. Up to 20 different fans/blowers for use anywhere in the building/HVAC system.

6. Up to 90 shafts or ducts made up of any combinations of the following, except as indicated:

    a. Elevator shafts to a maximum of 16,

    b. Stairwells,

    c. Air supply ducts/shafts,

    d. Ventilation ducts/shafts,

    e. Cable/pipe/duct shafts,

    f. Window HVAC unit pipe shafts.

7. Up to 70 sets of non-fan/blower coupling parameters.

8. Up to 10 external wind functions which are linearly variable as a function of height.

9. Up to 20 single temperature values for spatial temperature specification and 20 temperature-height functions for shaft/duct temperature specification.

Many other features are also included in the program design, such as:

1. Inlet fans/blowers to pressurize shafts, such as stairwells;

2. HVAC air supply to stairwells;

3. External leakage to

    a. Corridors,

    b. Compartments,

    c. Stairwells, to a maximum of 20,

    d. HVAC window unit shafts,

4. Ventilation fans from corridors and compartments to ventilation shafts and directly to the outside, and

5. Outlet fans from the various forms of shafts.

Although all characteristics of all building/HVAC systems cannot be specifically represented by the capability of the computer program developed, the functional representation of almost all characteristics can be modeled by imaginative use of the available characteristics.

3.3.4. Field Trip Comparisons and Parametric Studies

In order for the computer program to be useful in evaluating the smoke control system, and as a design tool, the following tasks need to be performed:

1. In applying the program a complete specification must be made from the architectural drawings of the layout of the building of the spaces, the vertical and horizontal connecting paths, and the exact layout and specification of the HVAC systems and smoke control flow input. Also, it is necessary to establish the building leakage characteristics through walls and floors; the size of cracks around doors and windows, and which doors and windows are open. In addition, the fire must be characterized in terms of its temperature, pressure, volume outflow, and smoke concentrations. Finally, the environmental conditions prevailing at the time of the fire must be determined.

2. Due to the complexity of the numerous inputs needed to specify the basic model of a building it is almost imperative that the computer program be "calibrated" for each building before any reliance on the application of the computer program for smoke control studies, controlling variable (parametric) and design studies. The "calibration" approach adopted in the present study is first to obtain a set of field pressure measurements from strategic locations throughout the building with the building HVAC system in normal operation. This basic set of pressure measurements then serves as an input for the specification of building leakage in the computer program. The computer building leakage input is considered to be "calibrated" for a given building when the computer output simulating the building in normal HVAC operation matches the basic pressure measurement.

3. A calibrated computer program can now be used to predict smoke concentrations as a function of time with the building HVAC system under various smoke control operations, and to verify experimental findings. In addition,

a calibrated computer program tailored to a given building can become a powerful tool in extending the validity of any given smoke control concept under varying environmental conditions and internal building modifications, and leakage parametric variations (door and window openings, etc.). A calibrated computer program is also the most efficient tool for smoke control design optimization studies by varying the needed airflow requirements.

3.3.5. Computer Simulation of the San Diego VA Hospital

A computer simulation, field test comparison and parametric analysis for this hospital were performed to confirm and extend the results of our experiment findings. Details of the building characterization, input description, model calibration, field test comparisons, and parametric studies for varying door openings and wind conditions are contained in Appendix D to this report [24].

The comparative results, in general, are in good agreement. This implies that the computer simulation model utilized was reasonably representative of the building and the test conditions at the time of the field pressure difference collection. The elevator pressure difference comparisons appeared to be somewhat better than the outside wind function and external door comparisons. Overall behavior appeared to be consistent and representative of the actual building system. Occasional points varied, but there was uncertainty about some of the measurements taken, as well as the wind that fluctuated.

4. CONCLUSIONS

1. Based on the SF_6 concentrations and pressure difference measurements for the two simulated smoke control modes discussed in sections 3.1 and 3.2 one can conclude that air-handling systems in the San Diego VA Hospital can be effective in controlling smoke movement in a typical San Diego climate if the proper vertical and horizontal systematic pressurization concepts as described in this report are applied.

2. Results of the computer simulation of smoke movement in the VA Hospital indicate the capabilities of the computer program to confirm and extend the results of our experimental findings. This signals the application of computer simulation for smoke control design optimization and design guidelines by parametric variations of building characteristics and environmental conditions.

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Table 1. San Diego Pressure Test Configurations

Test No.	Air-Handling System Configuration	Temperatures				Wind		Other Conditions
		Indoor		Outdoor		mph W	kmph	
		°F	°C	°F	°C			
1.	HVAC in normal mode on all floors.	75	23.9	71	21.7	8	12.8	
2.	Third floor south Wing 100% exhaust. Third floor other Wings 100% supply. HVAC in normal mode on other floors.	76	24.4	76	24.4	11.4	18.2	
3a.	HVAC system configuration same as test 2.	74	23.3	75	23.9	11.4	18.2	West Wing exterior door open.
3b.	HVAC system configuration same as test 2.	74	23.3	75	23.9	11.4	18.2	East Wing exterior door open.
3c.	HVAC system configuration same as test 2.	74	23.3	75	23.9	11.4	18.2	North Wing exterior door open.
3d.	HVAC system configuration same as test 2.	74	23.3	75	23.9	11.4	18.2	South Wing exterior door open.
3e.	All conditions same as test 2 except all doors closed.							
4.	Entire third floor 100% exhaust. Entire fourth floor 100% supply.	74	23.3	70	21.1	7	11.2	
5.	Entire second floor 100% supply. Entire third floor 100% exhaust. Entire fourth floor 100% supply. All other floors HVAC in normal mode.	75	23.9	70	21.1	10.8	17.2	
6.	Fifth floor in 100% exhaust except west Wing where both supply and exhaust are on. Sixth floor in 100% supply except south Wing where both supply and exhaust are on. All other floors HVAC in normal mode.	74	23.3	72	21.7	10.8	17.2	

Table 2. Third Floor Smoke Simulation with HVAC in Normal Mode

Sample Location*	Normalized SF_6 Concentration** at;			
	5 min.	20 min.	35 min.	60 min.
3-1	14.6	19.8	25.6	34.5
3-2	6.1	22.2	32.1	34.5
3-3	6.1	18.0	27.0	34.0
3-4	6.8	6.8	9.8	13.0
3-5	1.3	—	2.6	3.3
3I-1	1.3	—	3.3	4.0
3I-2	0.6	0.6	1.3	1.0
4-1	0.0	1.3	1.6	2.6
4-2	0.0	1.6	2.6	2.6
4-3	0.0	—	2.6	2.6
4-4	0.0	1.3	2.6	1.6
4-5	0.0	1.3	2.6	1.6

*First number indicates floor number, second number indicates third floor sampling location as shown in figure 3. I denotes interstitial space.

**Percentage SF_6 concentration normalized with respect to burn-room concentration.

Test Conditions:

1. HVAC system in normal mode.
2. Third floor interstitial exhaust fans on.
3. Simulated burn-room: Room 3179.

Burn-Room Conditions:

1. Out flow from burn-room 13.42 cubic meters (474 cfm) per minute.
2. SF_6 concentration: 121.6 ppb.
3. Pressure differential across doorway: 45 Pascals (0.18 inch H_2O)

Temperatures:

Outdoor: 18.3 °C (65 °F)

Indoor: 23.9 °C (75 °F)

Burn-room: 26.7 °C (80 °F)

Table 3. Third Floor Smoke Simulation with HVAC in Control Mode

Sample Location*	Normalized SF_6 Concentration** at;		
	10 min	30 min	40 min
3-1	63.1	86.0	86.9
3-2	0.0	0.7	2.0
3-3	0.0	0.0	0.0
3-4	0.0	0.0	0.0
3-5	0.0	0.0	0.0
3I-1	0.6	8.6	18.6
3I-2	0.0	0.0	0.0
4 6	All samples on the fourth and sixth floors showed no traces of SF_6 contamination.		

*First number indicates floor number, second number indicates third floor location as shown in figure 3. I denotes interstitial space.

**Percentage SF_6 concentration normalized with respect to burn-room concentration.

Test Conditions;

1. Third floor south wing exhaust.
2. Third floor north, east, west wings supply.
3. Third floor interstitial exhaust fans off except south wing 3I exhaust which was on.
4. Rest of building HVAC normal.
5. Simulated burn-room: Room 3179.

Burn-room Conditions:

1. Out flow from burn-room: 11.33 cubic meters (400 cfm) per minute.
2. SF_6 concentration: 114.2 ppb.
3. Pressure differential across doorway: 45 Pascals (0.18 inch H_2O).

Temperatures:

Outdoor: 20.6 °C (69 °F)

Indoor: 23.9 °C (75 °F)

Burn-Room: 26.1 °C (79 °F)

Table 4. Second Floor Smoke Simulation with HVAC in Normal Mode

Sample Location*		Normalized SF_6 Concentration** at:						
		5 min	15 min	20 min	30 min	35 min	40 min	45 min
2-1	Core	7.3	30.7	56.3	—			
2-2	East	0.0	1.4	1.4	1.4			
2-3	North	4.2	22.7	—	34.6			
2-4	West	1.9	33.3	48.6	46.8			
2-5	South	0.7	0.7	0.7	0.7			
2I-1		0.7	8.0	10.5	7.3			
6-1		0.0		0.2		2.2		1.6
6-2		0.0		0.0		0.0		0.0
6-3		0.0		3.4		2.8		2.0
6-4		0.0		3.0		4.2		4.2
6-5		0.0		0.0		0.0		0.0

*First number indicates floor number, second number indicates second floor sample location as shown in figure 4. I denotes interstitial space.

**Percentage SF_6 concentration normalized with respect to burn-room concentration.

Test Conditions:

1. HVAC in normal mode.
2. Second floor interstitial fans off.
3. Simulated burn-room: Room 2014.

Burn-Room Conditions:

1. Out flow from burn-room: 11.78 cubic meters (416 cfm) per minute.
2. SF_6 concentration: 134.1 ppb.
3. Pressure differential across doorway: 40 Pascals (0.16 inch H_2O).

Temperatures:

Outdoor: 20.6 °C (69 °F) Indoor 23.9 °C (75 °F) Burn-Room 27.2 °C (81 °F)

Table 5. Second Floor Smoke Simulation with HVAC in Control Mode

Sample Location*	Normalized SF_6 Concentration** at:			
	5 min	15 min	25 min	35 min
2-1 Center	0.0	1.2	1.2	3.8
2-2 East	0.0	0.0	0.0	0.0
2-3 North	0.0	0.0	0.0	0.0
2-4 West	6.9	12.4	8.6	14.0
2-5 South	17.3	30.1	33.2	33.2
2I-1	0.6	1.2	0.6	0.6
3 6	All measurements from the third and sixth floors showed no traces of SF_6 contamination.			

*First number indicates floor number, second number indicates second floor location as shown in figure 4. I denotes interstitial space.

**Percentage SF_6 concentration normalized with respect to burn-room concentration.

Test Conditions:

1. Second floor 100% exhaust, 5 Pascals (.02" H_2O) Δp across elevator doors, flow from elevator shaft to floor.
2. Third floor 100% supply 5 Pascals (.02" H_2O) Δp across elevator doors, flow from floor into elevator shaft.
3. Third floor interstitial fans off.
4. HVAC normal in the rest of the building.
5. Simulated burn-room: Room 2014.

Burn-Room Conditions:

1. Out flow from burn-room: 11.89 cubic meters (420 cfm) per minute.
2. SF_6 concentration: 130.4 ppb.
3. Pressure differential across doorway: 40 Pascals (0.16 inch H_2O).

Temperatures:

Outdoor: 21.2 °C (70 °F)

Indoor: 23.9 °C (75 °F)

Burn-Room: 27.2 °C (81 °F)

Table 6. Third Floor SF_6 Decay Study

Sample Location*	Normalized SF_6 Concentration** at:			
	0 min	10 min	20 min	30 min
3-1 Center	53.5	17.1	3.4	1.3
3-2 East	0.8	0.0	—	—
3-3 North	0.8	0.0	—	—
3-4 West	1.7	0.0	—	—
3-5 South	0.8	0.0	—	—
3I-1	9.0	8.0	3.9	3.0
3I-2	0.9	0.0	0.0	0.0

* First number indicates floor number, second number indicates third floor location as shown in figure 3. I denotes interstitial space.

** Percentage SF_6 concentration normalized with respect to burn-room concentration.

Test Conditions:

1. 3I interstitial exhaust fan on.
2. HVAC system in normal mode.
3. Simulated burn-room before shut down: Room 3179.

Burn-Room Conditions:

1. SF_6 release turned off at time zero.
2. Burn-room fan shut down at time zero.
3. Initial burn-room concentration: 99.94 ppb.

Temperatures:

Outdoor: 20.6 °C (69 °F)

Indoor: 25.0 °C (77 °F)

Burn-Room: 26.7 °C (80 °F)

Table 7. Third Floor Interstitial Space SF_6 Purging Study

Sample Location*	Normalized SF_6 Concentration** at;					
	0 min	5 min	15 min	25 min	40 min	45 min
3-1	0.0	0.0	0.0	0.0	0.0	0.0
3-2	0.0	0.0	0.0	0.0	0.0	0.0
3-3	0.0	0.0	0.0	0.0	0.0	0.0
3I-1	0.0	0.6	0.6	0.6	—	—
3I-2	0.0	0.6	0.6	1.7	—	—
3I-3	0.0	7.6	100	92.3	100	100
Exhaust Duct	—	—	—	—	100	100

*First number indicates floor number, second number indicates third floor location as shown in figure 5. 3I sample locations are as shown in figure 5 but are directly above in interstitial space.

**Percentage concentration normalized with respect to maximum concentration in interstitial space.

Test Conditions:

1. SF_6 released in open interstitial space as shown in figure 3 .
2. Maximum interstitial space SF_6 concentration: 133.6 ppb.
3. Interstitial space exhaust fan on.
4. HVAC in normal mode.

Temperatures:

Outdoor: 21.1 °C (70 °F) Indoor: 23.9 °C (75 °F) Interstitial: 24.4 °C (76 °F)

Table 8. Temperature and Wind Conditions

	Case	Indoor Temp		Outdoor Temp		Fan No.	Wind Speed		Direction
		(°F)	(°C)	(°F)	(°C)		(mph)	(kmph)	
Simulated Conditions	All	74	23.3	73	22.8	1	0		
						2	11	17.6	
						3	5	8	
						4	8	12.8	
Actual Conditions	1	75	23.9	71	21.7		8	12.8	Westerly
	2	76	24.4	76	24.4		11.4	18.2	Westerly
	3	74	23.3	75	23.9		11.4	18.2	Westerly
	4	74	23.3	70	21.1		7	11.2	Westerly
	5	74	23.3	70	21.1		10.8	17.2	Westerly
	6	74	23.3	72	21.7		10.8	17.2	Westerly

Table 9. Pressure Difference Across Doors

Locations*	Test 1			Test 2			Test 4		Test 5			Test 6		
	2nd Floor	3rd Floor	4th Floor	2nd Floor	3rd Floor	4th Floor	3rd Floor	4th Floor	2nd Floor	3rd Floor	4th Floor	4th floor	5th floor	6th floor
1	+.01	0	-.01	0	+.01	0	-.02	+.03	+.035	-.02	+.03	+.04	-.03	+.01
2	0	0	-.01	0	+.01	0	-.02	+.03	+.03	-.02	+.02	+.03	-.03	+.01
3	+.01±.01	.01	-.01	0	+.01	+.005	-.02	+.03	+.035	-.02	+.02	+.03	-.03	+.01
4	0	0	0	0	-.03	0	-.015	-.01	0	-.025	-.01	-.015	+.015	-.02
5	-.02	0	+.02	0	0	-.015	-.04	+.02	+.03	-.02	+.025	+.02	-.03	+.01
6	-.01±.01	.01	+.01	0	+.015	-.015	-.035	0	+.015	-.02	-.005	+.02	-.01	
7	-.01±.01	-.01	-.01	-.02	-.03	-.01	-.02	-.01	-.03	-.01	-.01	-.015	-.01	-.01
8	-.02	0	-.02	-.02	0	-.02	-.03	+.02	+.015	-.02	+.04	+.035	-.015	+.025
9	-.02	-.025	+.01	-.05	-.04	-.08	-.05	+.035	-.015	-.06	-.00	-.02		-.04
10	-.02	0	-.0	0	+.02	0	+.02	0	-.01	+.035	0	-.01	-.01	+.01
11	+.01	.01	-.02	+.01	+.025	+.03	0	+.05	+.05	+.01	+.05	+.01	0	+.04
12	+.015	.01	0	-.02	+.01	+.02	-.02	+.01	+.07	-.01	+.02	+.005	-.01	+.01
13	0	-.01	0	0	-.02	+.01	+.015	-.005	0	+.025	0	0	+.02	-.01
14	+.03	.01	+.015	+.02	+.02	+.025	-.01	+.02	+.035	+.01	+.045	+.05	0	+.045
15	+.01	0	+.01	0	-.01	+.01	-.025	+.01	+.02	-.01	+.01	+.01	-.01	0

Location*	Test 3a 3rd Floor	Test 3b 3rd Floor	Test 3c 3rd Floor	Test 3d 3rd Floor	Test 3e 3rd Floor
4	-.03	-.03	-.02	-.02	-.03
7	+.04±.01	-.04	-.04	-.035	-.04
10	+.06	+.06	+.04	+.05	+.04
13	+.02	+.01	+.01	+.005	+.005

*Location of numbered doors as shown on figure 6.

Positive Pressure: 1. Building core is at higher pressure vs shaft or corridor of each wing.
2. Building interior is at higher pressure versus exterior.

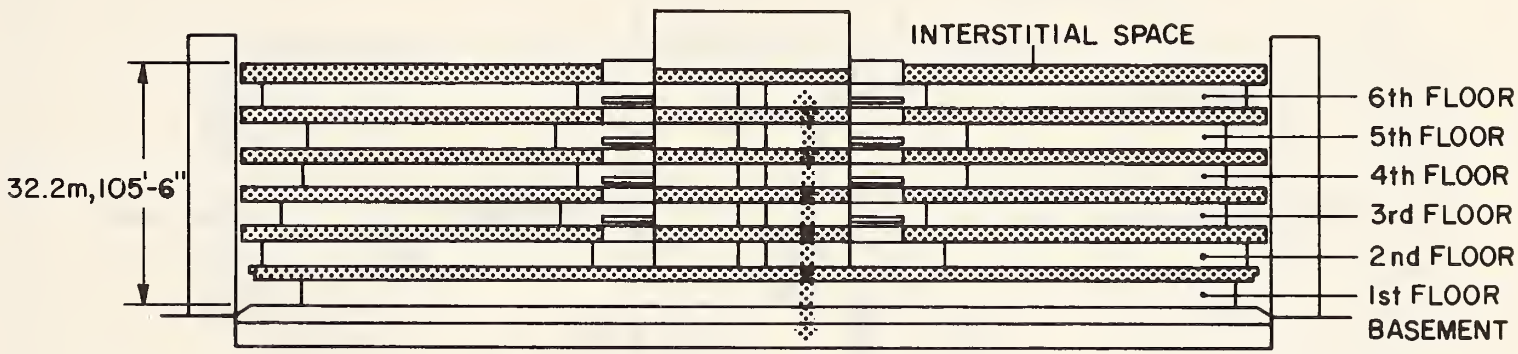

Figure 1. Elevation of San Diego VA Hospital

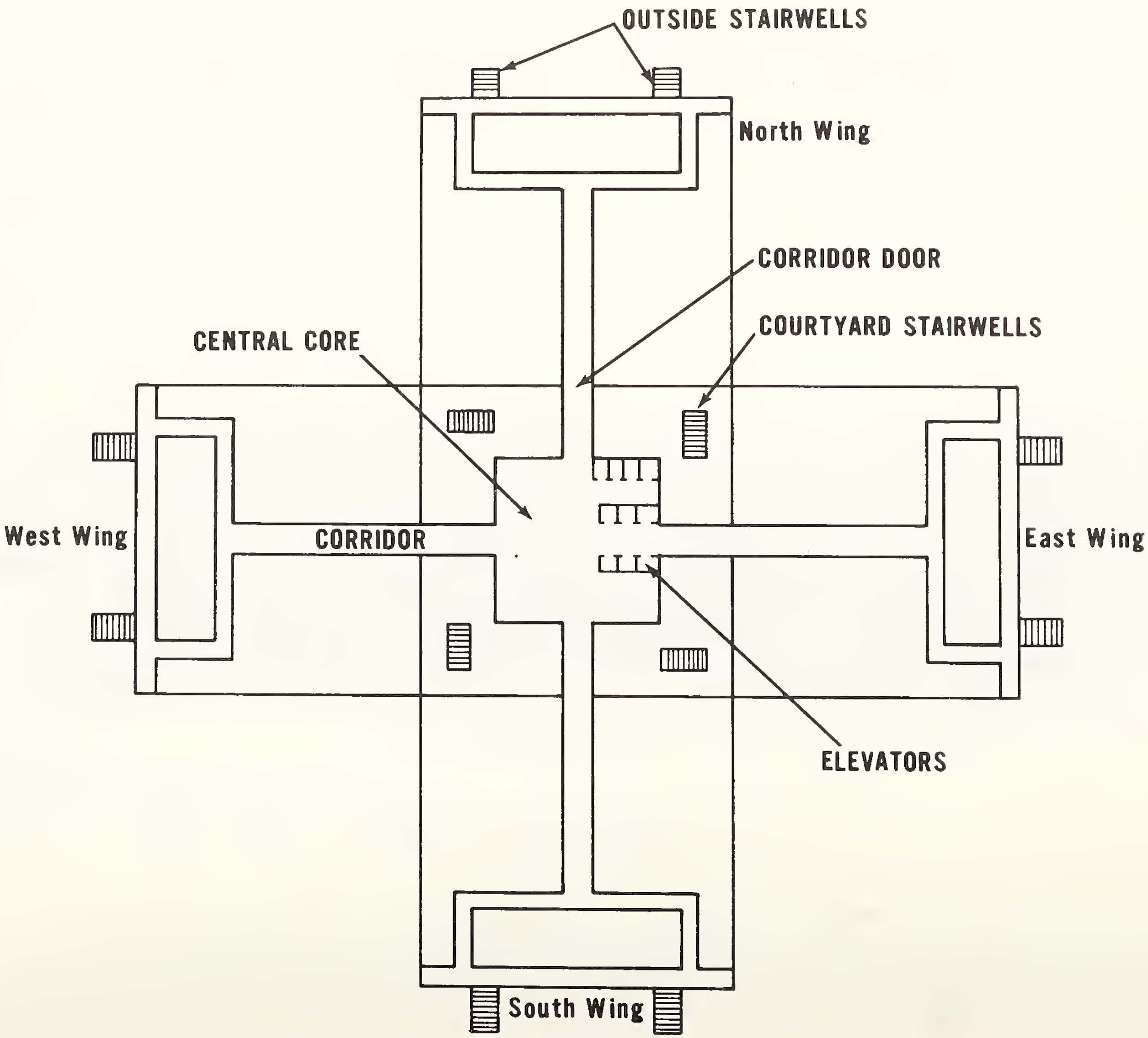

Figure 2. San Diego VA Hospital Typical Floor Plan

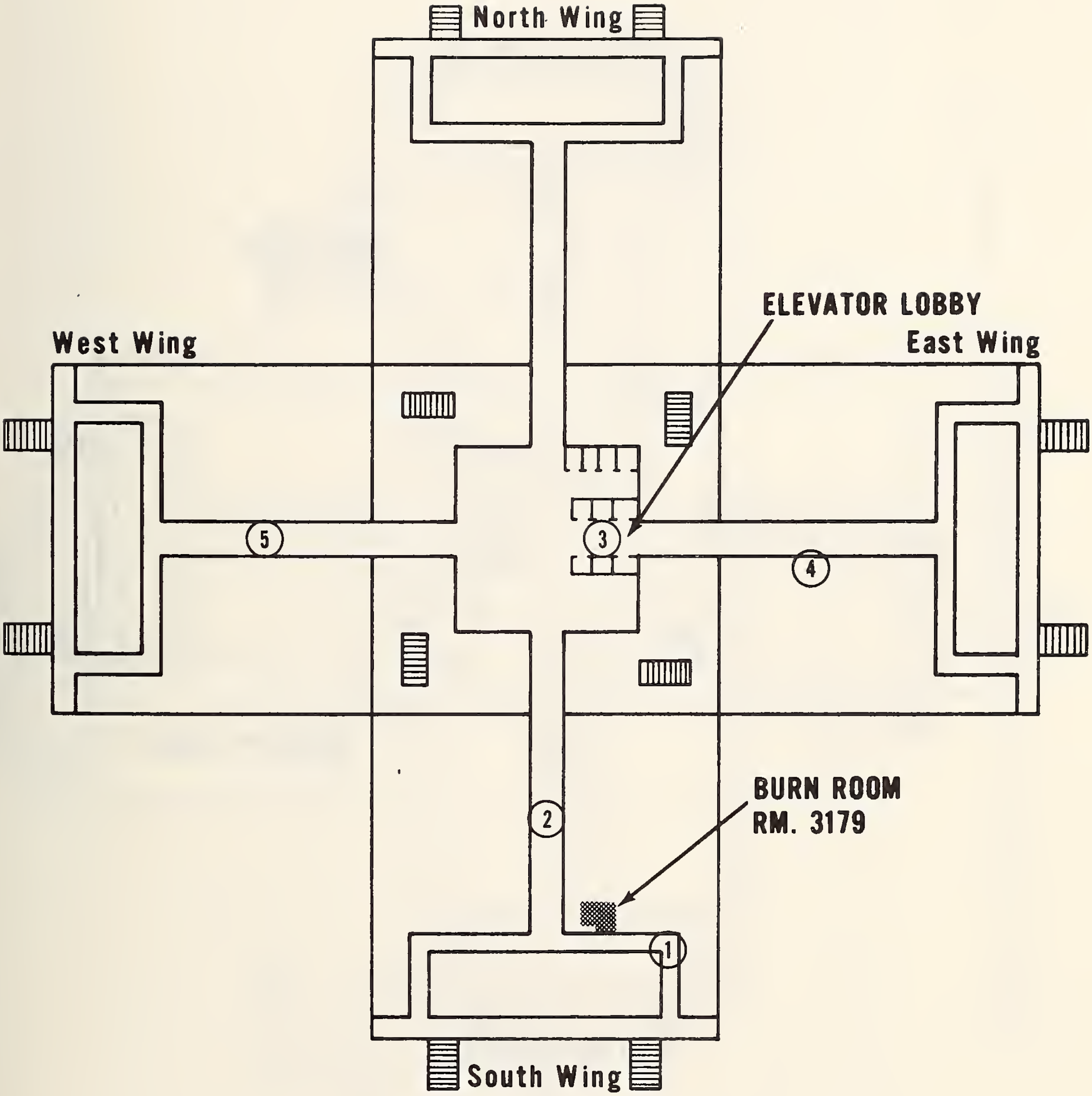

Figure 3. Third Floor, Floor Plan

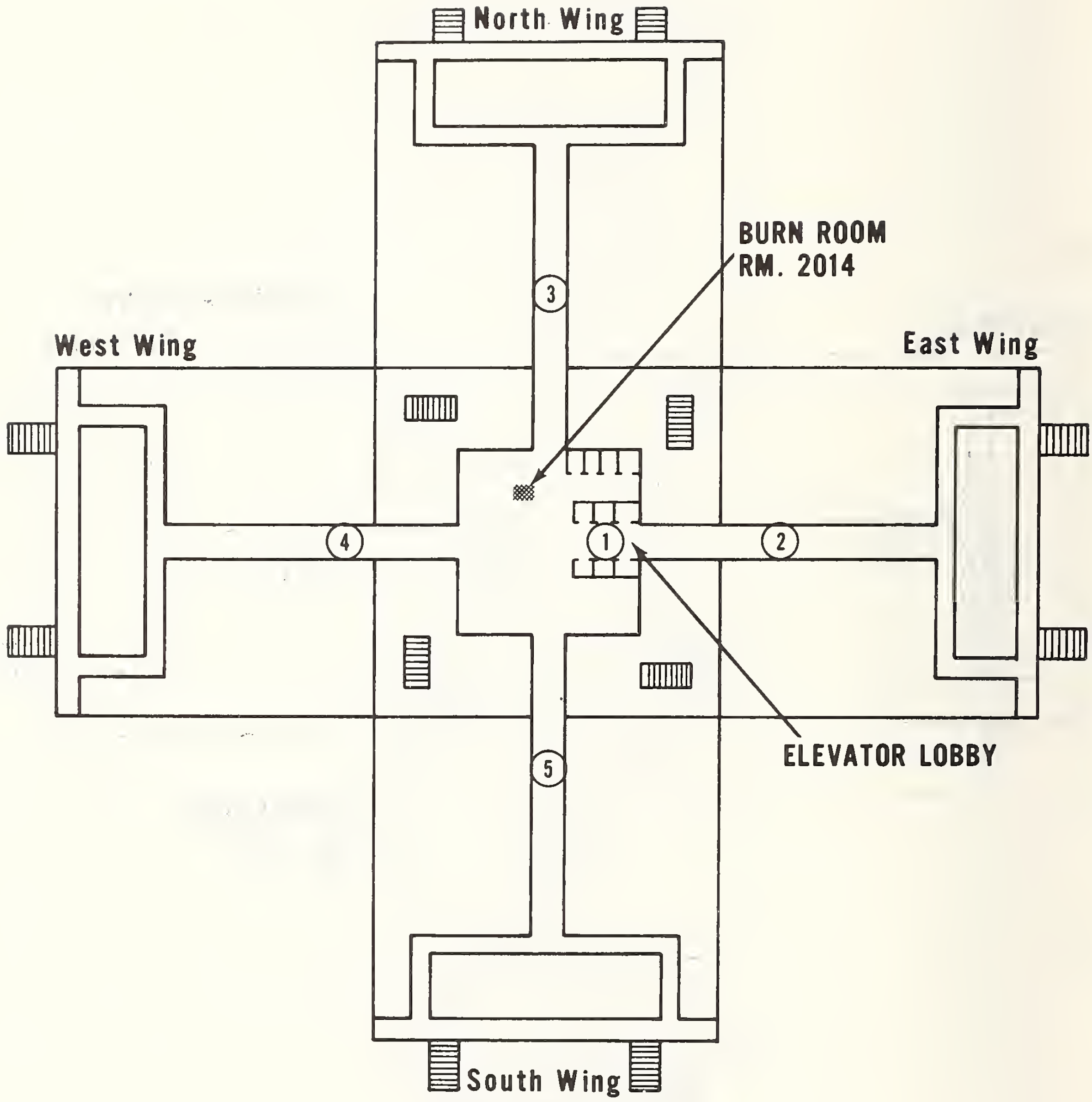

Figure 4. Second Floor, Floor Plan

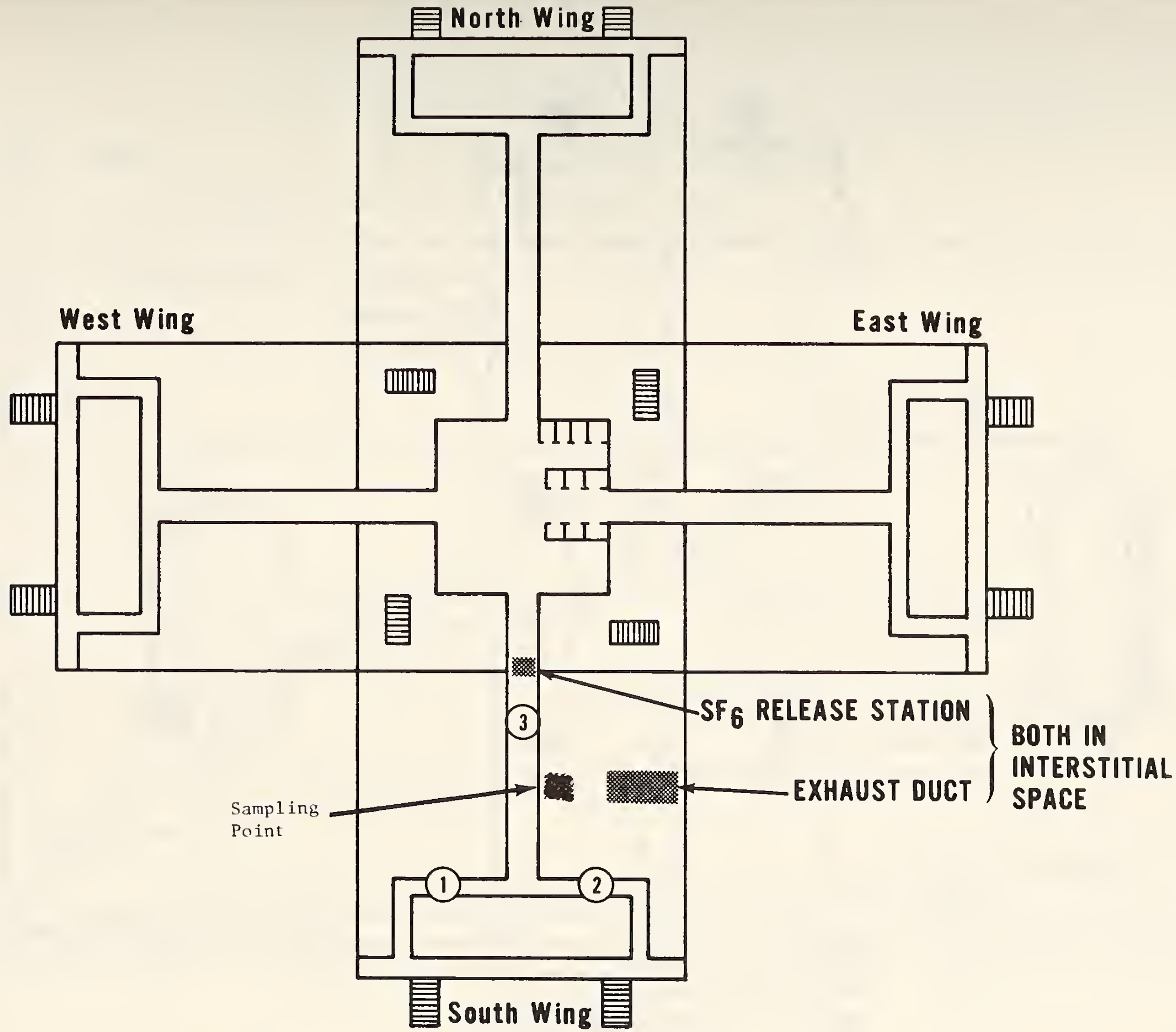

Figure 5. Sampling Locations for Smoke Test (Samples Collected from Third Floor and also Interstitial Space)

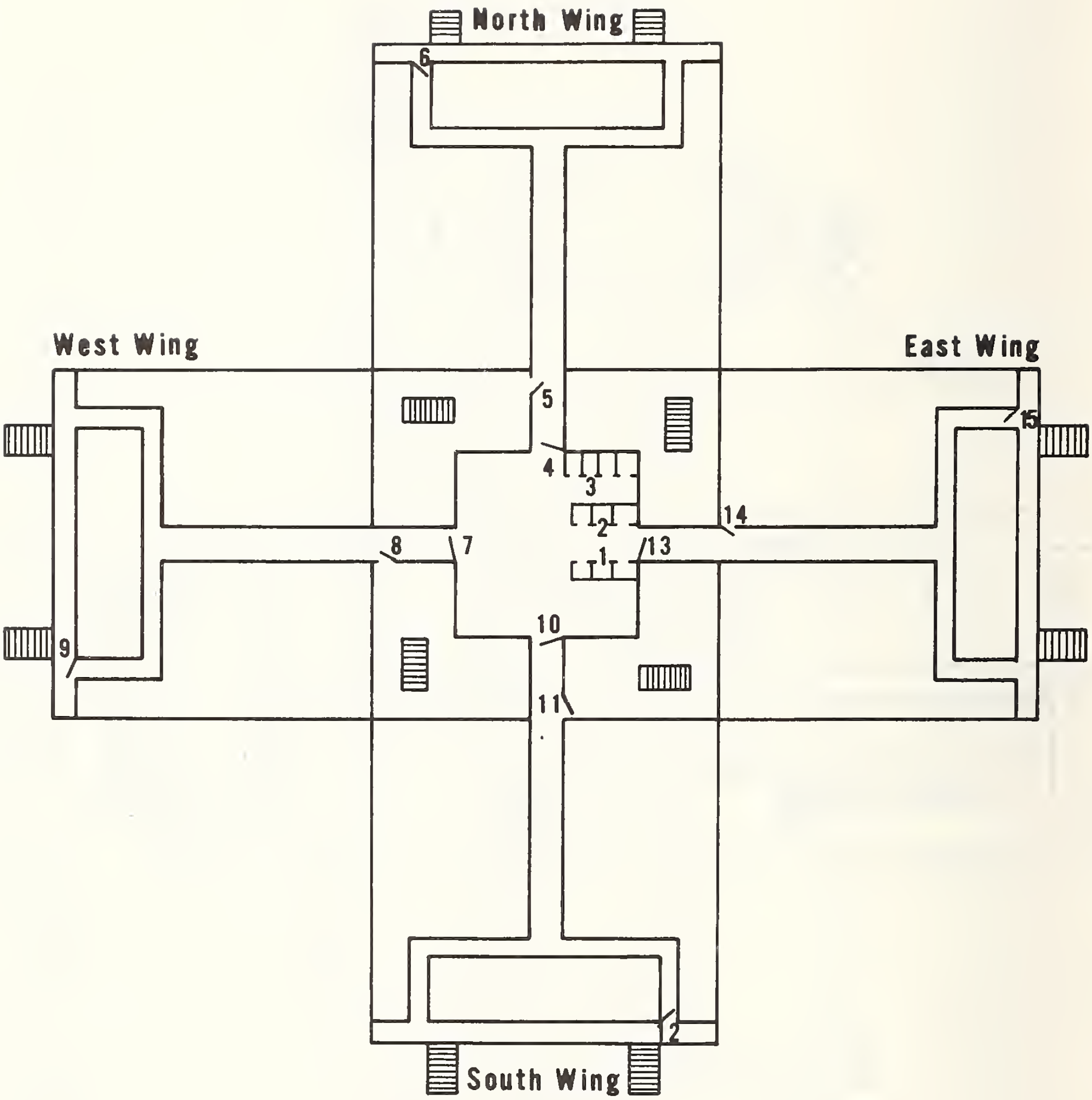

Figure 6. Sampling Locations for Pressure Monitor Experiments (Interior Corridor Doors 4, 7, 10, 13 were Open Unless Otherwise Noted. All Other Exterior Doors were Closed Unless Otherwise Noted.)

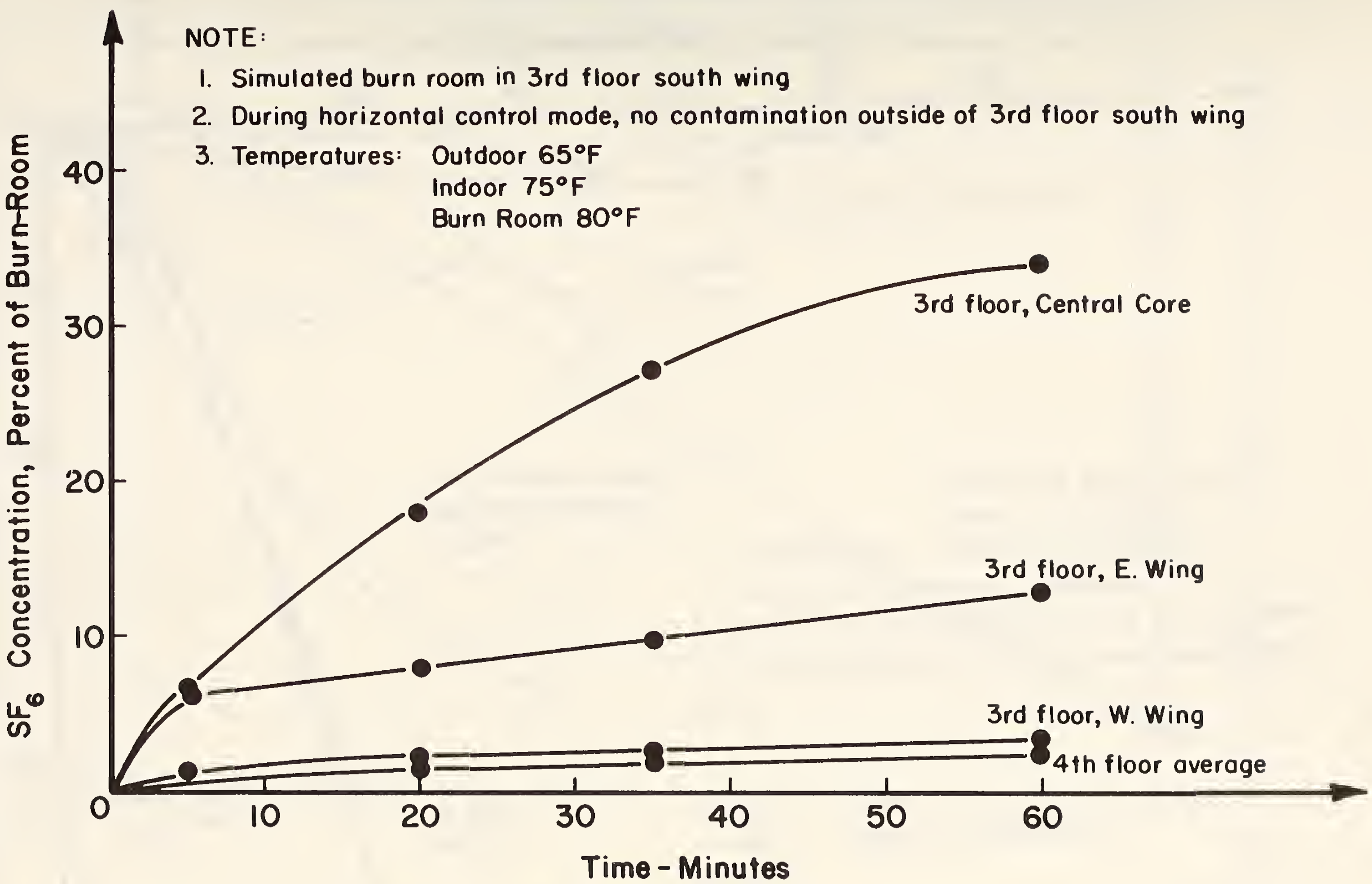

Figure 7. San Diego VAH, Horizontal Smoke Movement Experiment [Test 1]

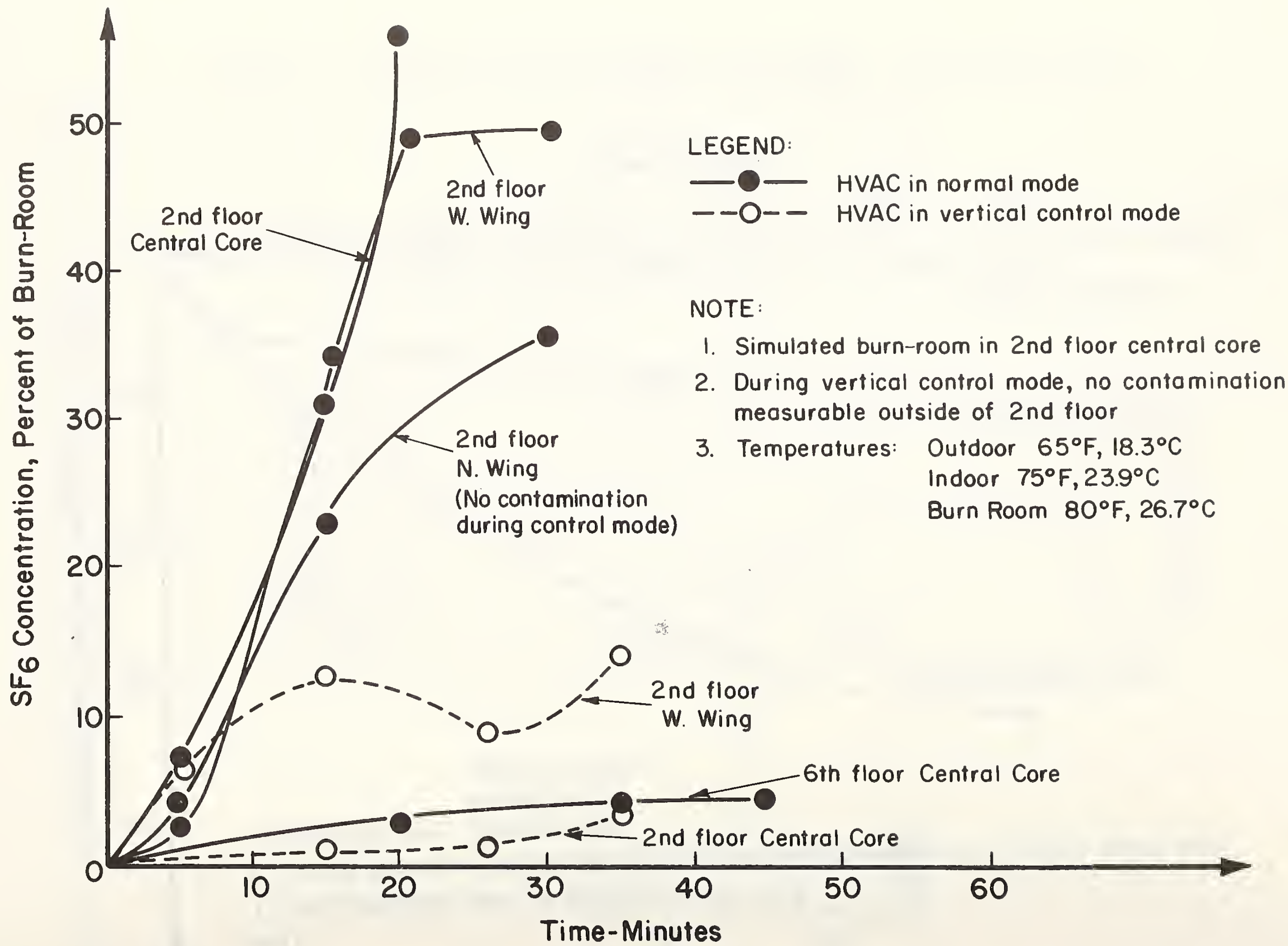

Figure 8. San Diego VAH, Vertical Smoke Movement Experiment [Tests 3 and 4].

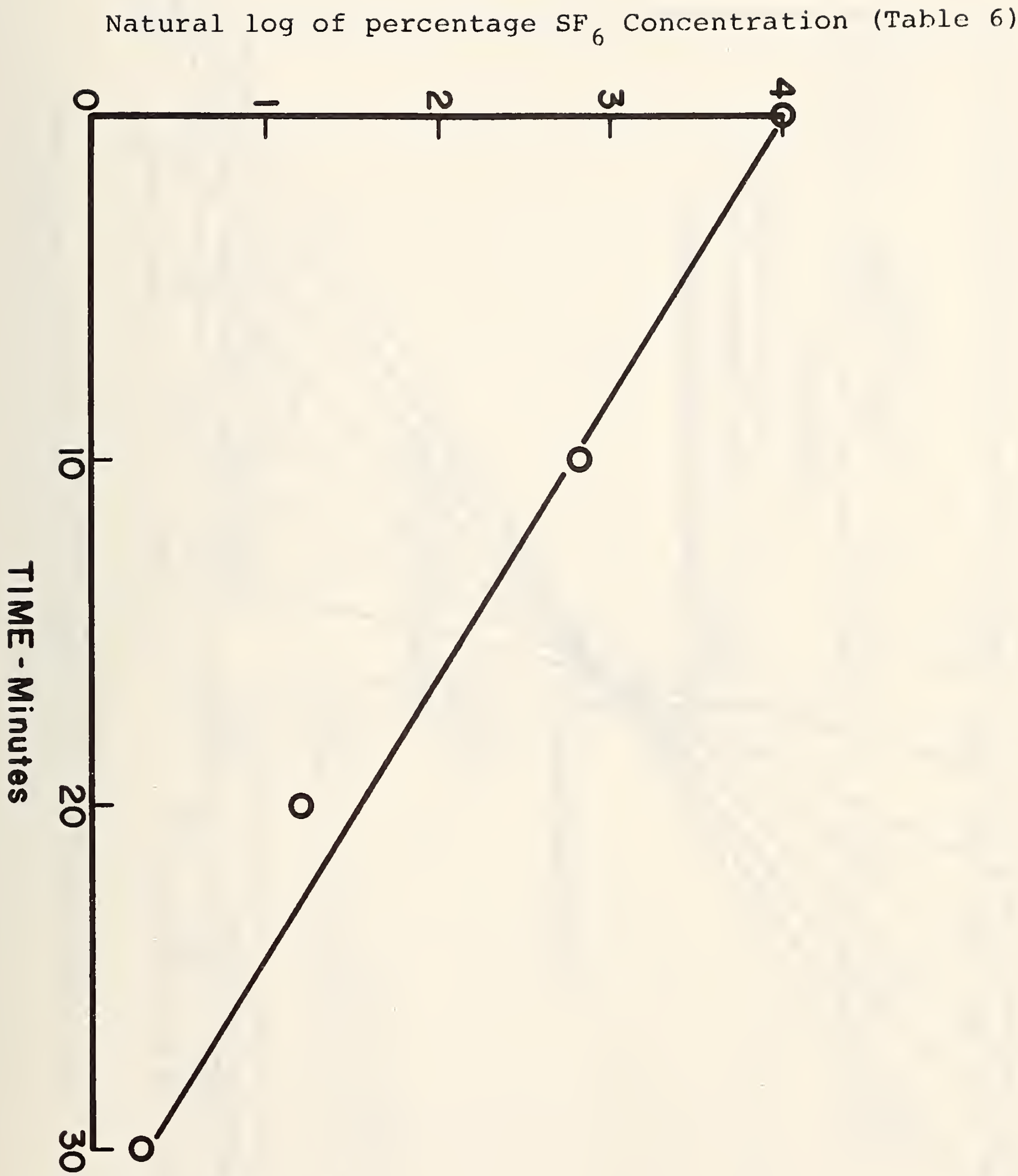

Figure 9. Third Floor SF_6 Decay Study, Location 3-1 [Test 5].

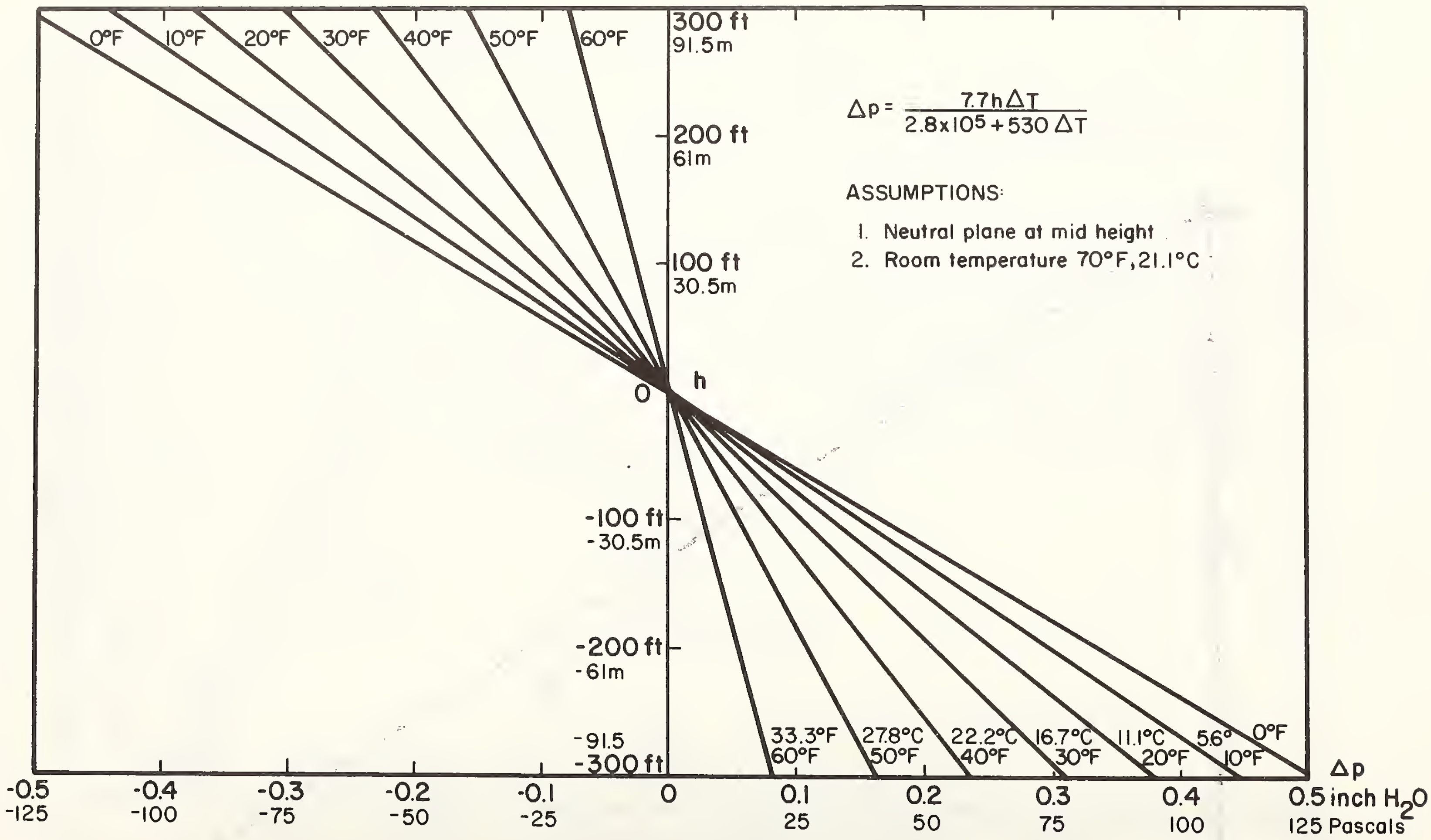

Figure 10. Stack Effect versus Building Height for Different Outside Temperatures

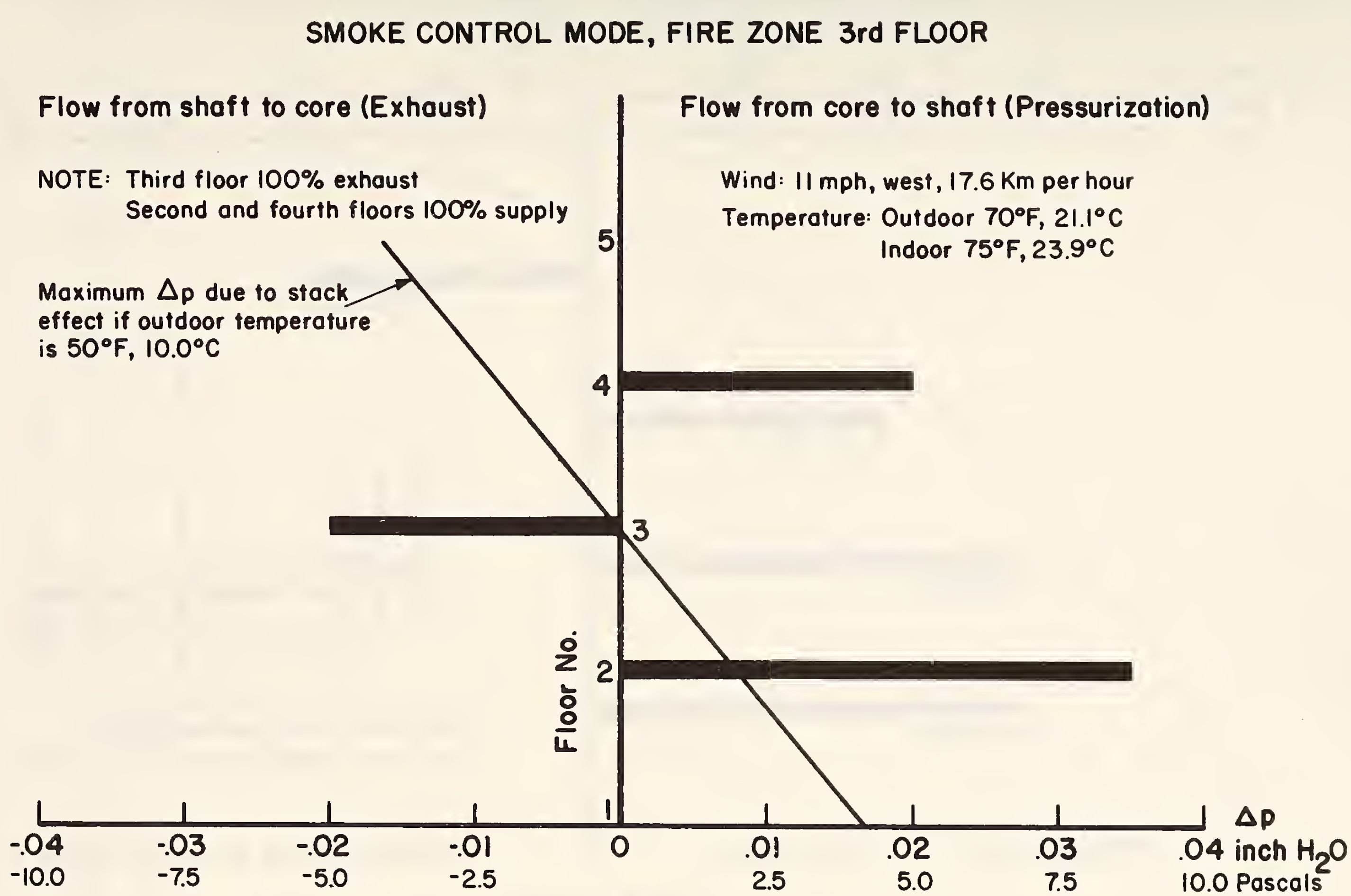

Figure 11. San Diego VAH Elevator Shaft Pressure Profile, Smoke Control Mode [Test 4].

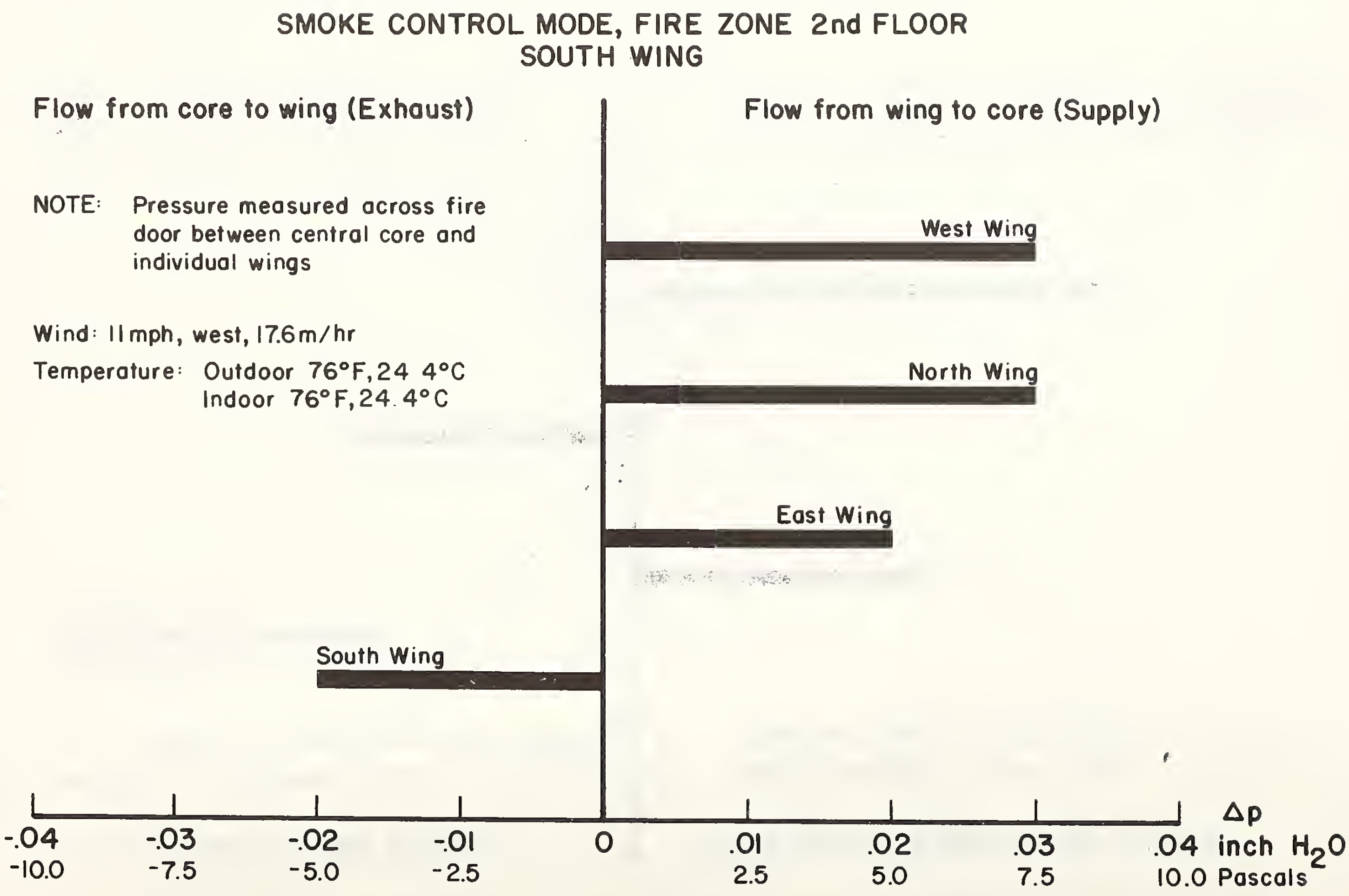

Figure 12. San Diego VAH Center Core Pressure Profile, Smoke Control Mode [Test 2].

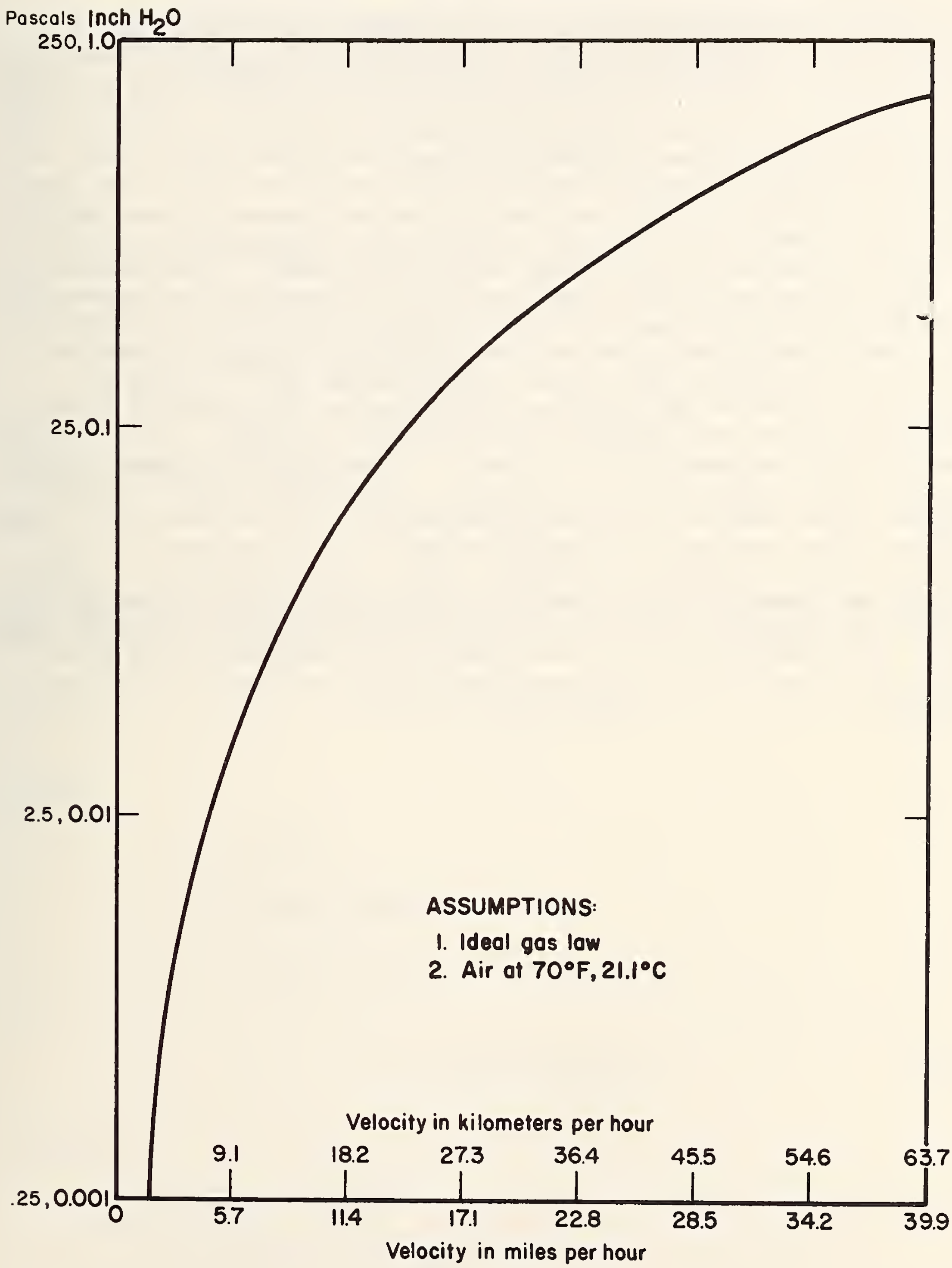

Figure 13. Pressure versus Velocity Head

APPENDIX A. DESCRIPTION OF AIR-HANDLING SYSTEM

The air-handling systems for the San Diego VA Hospital are all housed in the "interstitial space" between each floor. Each wing on each floor gets its own air supply unit and several exhaust fans. For a brief description of the construction features of the San Diego Hospital and the interstitial space, one is referred to references [19] and [25]. Each air-handling system contains one supply unit (600 cubic meters or 20,000 cubic feet per minute) and several exhaust fans (total 480 cubic meters or 16,000 cubic feet per minute) that are located in separate mechanical rooms within the interstitial space. The rooms containing the supply units are located close to the center core of the building and the supply units draw 100 percent outside air through grills mounted in the interstitial overhang. The exhaust equipment rooms are located in the opposite end of each quadrant from the supply equipment rooms and are close to the end of each wing, permitting the wind to sweep the exhaust away from the building and thus lessening the chance of cross contamination from the exhaust to the outside air intake. The air supply systems are of the single duct, variable-volume-type with reheat coils mounted in the volume control terminals. The moderate size of the air-handling units permits the units to be located in the interstitial spaces. Moreover, these systems are capable not only of handling the initial loads but, also, of handling increased loads, when they need to. Thus the systems themselves can be modified without disruption of the entire hospital or the entire floor. With ductwork, piping, and equipment mounted within the interstitial space, servicing of the equipment as well as future modifications may be accomplished without disruption of patient treatment.

APPENDIX B. PRESSURE FORCE DUE TO STACK EFFECT

The well known stack effect in a high-rise building is caused by the difference in hydrostatic pressure due to two air columns at different temperatures. Thus the pressure difference is given by:

$$\Delta p = (\rho_o - \rho)\, gh. \tag{B1}$$

where

ρ_o = the outside air density

ρ = the inside air density

g = the gravity constant

h = distance from the neutral plane.

Assuming the ideal gas law

$$\Delta p = \frac{pg}{R}\left(\frac{1}{T_o} - \frac{1}{T}\right) h. \tag{B2}$$

Considering standard atmospheric condition, we can express the above as

$$\Delta p = 7.7 \left(\frac{1}{T_o} - \frac{1}{T}\right) h. \tag{B3}$$

where

h = is in feet

T = in degrees Rankine

Δp = in inches of water

or

$$\Delta p = 3600 \left(\frac{1}{T_o} - \frac{1}{T}\right) h. \tag{B4}$$

where

h = height in meters

T = temperature in degrees Kelvin

Δp = pressure difference in Pascals

The above formula indicates that for a 100-ft tall building with neutral plane at mid-height and a 70 °F temperature differential, a maximum of 0.1 inch H_2O pressure difference can be induced by stack effect.

APPENDIX C. PRESSURE FORCE DUE TO WIND EFFECT

Consider air motion caused by a generalized pressure force, p. The momentum equation for the flow field in this case can be simply written as,

$$\rho\overline{V} \cdot \nabla\overline{V} = - \Delta p \tag{C1}$$

where

ρ = the gas density,

$\overline{V}$ = the gas velocity vector,

p = the pressure distribution of the flow field, and

∇ = the gradient operator.

Integrating (C1) along the direction of smoke motion one obtains

$$1/2\rho V^2 = |\Delta p| \tag{C2}$$

where

Δp = the pressure difference

Assume that gas density change is governed by the ideal gas law,

$$p = \frac{P}{RT} \tag{C3}$$

where

T = the absolute temperature, and

R = the gas constant.

Combining (C2) and (C3) and evaluating for air under standard atmospheric condition, with R equaling 53.3 ft lb_f/lb_m °R one obtains

$$V = 174\sqrt{\Delta pT} \tag{C4}$$

where

V = velocity in feet per minute,

T = temperature in degrees Rankine, and

Δp = pressure difference in inches of H_2O.

or

$$V = 4.49\sqrt{\Delta pT} \tag{C5}$$

where

V = velocity in meters per minute,

T = temperature in degrees Kelvin, and

Δp = pressure difference in Pascals.

APPENDIX D. FIELD TEST COMPARISON AND PARAMETRIC ANALYSIS SAN DIEGO VETERANS ADMINISTRATION HOSPITAL

Development of an Air Movement Simulation Program

APPENDIX D. FIELD TEST COMPARISON AND PARAMETRIC ANALYSIS SAN DIEGO VETERANS ADMINISTRATION HOSPITAL

DEVELOPMENT OF AN AIR MOVEMENT SIMULATION PROGRAM

J.W. Fothergill, P.A. Fothergill, M.A. Johnson

Prepared for:
Center for Fire Research
Fire Safety Engineering Division
National Bureau of Standards

Under Contract No. 5-35727

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Rockville, Maryland 20852

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INTRODUCTION

Under the sponsorship of the Fire Research Center of the National Bureau of Standards, a realistic computer simulation program was developed for predicting the steady state movement of air through high-rise building complexes. The objective of this work was to provide a more representative building/HVAC system modeling capability than was currently available (1), (2) at the Fire Research Center. The available air movement simulation capability (1) was based upon an extremely simplistic representation of a building/HVAC system. Since the Fire Research Center had been and was conducting trace gas field tests of various Federally owned or controlled buildings to test, evaluate, and make recommendations for smoke control features in these buildings, it was also necessary to provide a means to simulate smoke concentrations within a building from a simulated source in the computer simulation capability. However, this effort did not include the development of a "second generation" smoke concentration computer simulation program which matched the newly developed air movement simulation program. Rather, it was decided to achieve a meaningful air movement simulator in this effort and attack the smoke concentration simulator at a later time.

In order to provide a minimal smoke concentration prediction capability, an output data interface was developed in the new air movement simulator which was compatible to the smoke concentration simulation program currently available (1) at the Fire Research Center. This allowed the use of a very limited portion of the simulated air movement data to be input to a smoke concentration predictor. The use of this smoke concentration predictor must be made with extreme care, since its representation of a building/HVAC system is limited to corridors coupled to a maximum of 10 vertical shafts and two external walls. Results from the use of this smoke concentration predictor can be completely misleading when it is coupled to the newly developed air movement program.

In order to verify the newly developed air movement computer simulation and to demonstrate its capability, several buildings which had undergone trace gas tests and pressure data measurement by personnel of the Fire Research Center were simulated to some degree during this project. The most extensive computer simulation effort was accomplished in the San Diego Veterans' Hospital. Three levels of simulation were performed, i.e.:

1. Calibration of the parametric model of the San Diego VA Hospital building/HVAC system against pressure data collected on site under various states of the building/HVAC system

2. Simulation of the field-conducted trace gas tests

3. Simulation of hypothetical conditions of the hospital by varying different parameters to gain insight into the level of effectiveness of the smoke control techniques available.

This appendix presents a description of the model of the hospital used in the newly developed air movement program, the manner in which the simulated model was calibrated, and the results of the calibration, the trace gas tests simulated and the results of the simulation, the parametric variations of the hospital's states simulated and the results of these simulations, and some of the conclusions reached regarding the use of the computer simulation programs on this building.

SIMULATION MODEL CONFIGURATION

Many variations are available in the newly developed air movement computer simulation program to represent a building such as the San Diego VA Hospital. Three basic configurations were immediately obvious, i.e.:

1. As one integral building with the interstitial spaces represented as floors between the occupancy floors, one main corridor open and connecting the core and all wings on each occupancy floor, office spaces on occupancy floors represented as compartments connecting to the main corridor, and the center core areas of the interstitial spaces as a pseudo-corridor with only leakage penetrations connecting to the wing interstitial spaces represented as compartments.

2. As one integral building, defined as above, except that the wing corridors would be separated from the core corridor as another compartment which was coupled to the wing compartments representing the office spaces in the wings on the occupancy floors.

3. As five separate buildings composed of the central core and wings connected by passageways between the core and the wings at each occupancy floor and each interstitial level.

The first model defined above was selected because it most closely represented the hospital in its normal mode. Separating the wing corridors into separate compartment spaces would have allowed a means to evaluate lateral smoke movement. However, the currently available smoke concentration simulator is not capable of simulating lateral smoke movement and the results from the air movement program could not have been utilized effectively. Use of the third model suggested above would have presented modeling of the couplings of the interstitial spaces with each other, and with common electrical equipment shafts, plumbing shafts, and stairwells.

The office spaces from the second floor upward were lumped into a single compartment for the core and a single compartment for each wing. This allowed a five-compartment representation on each occupancy floor. Segregation could have been made to a maximum of 10 compartments on each floor. However, it would not have provided any additional benefits to the simulation. The basement and the first floor were each reduced to a corridor and one compartment representation for all non-corridor space.

All of the inner stairwells and adjacent shafts were represented and coupled as they actually occurred. The shafts adjacent to stairwells 9 and 11 were also represented with their own air supply, as actually occurs. The outer stairwells were reduced to one on each wing rather than two because of the number and the fact that the effect of two could be represented by one simulated stairwell. The short stairwell connecting the basement and the first floor was also represented, as were the plumbing risers. All of the elevator shafts were represented as constructed, including the animal elevator. The pneumatic trash and laundry tube coupling was also represented as shown on the mechanical drawings. Leakage between each corridor and the interstitial space directly above was represented by the floor-to-floor leakage term. However, the office space areas were coupled to their interstitial spaces directly above by the use of pseudo shafts.

The availability of 90 simulated shafts and their versatility allows them to be used to couple any building spaces and external space as desired. Couplings between the wing interstitial spaces representing plumbing and conduit penetrations were accomplished in the same way.

Because of the limitations on the number of HVAC systems allowed by the program (25), it was not possible to represent each individual A/C unit. Each occupancy floor was lumped for air supply and air exhaust. However, each wing was represented correctly in the amount of supply and exhaust as reflected in the mechanical drawings. The core was exhausted by an independent exhaust fan representing TF-8. However, the penthouse was not modeled and the simulated TF-8 exhausted directly to the external space from the simulated sixth floor interstitial space.

One limitation was encountered in the program that hampered correct representation. This was the limitation on blower or fan parametric representations. The program only allows the use of 20 fans. This creates the need to compromise on the specifications of output capacities and static pressures so that each entry can be utilized to represent more than one actual fan or blower. This, in turn, creates difficulties in manipulation of the input data to represent non-normal operating states, such as smoke control modes of failure modes. The number of allowable blowers or fans should be increased to approximately 50 at some time in the future.

CALIBRATION OF THE MODEL

Comparison of simulated smoke tests in a building, using a tracer gas, with simulated computer smoke concentrations from the simulated model of the building does not provide an exact basis to determine how well the computer model represents a building's spatial configuration, air couplings and leaks, HVAC system, and air flow. It is only of an indicative nature. However, fitting the computer model to field-collected pressure difference data taken at all major airflow couplings, e.g., elevator doors, stairwell doors, etc., provides a very precise basis for adjusting the model to fit the air movement characteristics of a building. Consequently, pressure difference data was collected in the San Diego building with the HVAC system in various modes.

This section presents the results of fitting or calibrating the computer model of the San Diego VA Hospital to the field-collected pressure difference data.

Field-Collected Data

Six basic modes or conditions were established and pressure difference data was collected at 15 locations on each floor measured. At least two floors and, more generally, three floors were measured for each mode. Each of the six modes are described in this section and the measured data is presented in Tables 1, 2, 3, 4, 5, and 6. The sample points are illustrated in Figure 1.

The bank of elevators at sample location 1 are represented in a single sample. However, the banks located at sample location 3 is composed of two separate shafts and was simulated in that manner.

TABLE 1. TEST PRESSURE NO. 1

Sample Point \ Floor	2	3	6
1	+.01	+.00	-.01
2	+.00	+.00	-.01
3	+.01 ±.01	+.01	-.01
4	+.00	+.00	+.01
5	-.02	+.00	+.02
6	-.01 ±.01	+.01	+.01
7	-.01 ±.01	-.01	-.01
8	-.02	+.00	-.02
9	-.02	-.025	+.01
10	-.02	+.00	-.00
11	+.01	+.01	+.02
12	+.015	+.01	+.00
13	+.00	-.01	+.00
14	+.03	+.01	+.015
15	±.01	+.00	+.01

TABLE 2. TEST PRESSURE NO. 2

Sample Point \ Floor	2	3	4
1	.00	.01	.00
2	.00	.01	.00
3	.00	.01	.005
4	.00	-.03	.00
5	.00	±.00	-.015
6	.00	.015	.02
7	-.02	-.03	-.01
8	-.02	±.00	-.02
9	-.05	-.04	-.08
10	.00	.02	.00
11	+.01	.025	.03
12	-.02	.01	.02
13	.00	-.02	.01
14	.02	.02	.025
15	.00	.01	-.01

TABLE 3. TEST PRESSURE NO. 3

Floor / *Sample	3a	3b	3c	3d
	West Wing Door Open			
North Door	-.03	-.03	-.02	-.02
South Door	.06	.06	.04	.05
East Door	.02	.01	.01	.005
West Door	-.04 ±.01	-.04	-.04	-.035

*Samples taken with center core corridors closed at the center core corridor doors.

TABLE 4. TEST PRESSURE NO. 4

Sample Point \ Floor	3	4	
1	-.02	.03	
2	-.02	.03	
3	-.02	.03	
4	-.015	-.01	
5	-.04	.02	
6	-.035	.00	
7	-.02	-.01	
8	-.03	.02	
9	-.05	.035 ±.005	
10	.02	.00	
11	.00	.05	
12	-.02	.01	
13	.015	-.015	
14	-.01	.02	
15	-.025	.01	

TABLE 5. TEST PRESSURE NO. 5

Floor / Sample Point	2	3	4
1	.035	-.02	.03
2	.03	-.02	.02
3	.035	-.02	.02
4	.00	-.025	.01
5	.03	-.02	.025±.005
6	.015	-.02	±.015
7	-.03	-.01	-.01
8	.015	-.02	+.04
9	-.015	-.06	-.04
10	-.01	.035	.00
11	.05	.01	.05±.01
12	.07	-.01	+.02
13	.00	.025	.00
14	.035	.01	.045
15	.02	-.01	.01

TABLE 6. TEST PRESSURE NO. 6

Sample Point \ Floor	4	5	6
1	.04	-.03	.01
2	.03	-.03	.01
3	.03	-.03	.01
4	-.015	.015	-.02
5	.02	-.03	.01
6	.02	-.01	--
7	-.015	-.01	.01
8	.035	-.015	.025
9	-.02	--	-.04
10	-.01	-.01	.01
11	.07	-.00	.04
12	.005	-.01	.01
13	.00	.02	-.01
14	.05	.00	.045
15	.01	-.01	.00

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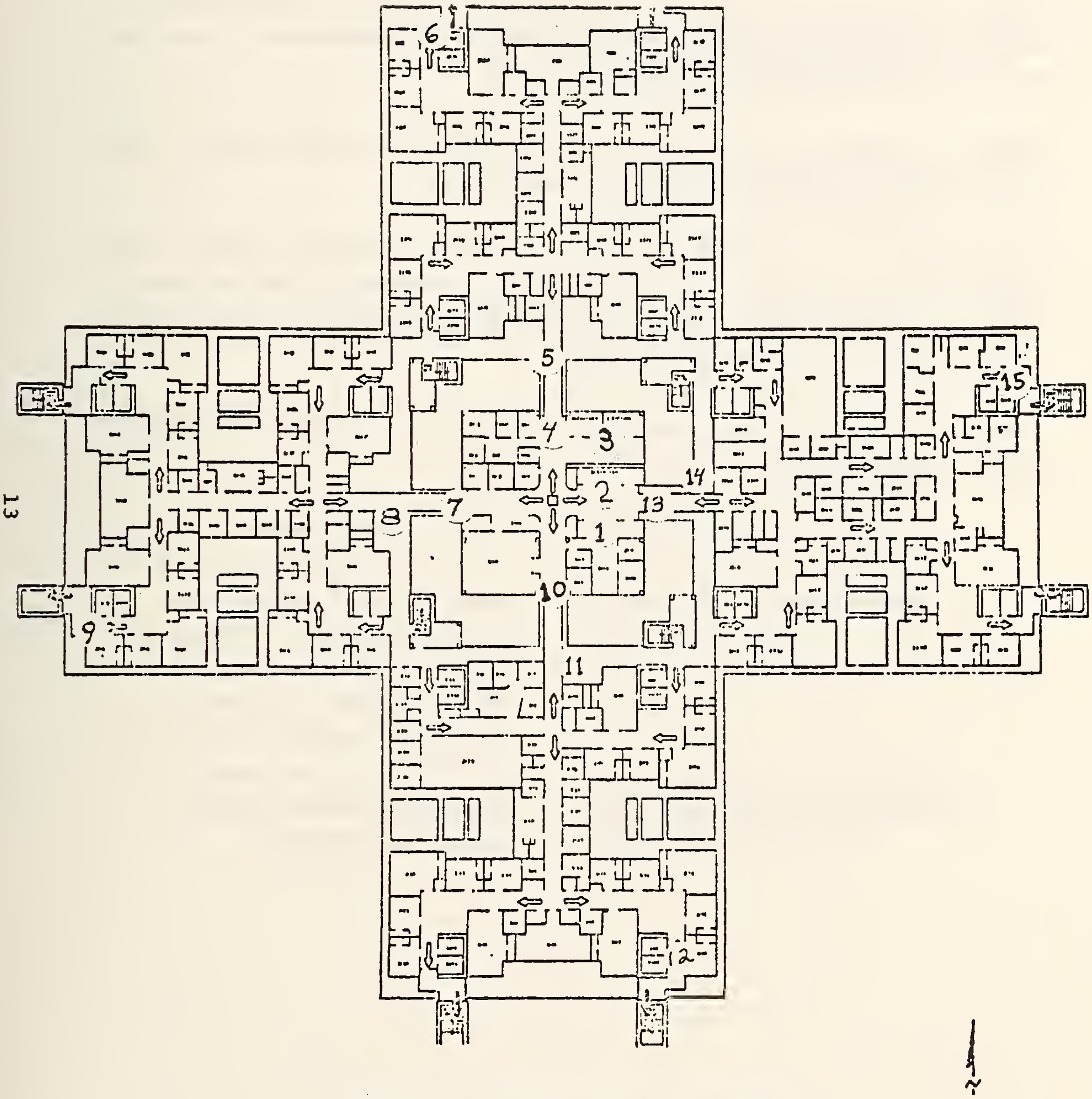

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FIGURE 1. SAMPLE POINT LOCATIONS

The samples taken at location 3 were from both shafts. Consequently, the sampled data from these locations must be compared with the computer simulation results from the two shafts in each respective bank of elevators.

Sample locations 4, 7, 10, and 13 were taken at the inner corridor doors, which are normally open, providing one continuously open and connected corridor throughout each floor.

Sample locations 5, 8, 11, and 14 were taken at external doors opening onto the outside decks of the inner ring.

Sample locations 6, 9, 12, and 15 were taken at external doors opening onto the outside decks at the outer perimeter of the building. Location 9 was directly exposed to the prevailing west wind, which was usually at a velocity of 11 mph.

The modes imposed during the field collection of pressure difference data were as follows:

1. Pressure Test Case No. 1 - HVAC in normal mode.

2. Pressure Test Case No. 2 - South wing of third floor on exhaust only, balance of third floor on supply only, balance of building in normal mode.

3. Pressure Test Case No. 3 - Same mode as Test Case 2, except as follows:

	Case 3A	Inner corridor doors to the west wing closed and west wing external door open (location 9) on the third floor.
	Case 3B	Same as 3A, except east wing (location 15) instead of west wing.
	Case 3C	Same as 3A, except north wing (location 6) instead of west wing.
	Case 3D	Same as 3A, except south wing (location 12) instead of west wing.
	Case 3E	All inner corridor doors and external doors closed.
4.	Pressure Test Case No. 4 -	Entire third floor on exhaust only, entire fourth floor on supply only, and balance of building in normal mode.
5.	Pressure Test Case No. 5. -	Entire second and fourth floors on supply only and entire third floor on exhaust only.

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6. Pressure Test Case No. 6 - Entire fourth floor on supply only, entire fifth floor on exhaust only, except the west wing on supply and exhaust, and entire sixth floor on supply only, except the south wing on supply and exhaust.

<u>Wind and Temperature Parameters</u>

The indoor and outdoor temperatures, the wind velocity existing at the time each test was made, and the parametric values used in the computer simulation are shown in Table 7. The small variation in indoor and outdoor temperatures justified the use of average values in the computer simulation.

The rationale used to represent the wind acting on the external doors is illustrated in Figure 2. The external door at location 9 was assumed to be receiving almost the direct effects of the prevailing west wind, and wind function No. 2 was set at 11 mph for this purpose. The external doors at locations 6 and 15 were assumed to be receiving indirect and turbulent actions due to the west wind. Wind function no. 4 at 8 mph was used for these locations in the computer simulation. The inner ring doors at locations 5, 9, 11, and 14 and the external door at location 12 were assumed to be in relatively stagnant areas. Wind function no. 3 at 5 mph was utilized for that representation.

TABLE 7. TEMPERATURE AND WIND CONDITIONS

	Case	Indoor Temp. °F	Outdoor Temp. °F	Wind Speed (mph)/ Direction
Simulated Conditions	All	74	73	Function No. 1 - 0 Function No. 2 - 11 Function No. 3 - 5 Function No. 4 - 8
Actual Conditions	1	75	71	8, westerly
	2	76	76	11.4, westerly
	3	74	75	11.4, westerly
	4	74	75	11.4, westerly
	5	74	72	10.8, westerly
	6	74	73	10.8, westerly

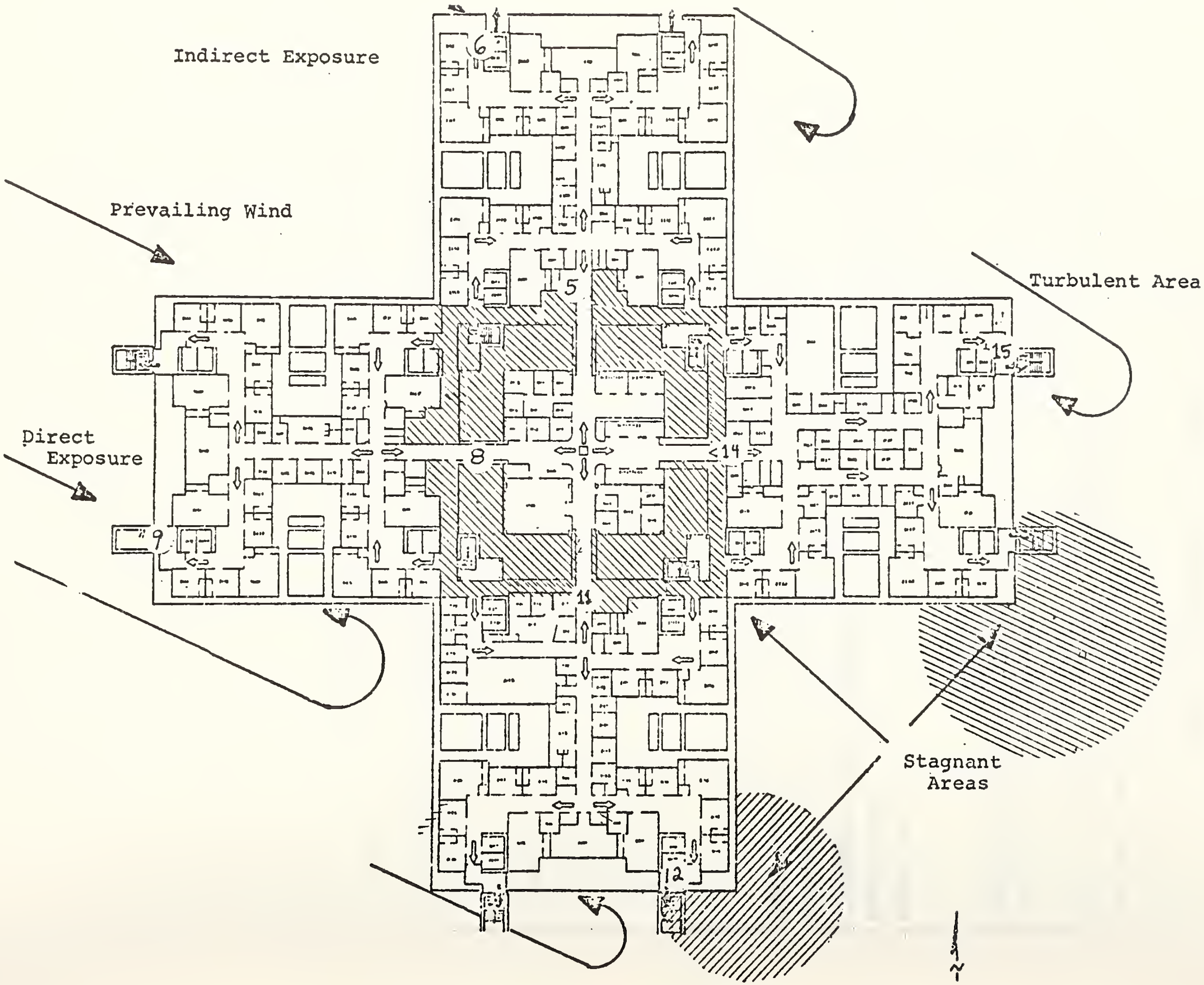

FIGURE 2. WIND EFFECTS

Results of Computer Simulations for Calibration

The comparative results between the field-collected pressure difference data and that produced by the computer model of the San Diego VA Hospital in the newly developed air movement program are presented in Figures 3 through 32, except for pressure test case no. 3. Because the model configuration utilized a single open and connected corridor, no pressure differences were generated between the center core corridor and the outer wing corridors by the computer simulation. Consequently, no comparative results were obtained.

The comparative results, in general, are in good agreement. This implies that the computer simulation model utilized was reasonably representative of the building and the test conditions at the time of the field pressure difference collection. The elevator pressure difference comparisons appeared to be somewhat better than the outside wind function and external door comparisons. Overall behavior appeared to be consistent and representative of the actual building system. Occasional points varied, but there was some uncertainty about some of the measurements taken, due to fluctuations in the measuring gages, as well as a wind that rapidly fluctuated between 500 and 1,200 fpm in speed.

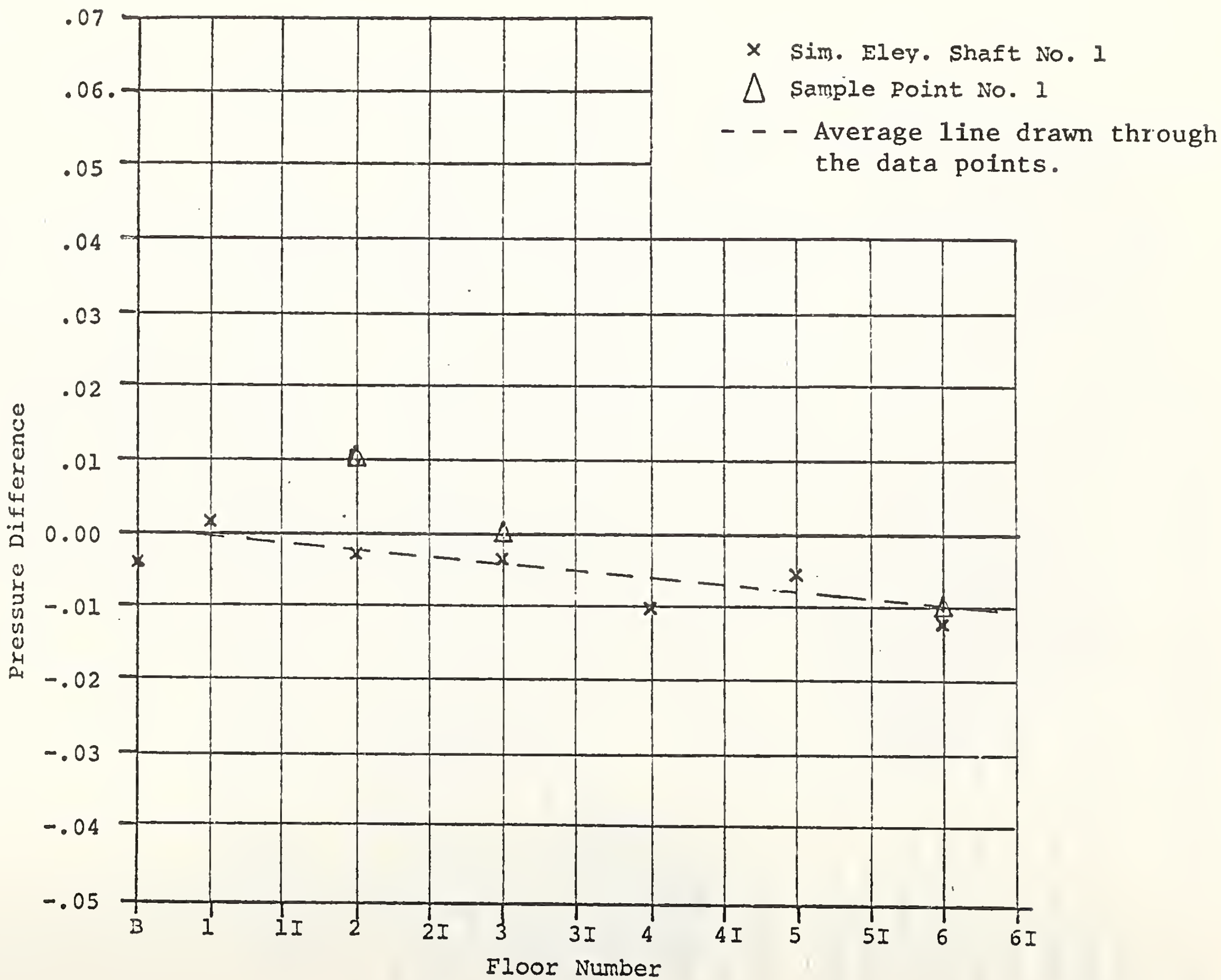

FIGURE 3. SIMULATED ELEVATOR SHAFT NO. 1 VS SAMPLE POINT NO. 1
(PRESSURE TEST CASE NO. 1)

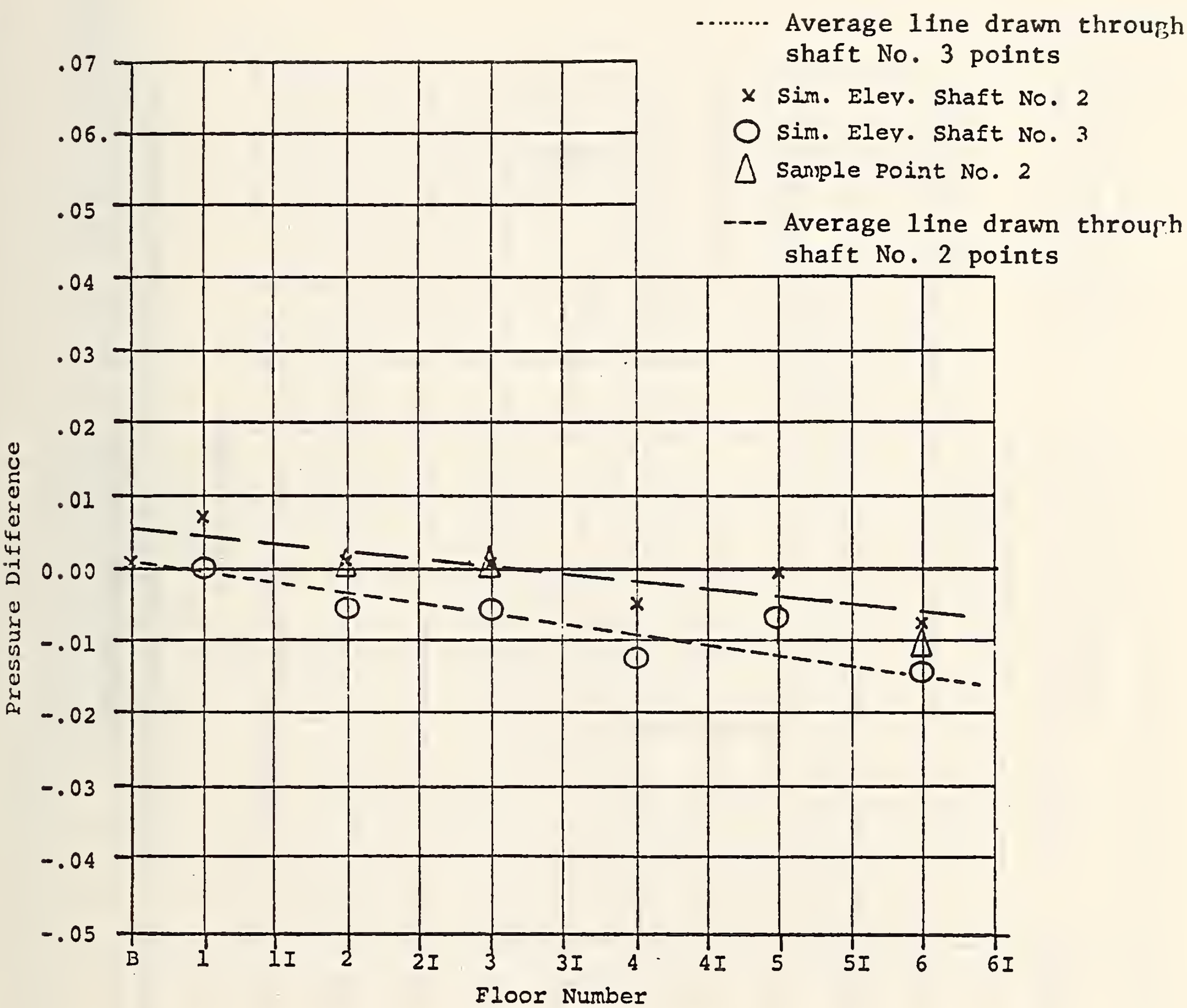

FIGURE 4. SIMULATED ELEVATOR SHAFTS NO. 2 AND 3 VS SAMPLE POINT NO. 2
(PRESSURE TEST CASE NO. 1)

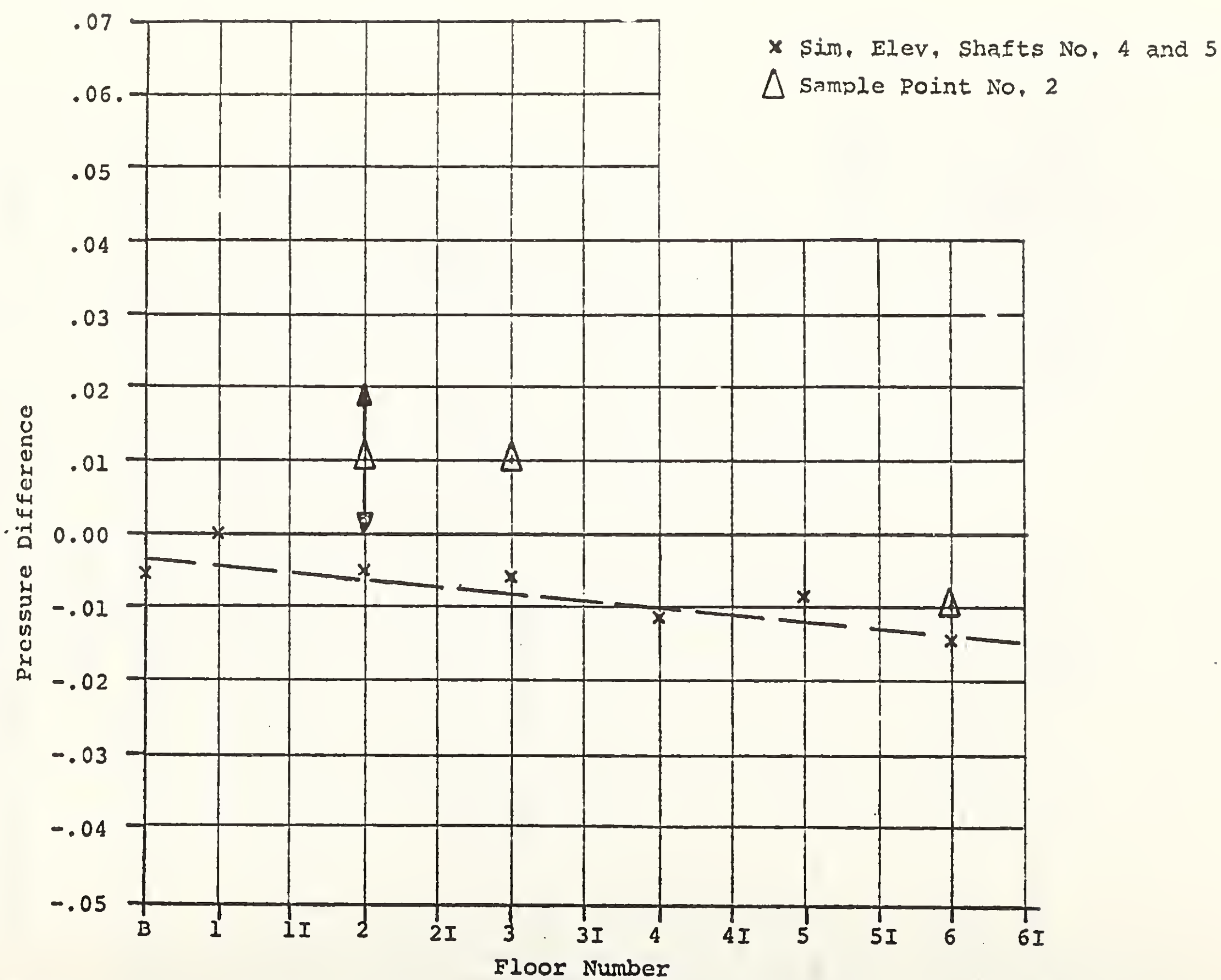

FIGURE 5. SIMULATED ELEVATOR SHAFTS NO. 4 AND 5 VS SAMPLE POINT NO. 2
(PRESSURE TEST CASE NO. 1)

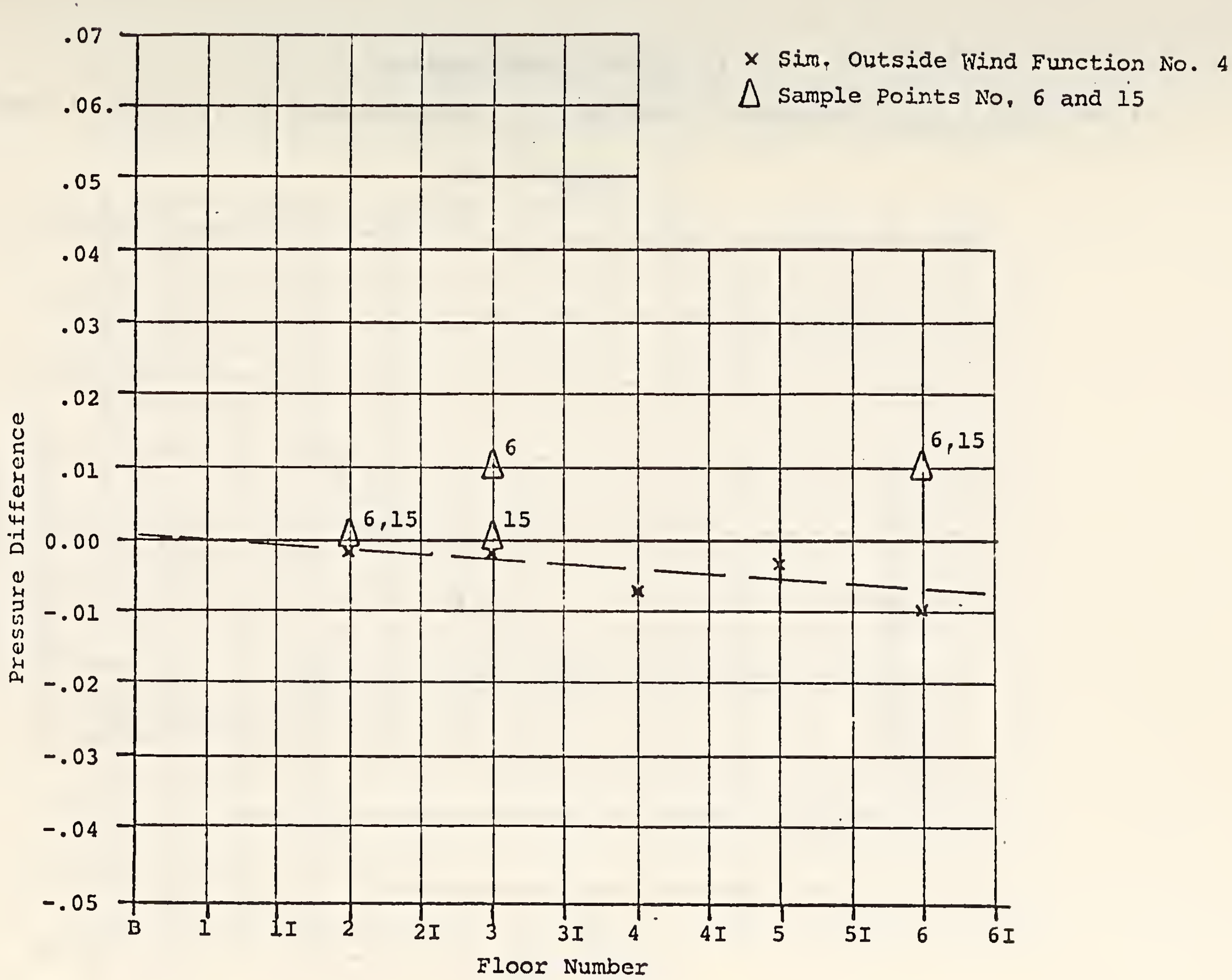

FIGURE 6. SIMULATED OUTSIDE WIND FUNCTION 4 VS SAMPLE POINTS 6 AND 15 PRESSURE TEST CASE NO. 1)

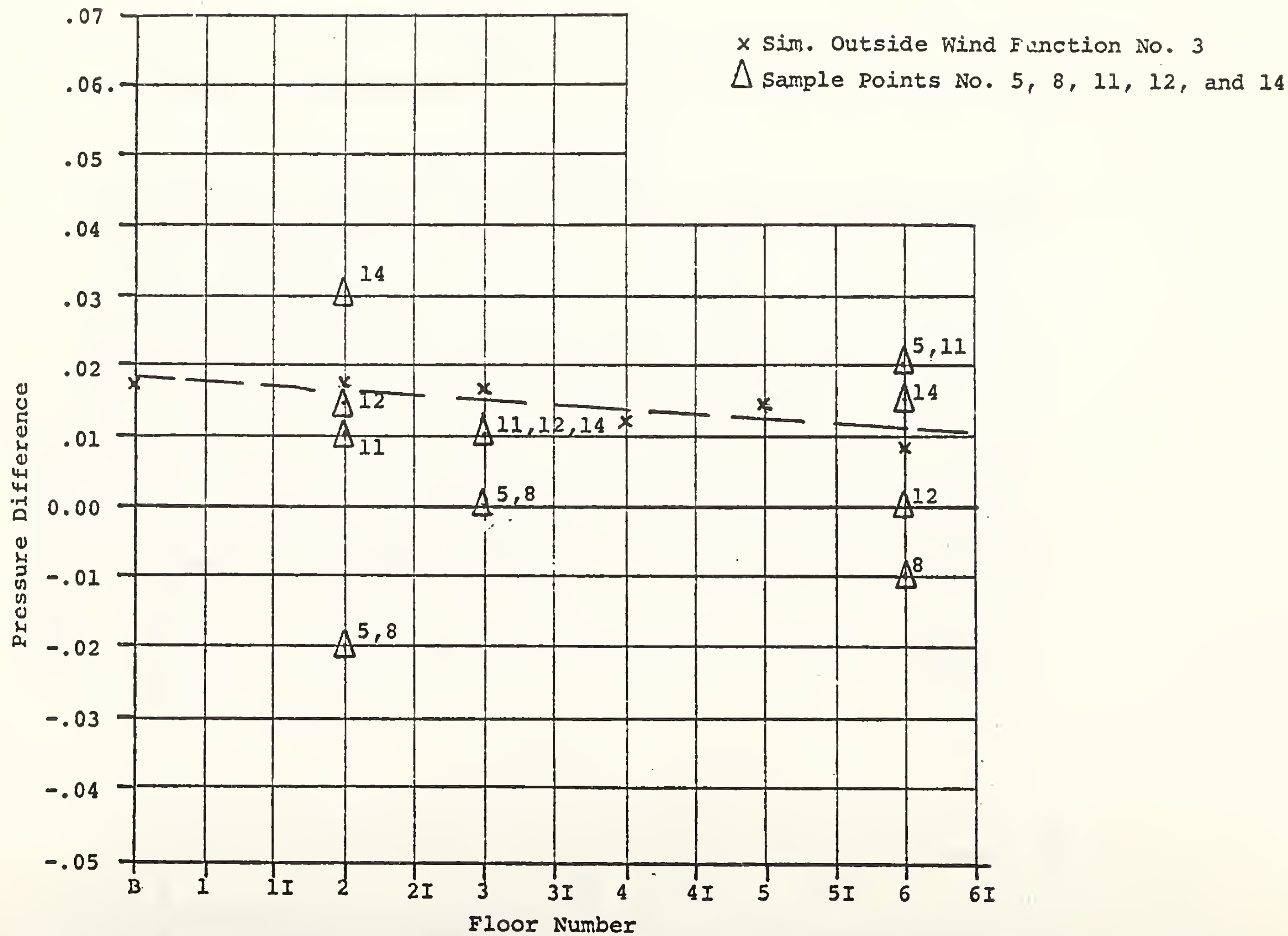

FIGURE 7. SIMULATED OUTSIDE FUNCTION NO. 3 VS SAMPLE POINTS NO. 5, 8, 11, 12, AND 14

(PRESSURE TEST CASE NO. 1)

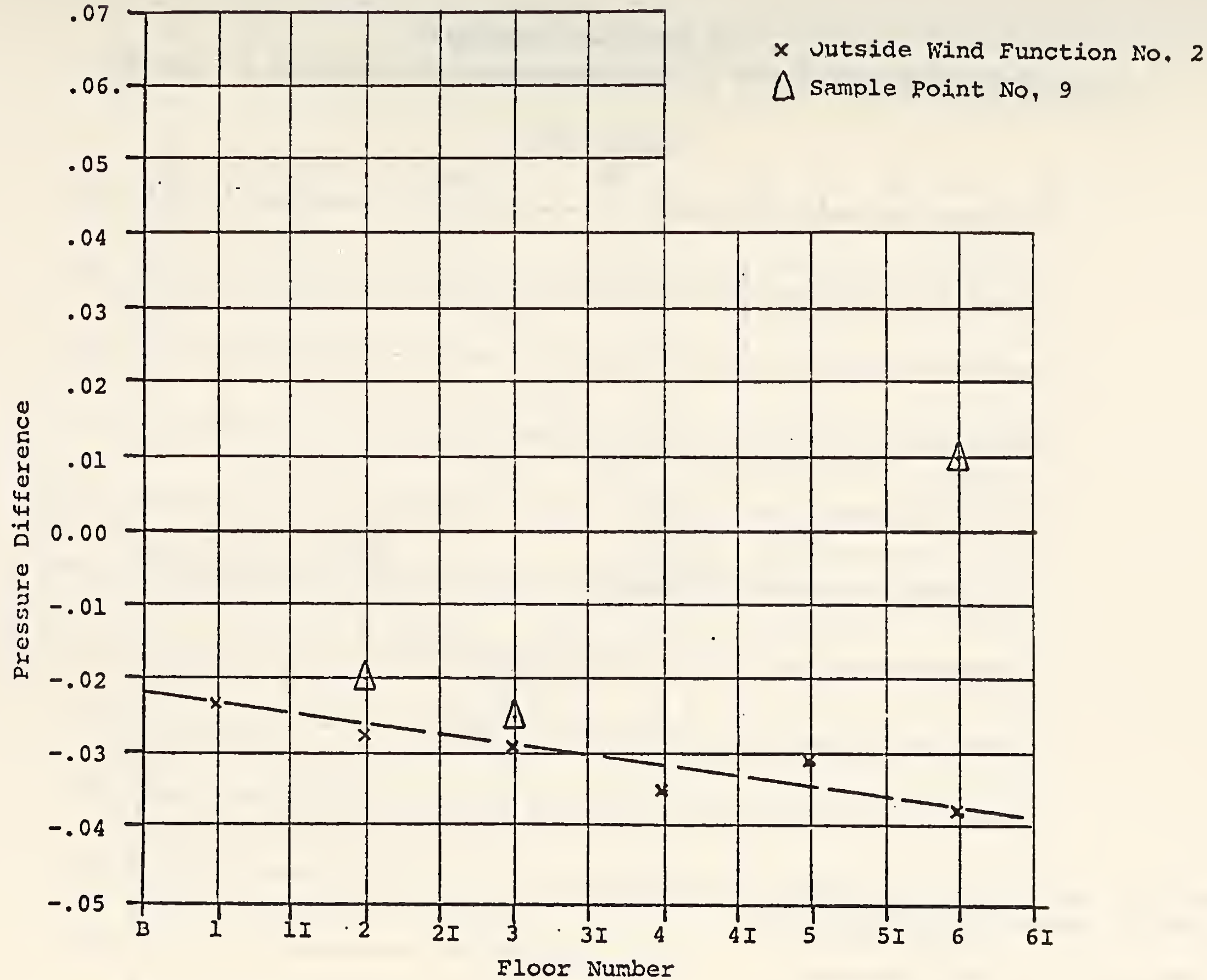

FIGURE 8. SIMULATED OUTSIDE WIND FUNCTION NO. 2 VS SAMPLE POINT NO. 9
(PRESSURE TEST CASE NO. 1)

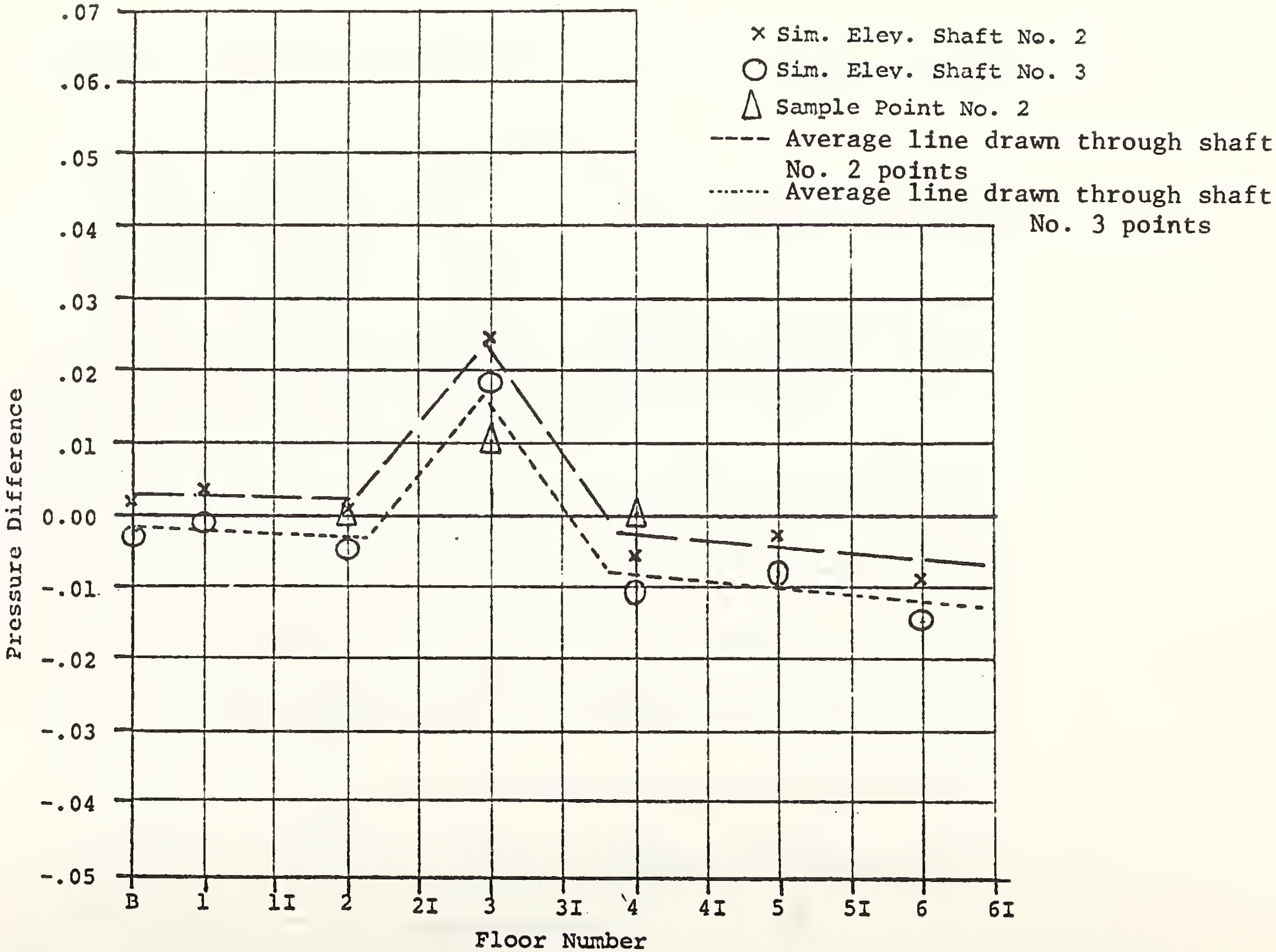

FIGURE 9. SIMULATED ELEVATOR SHAFTS NO. 2 AND 3 VS SAMPLE POINT NO. 2 (PRESSURE TEST CASE NO. 2)

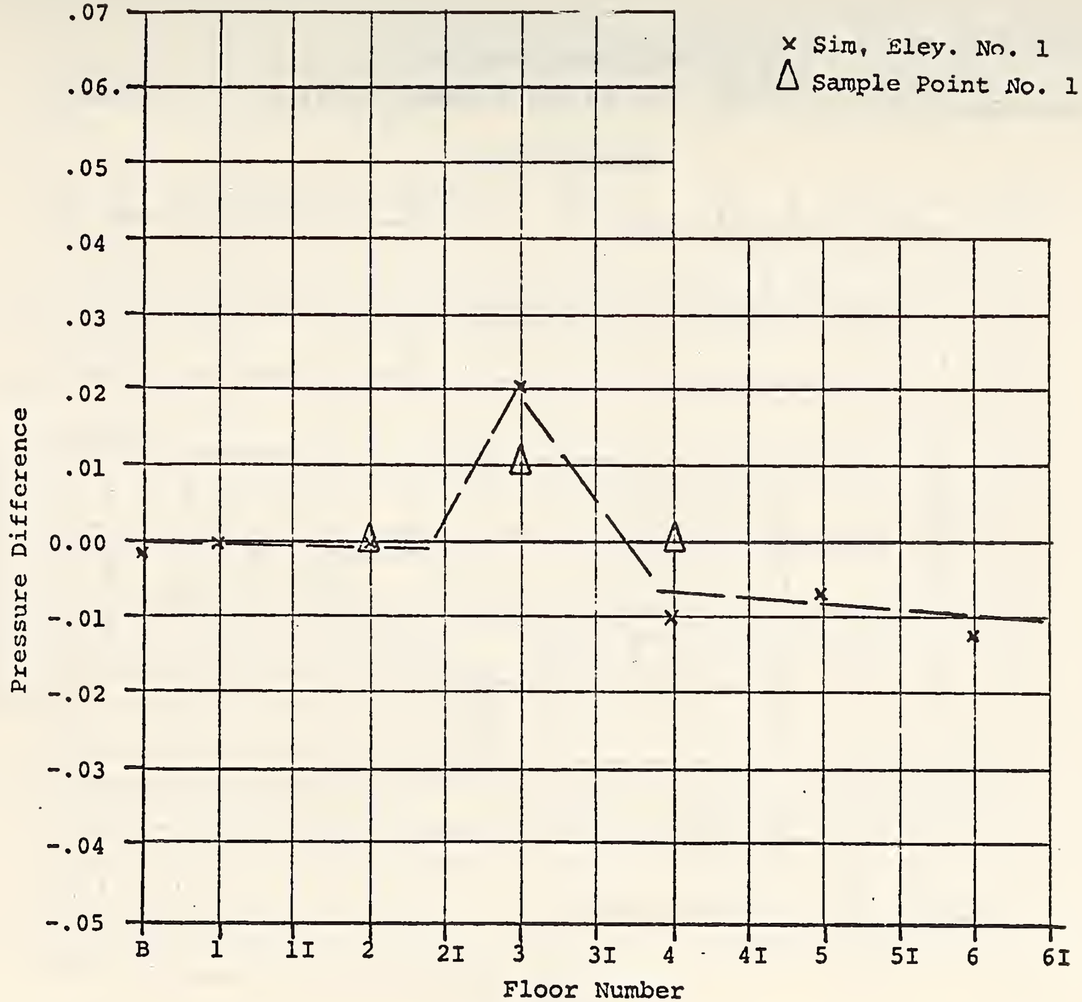

FIGURE 10. SIMULATED ELEVATOR SHAFT NO. 1 VS SAMPLE POINT NO. 1
(PRESSURE TEST CASE NO. 2)

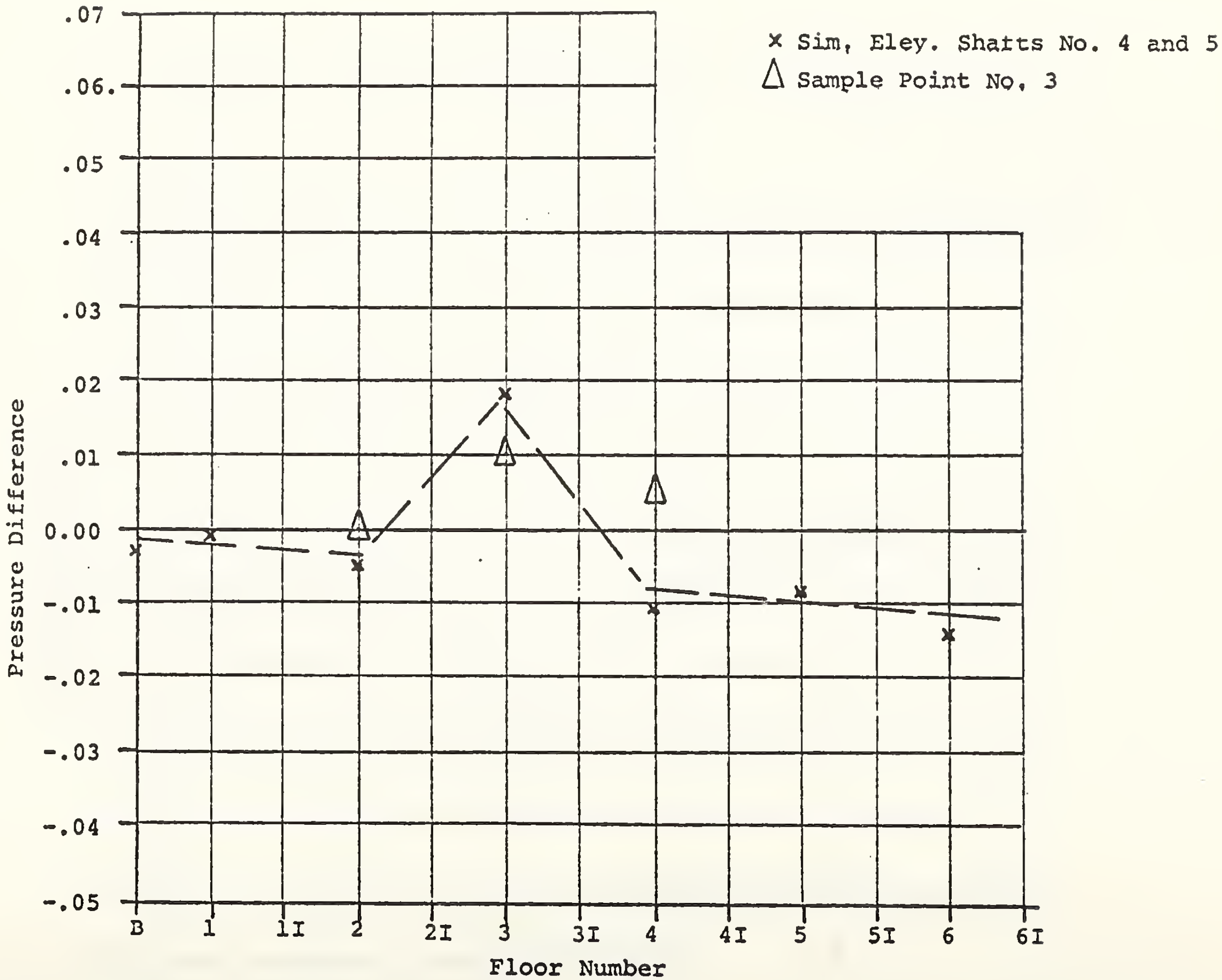

FIGURE 11. SIMULATED ELEVATOR SHAFTS NO. 4 AND 5 VS SAMPLE POINT NO. 3
(PRESSURE TEST CASE NO. 2)

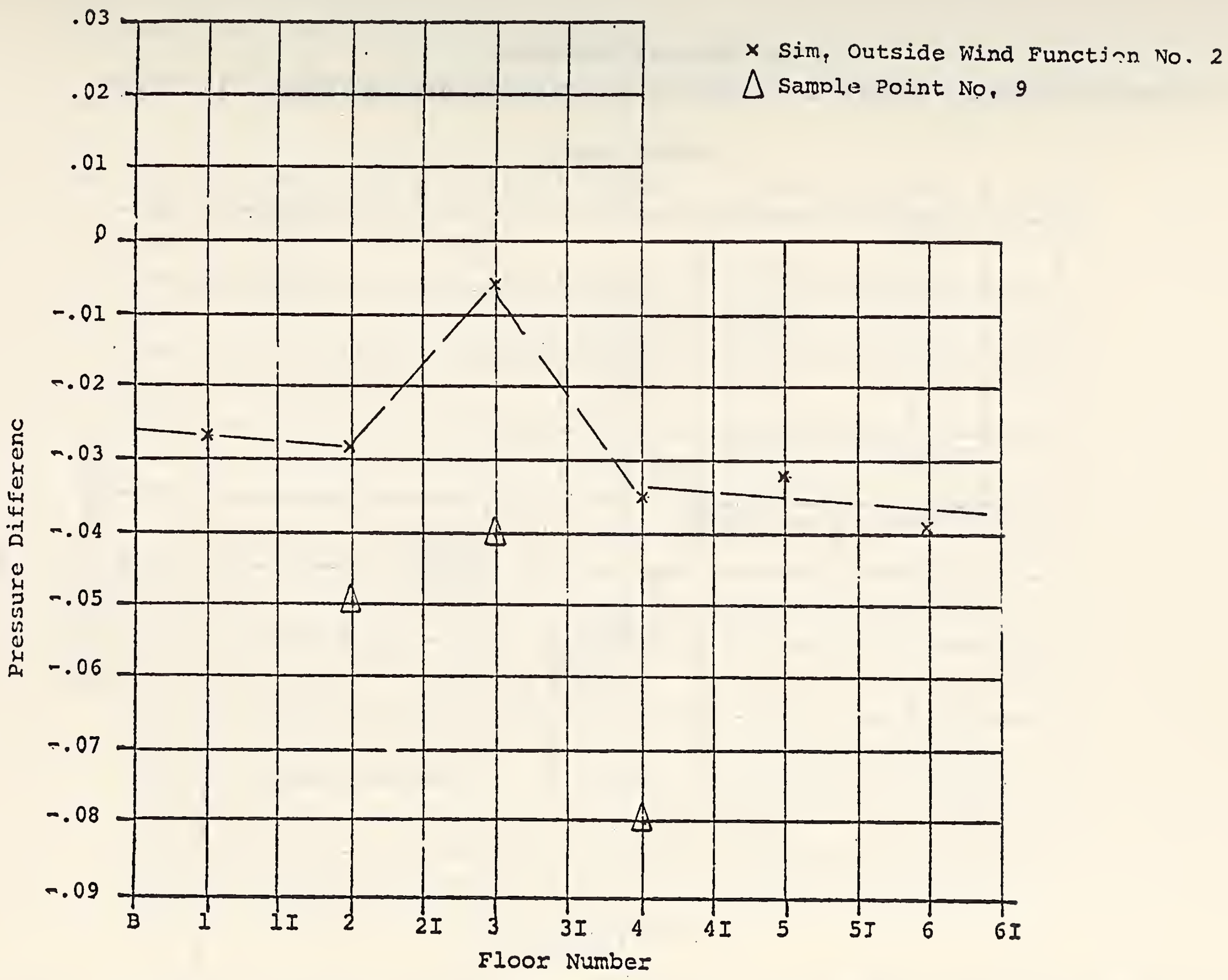

FIGURE 12. SIMULATED OUTSIDE WIND FUNCTION NO. 4 VS SAMPLE POINT NO. 9
(PRESSURE TEST CASE NO. 2)

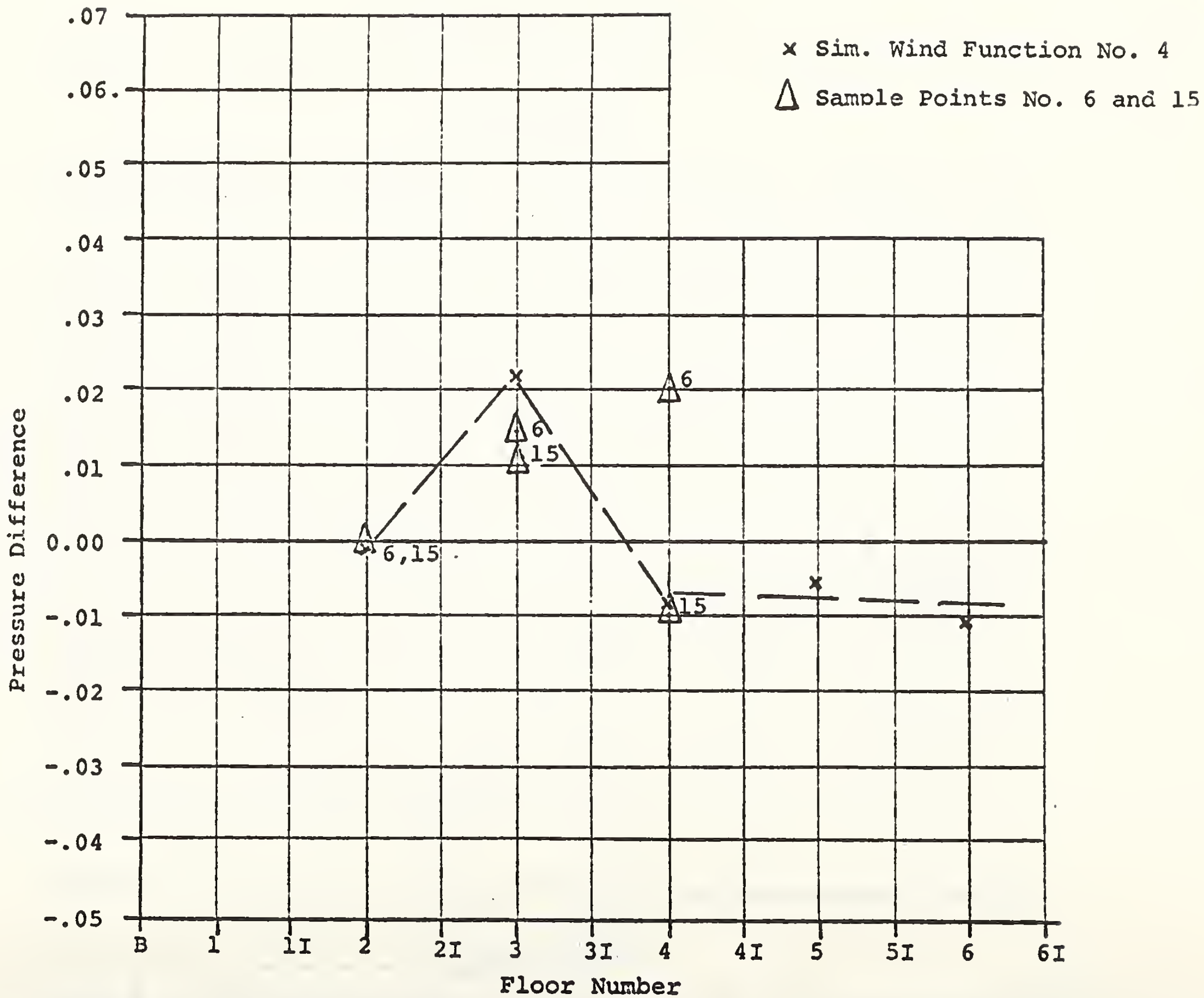

FIGURE 13. SIMULATED OUTSIDE WIND FUNCTION NO. 4 VS SAMPLE POINTS NO. 6 AND 15 (PRESSURE TEST CASE NO. 2)

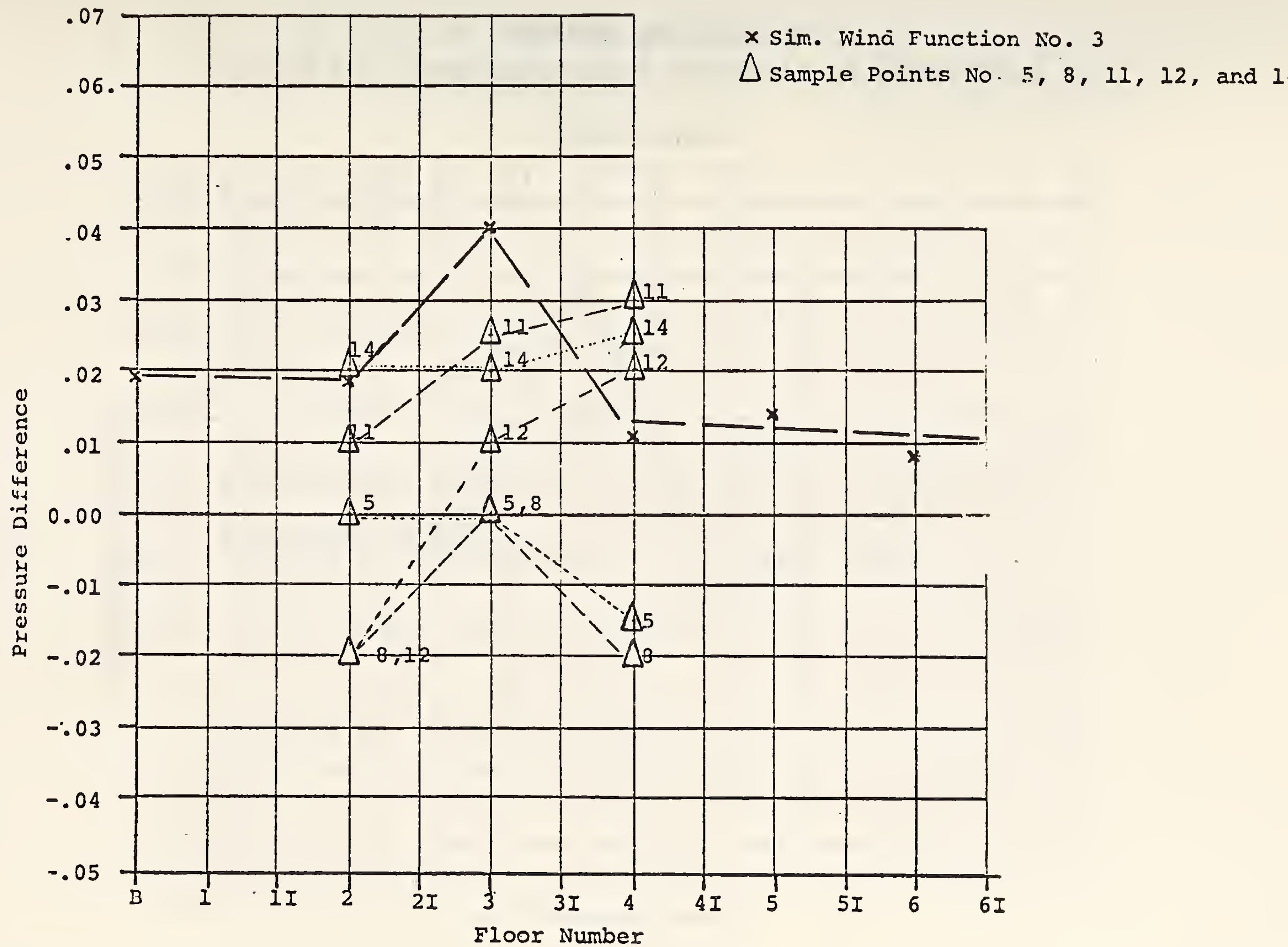

FIGURE 14. SIMULATED OUTSIDE WIND FUNCTION NO. 3 VS SAMPLE POINTS NO. 5, 8, 11, 12, AND 14 (PRESSURE TEST CASE NO. 2)

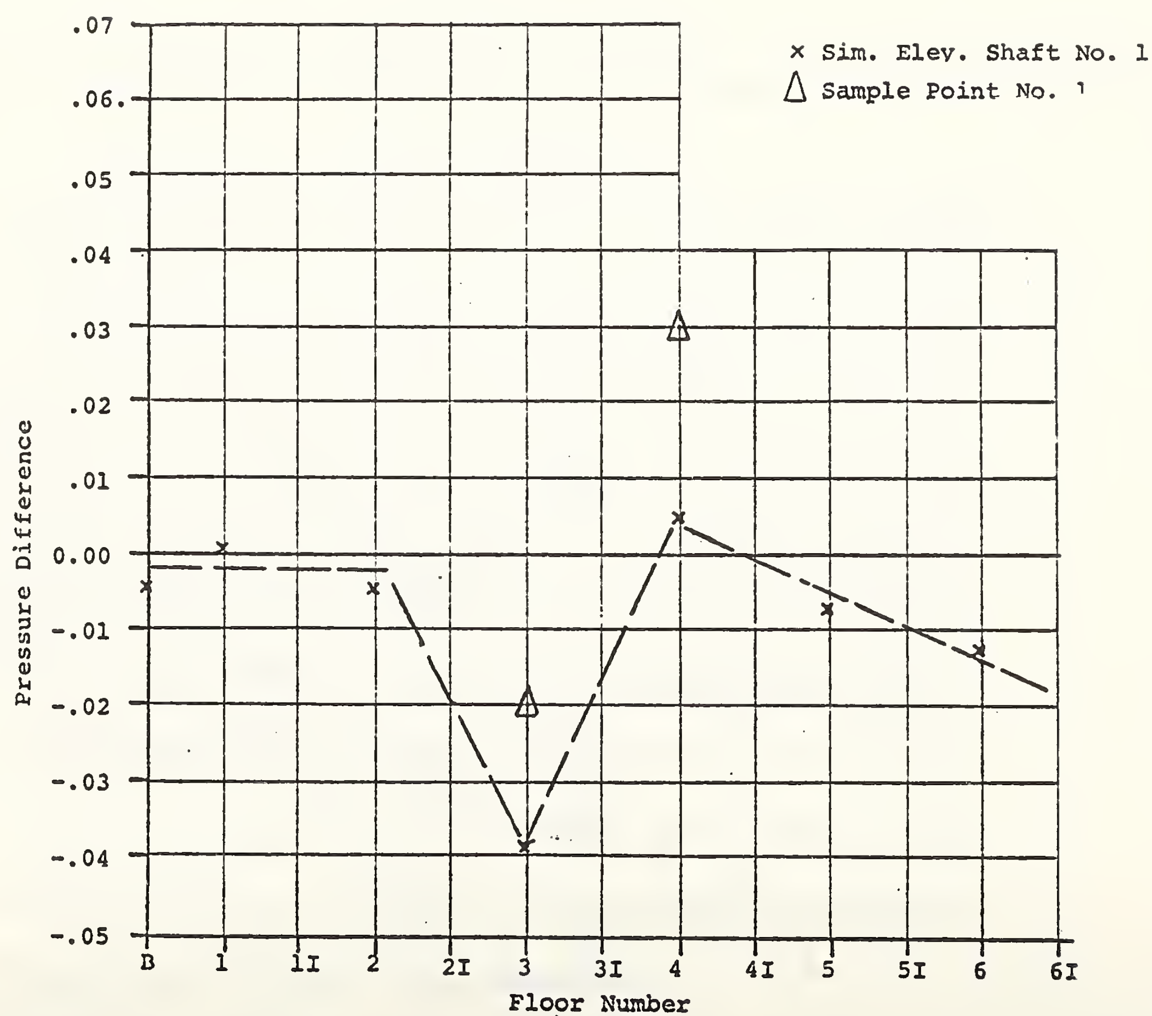

FIGURE 15. SIMULATED ELEVATOR SHAFT NO. 1 VS SAMPLE POINT NO. 1 (PRESSURE TEST CASE NO. 4)

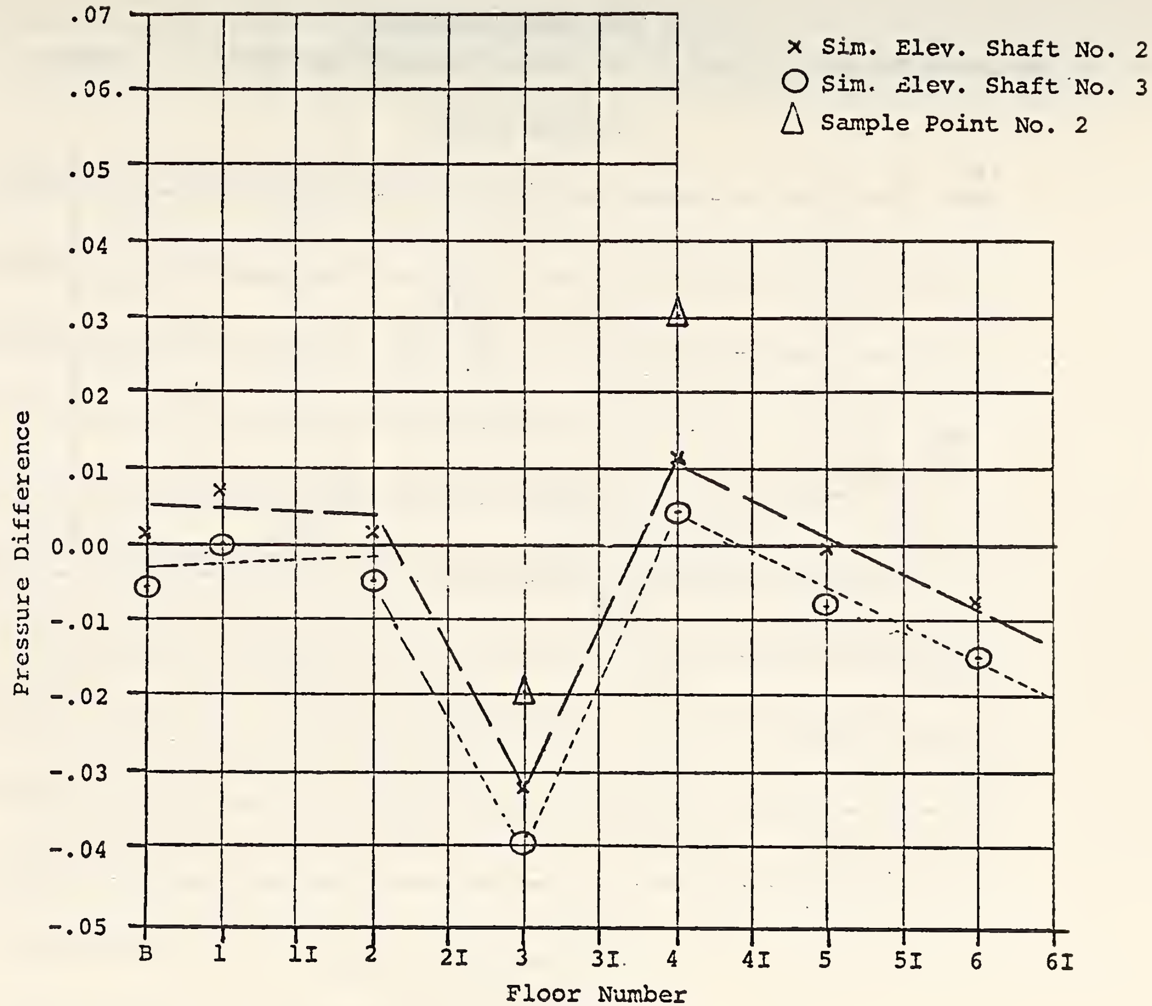

FIGURE 16. SIMULATED ELEVATOR SHAFTS NO. 2 AND 3 VS SAMPLE POINT NO. 2
(PRESSURE TEST CASE NO. 4)

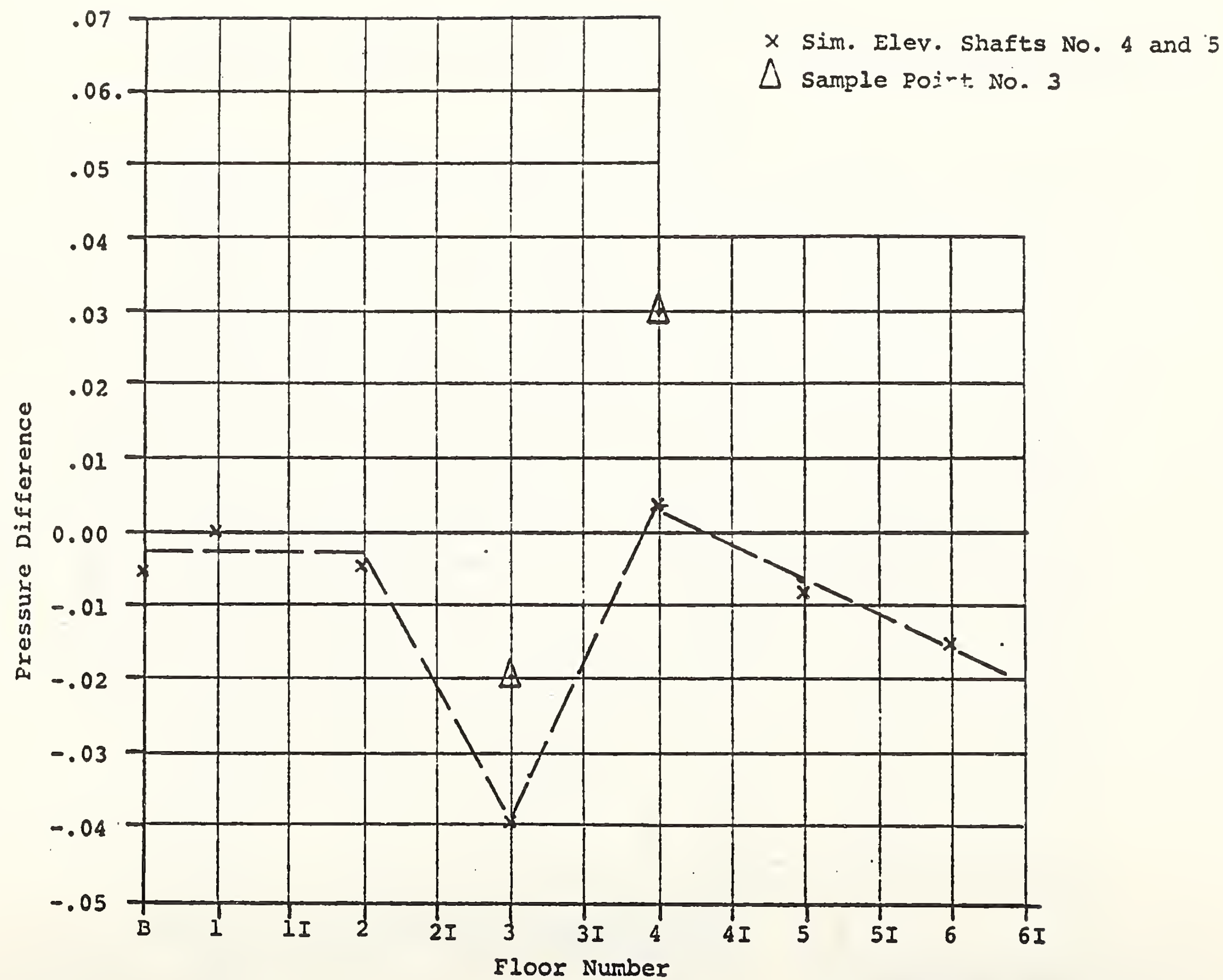

FIGURE 17. SIMULATED ELEVATOR SHAFTS NO. 4 AND 5 VS SAMPLE POINT NO. 3
(PRESSURE TEST CASE NO. 4)

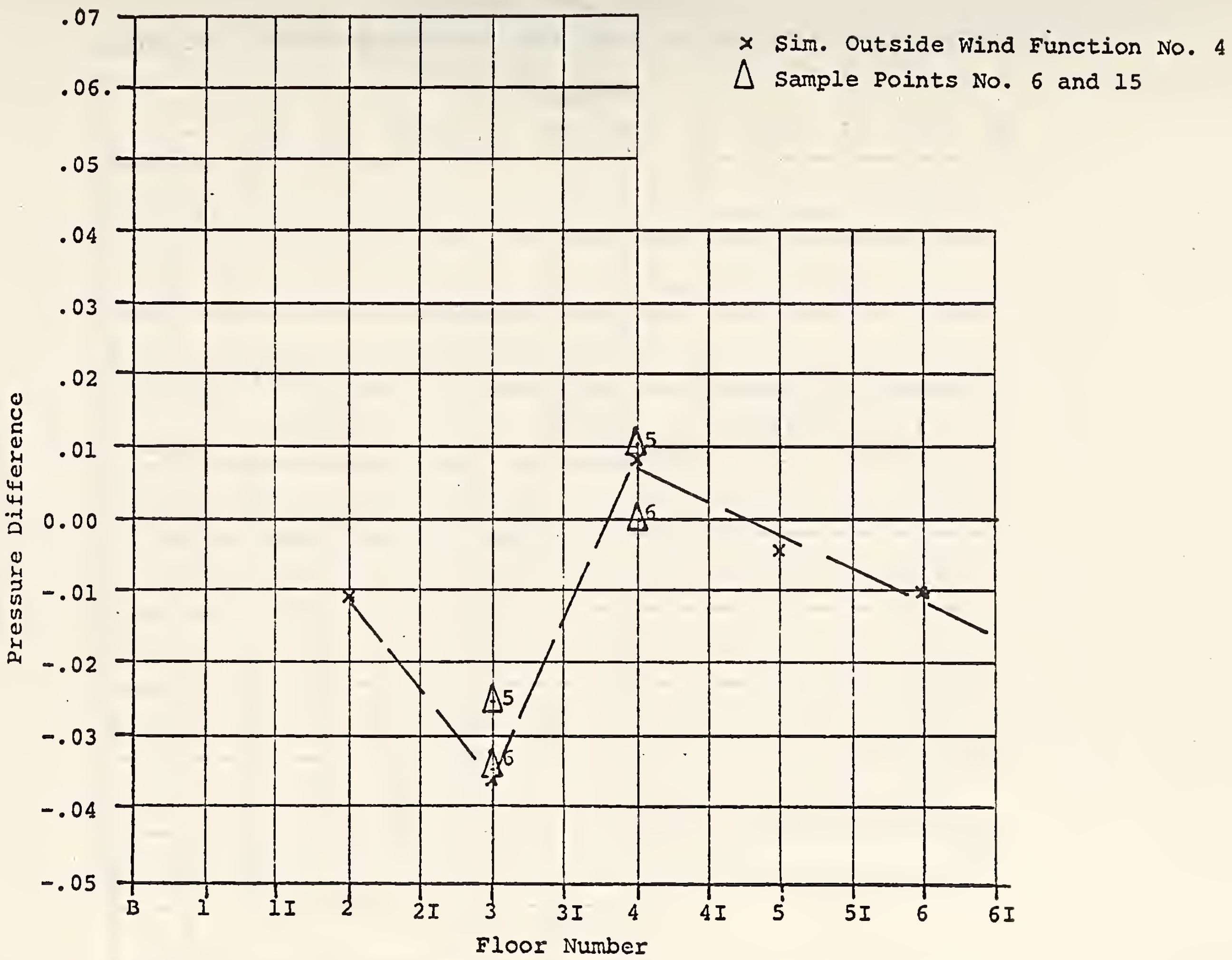

FIGURE 18. SIMULATED OUTSIDE WIND FUNCTION NO. 4 VS SAMPLE POINTS NO. 6 AND 15 (PRESSURE TEST CASE NO. 4)

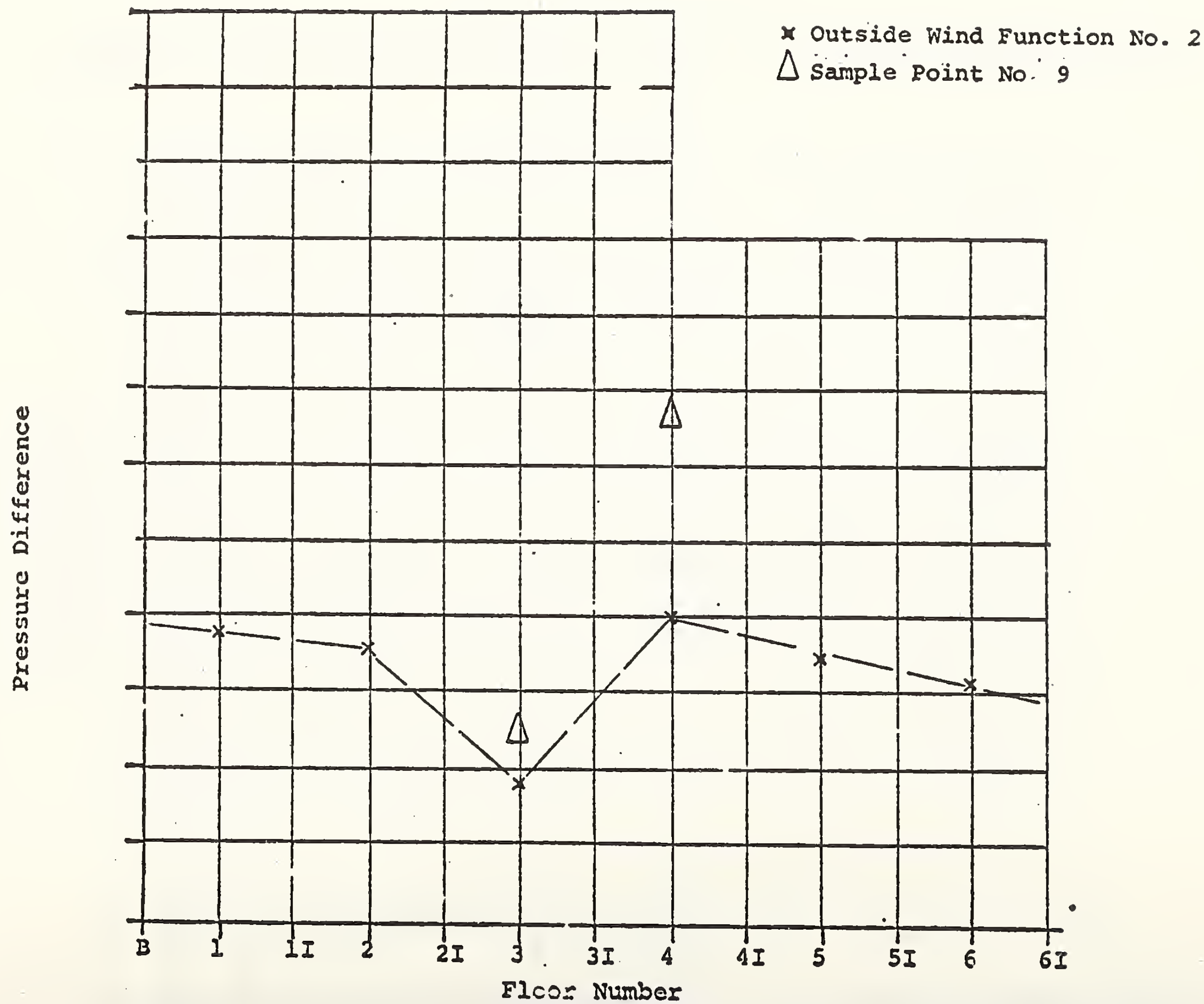

FIGURE 19. SIMULATED OUTSIDE WIND FUNCTION NO. 2 VS SAMPLE POINT NO. 9 (PRESSURE TEST CASE NO. 4)

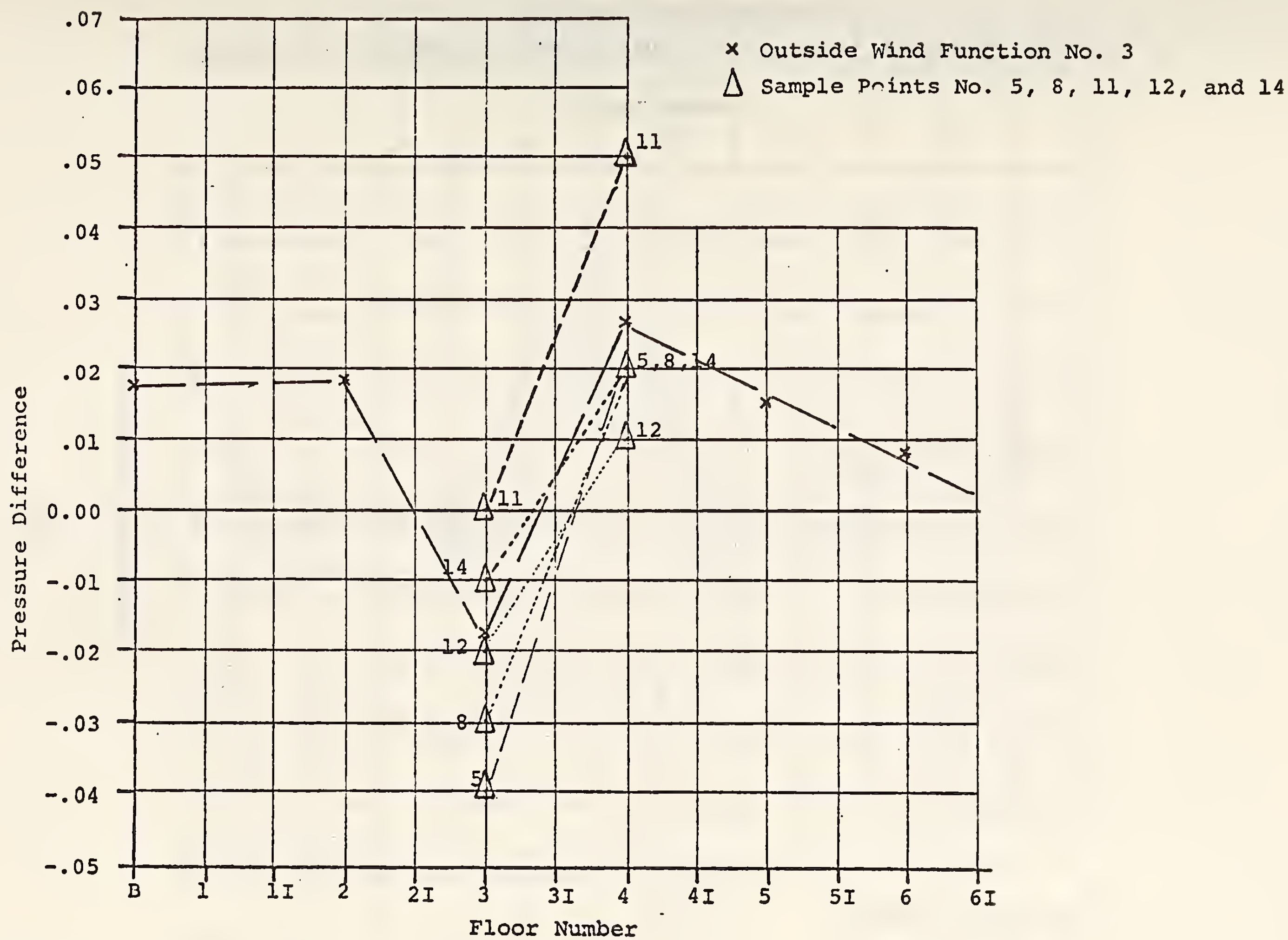

FIGURE 20. SIMULATED OUTSIDE WIND FUNCTION NO. 3 VS SAMPLE POINTS NO. 5, 8, 11, 12, AND 14 (PRESSURE TEST CASE NO. 4)

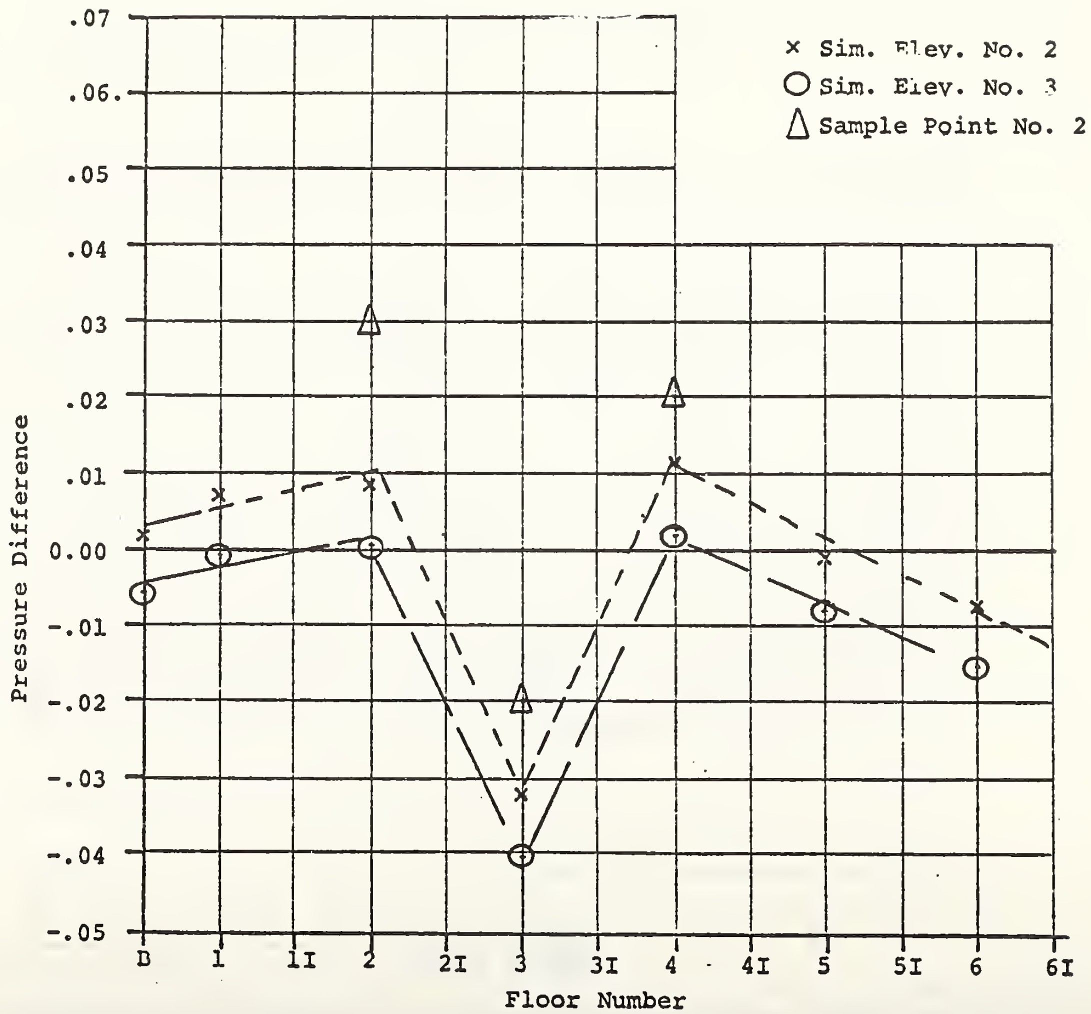

FIGURE 21. SIMULATED ELEVATOR SHAFTS NO. 2 AND 3 VS SAMPLE POINT NO. 2
(PRESSURE TEST CASE NO. 5)

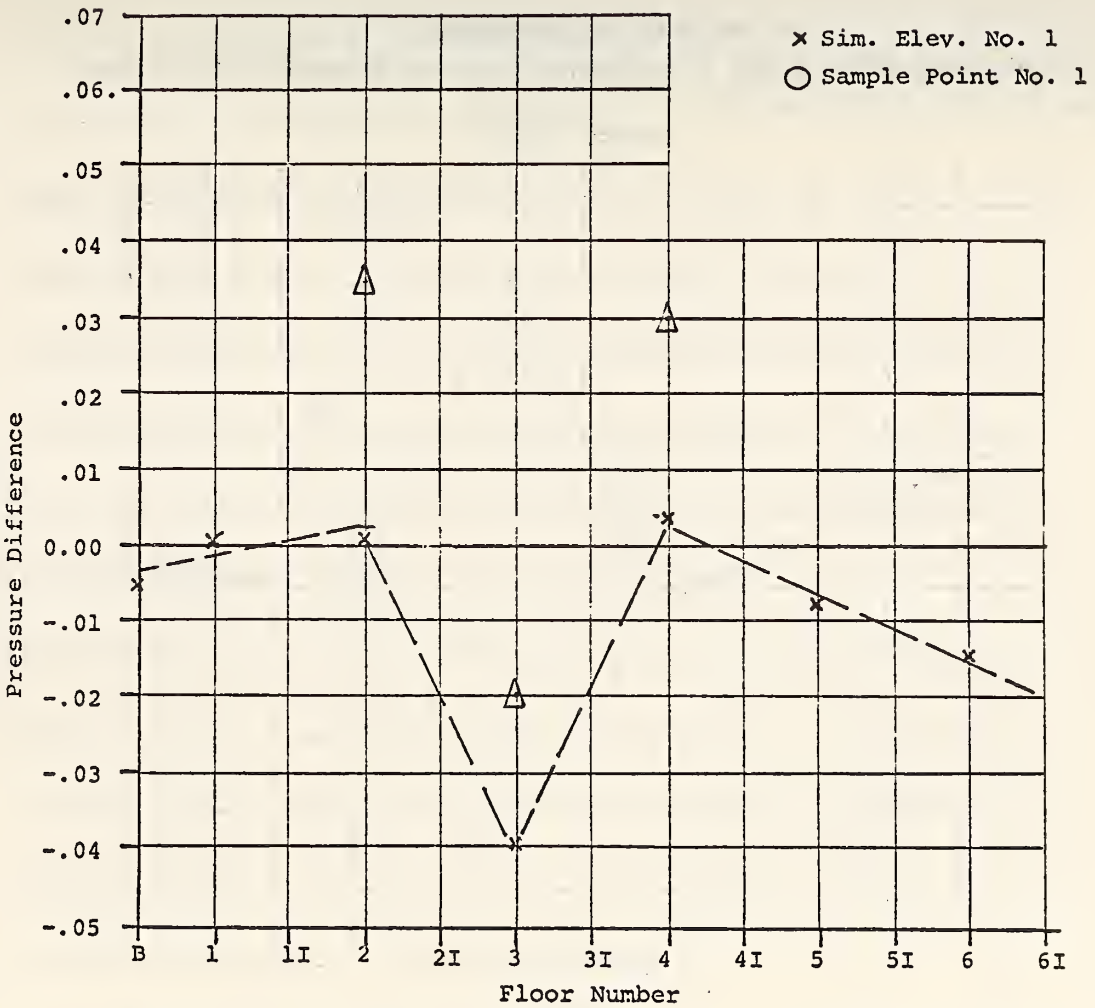

FIGURE 22. SIMULATED ELEVATOR SHAFT NO. 1 VS SAMPLE POINT NO. 1
(PRESSURE TEST CASE NO. 5)

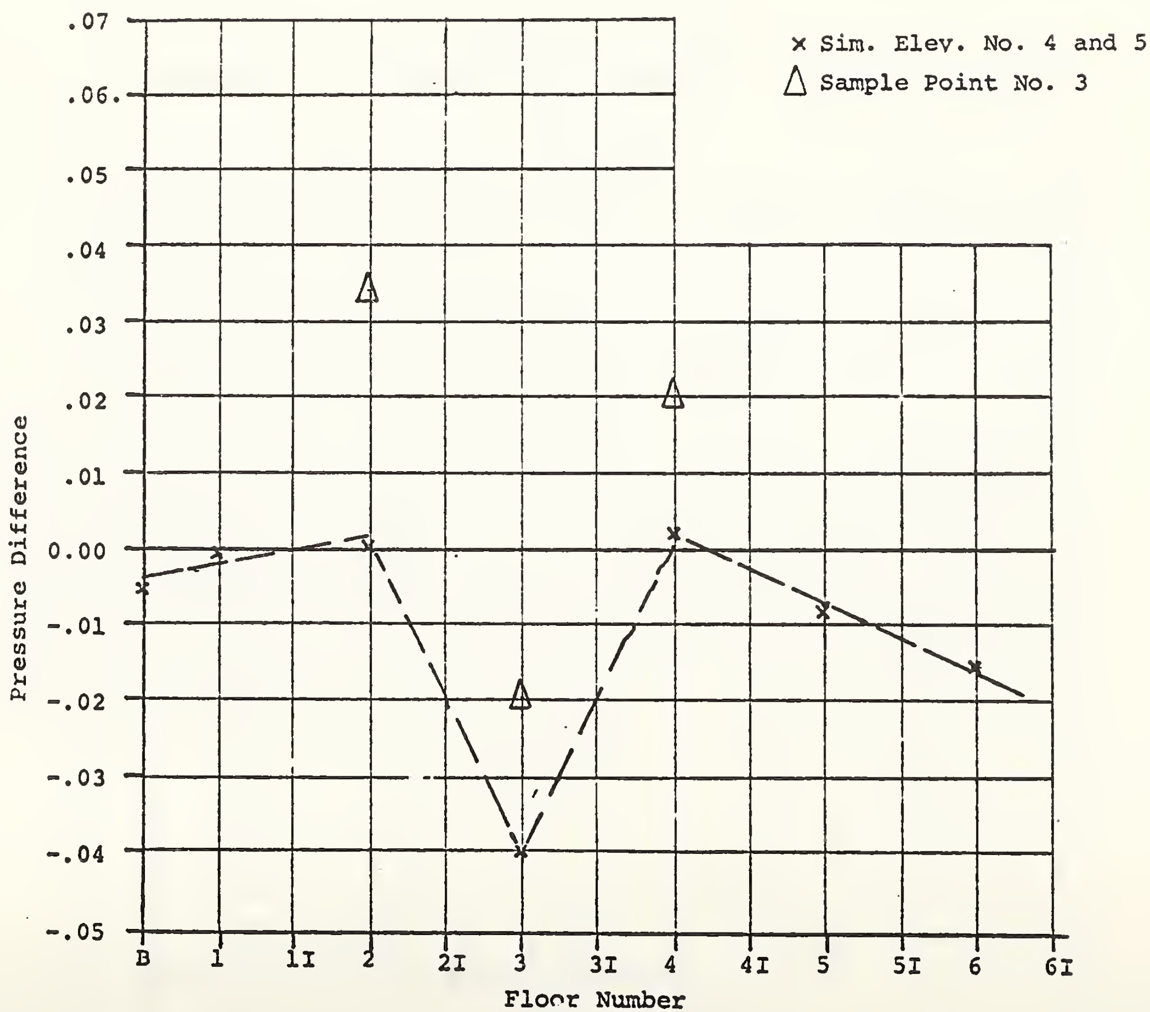

FIGURE 23. SIMULATED ELEVATOR SHAFTS NO. 4 AND 5 VS SAMPLE POINT NO. 3
(PRESSURE TEST CASE NO. 5)

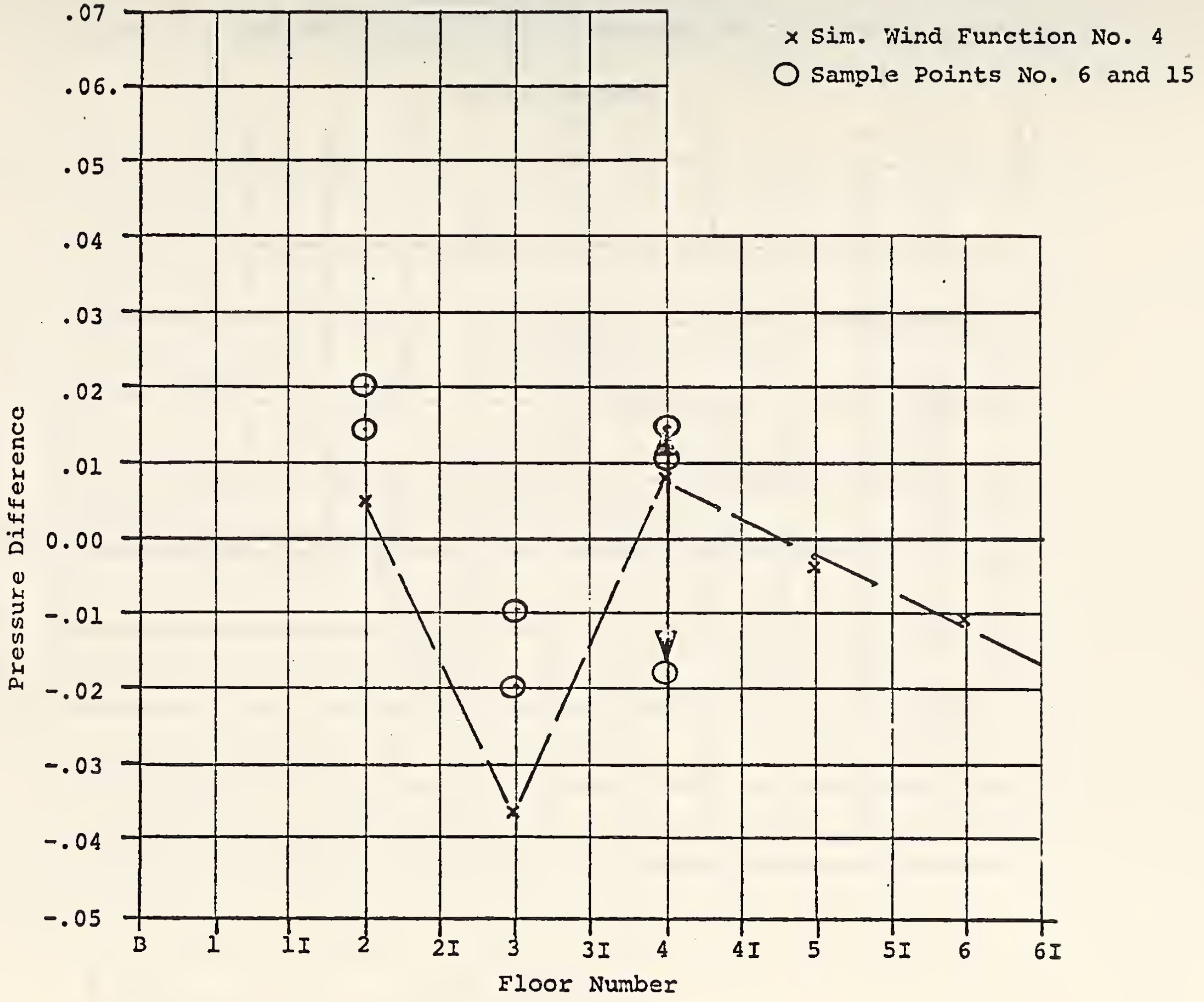

FIGURE 24. SIMULATED OUTSIDE WIND FUNCTION NO. 4 VS SAMPLE POINTS NO. 6 AND 15
(PRESSURE TEST CASE NO. 5)

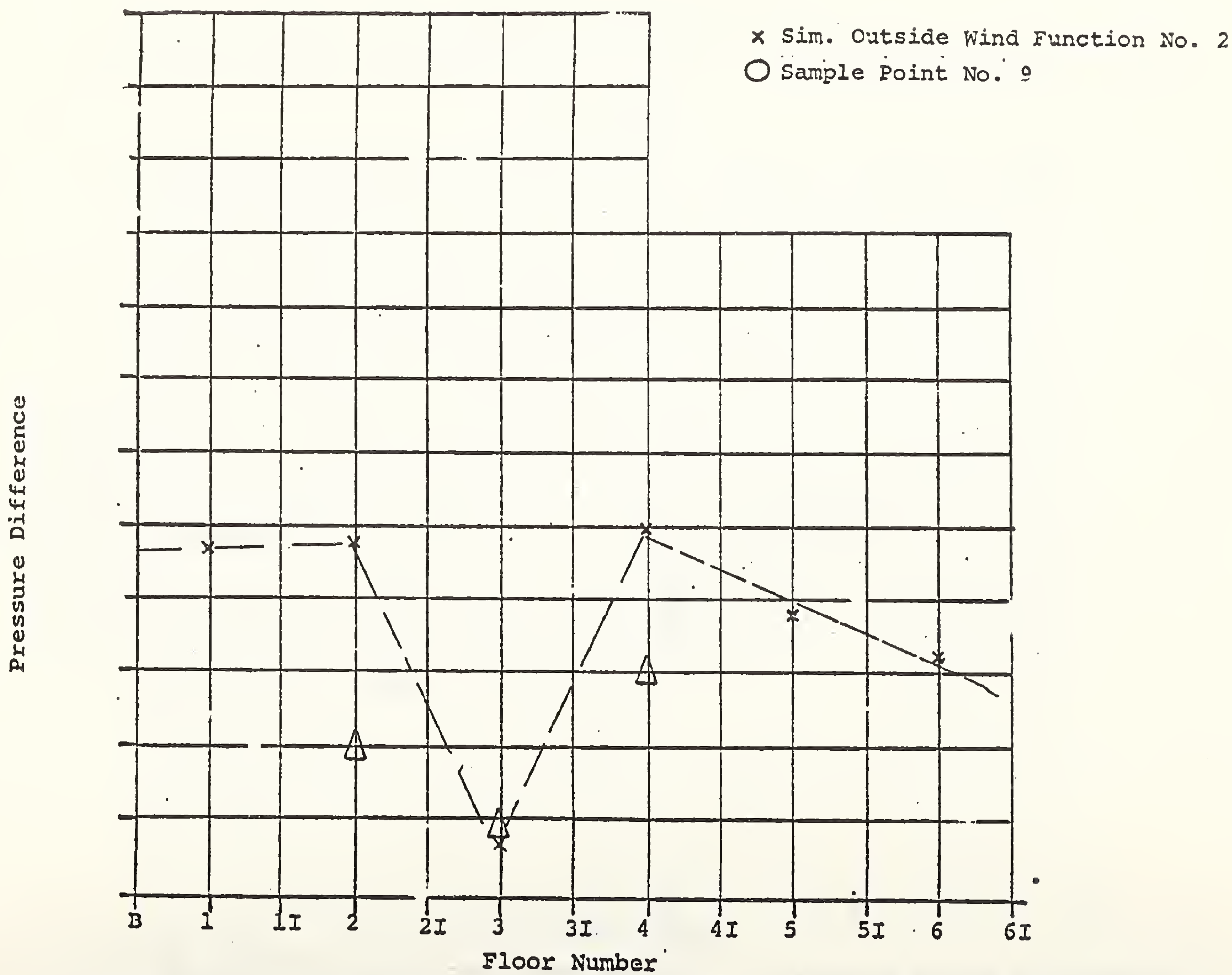

FIGURE 25. SIMULATED OUTSIDE WIND FUNCTION NO. 2 VS SAMPLE POINT NO. 9
(PRESSURE TEST CASE NO. 5)

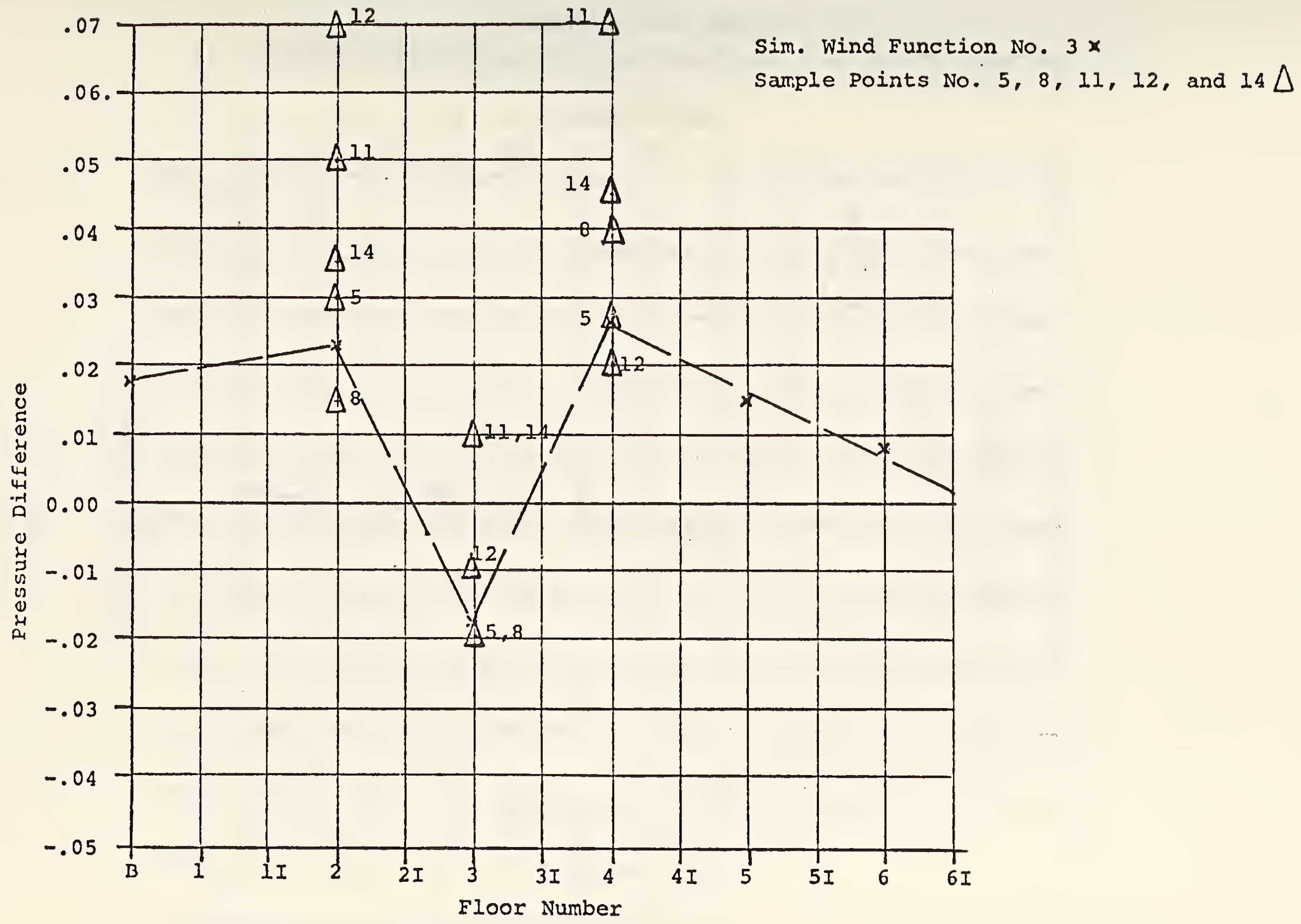

FIGURE 26. SIMULATED OUTSIDE WIND FUNCTION NO. 3 VS SAMPLE POINTS NO. 5, 8, 11, 12, AND 14 (PRESSURE TEST CASE NO. 5)

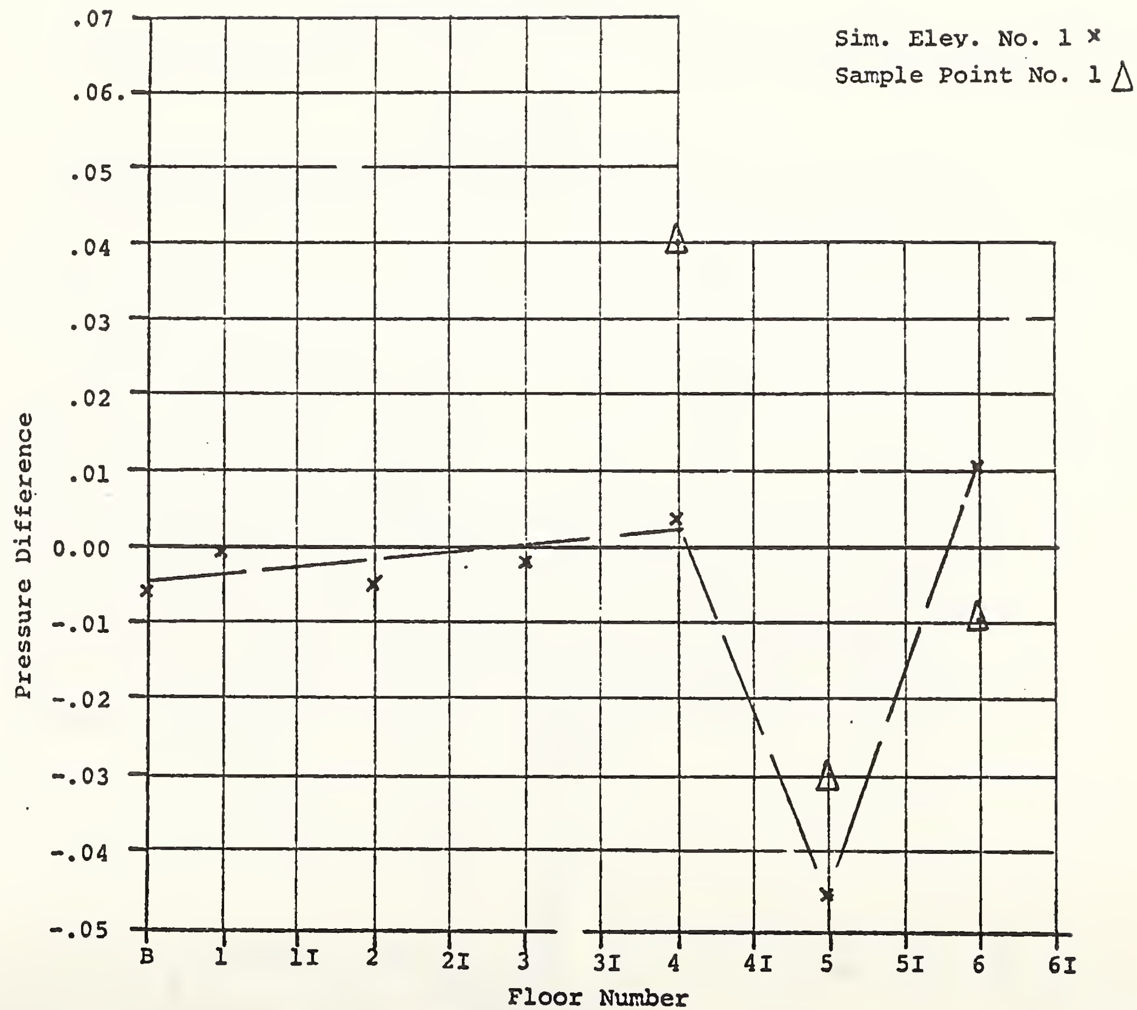

FIGURE 27. SIMULATED ELEVATOR SHAFT NO. 1 VS SAMPLE POINT NO. 1
(PRESSURE TEST CASE NO. 6)

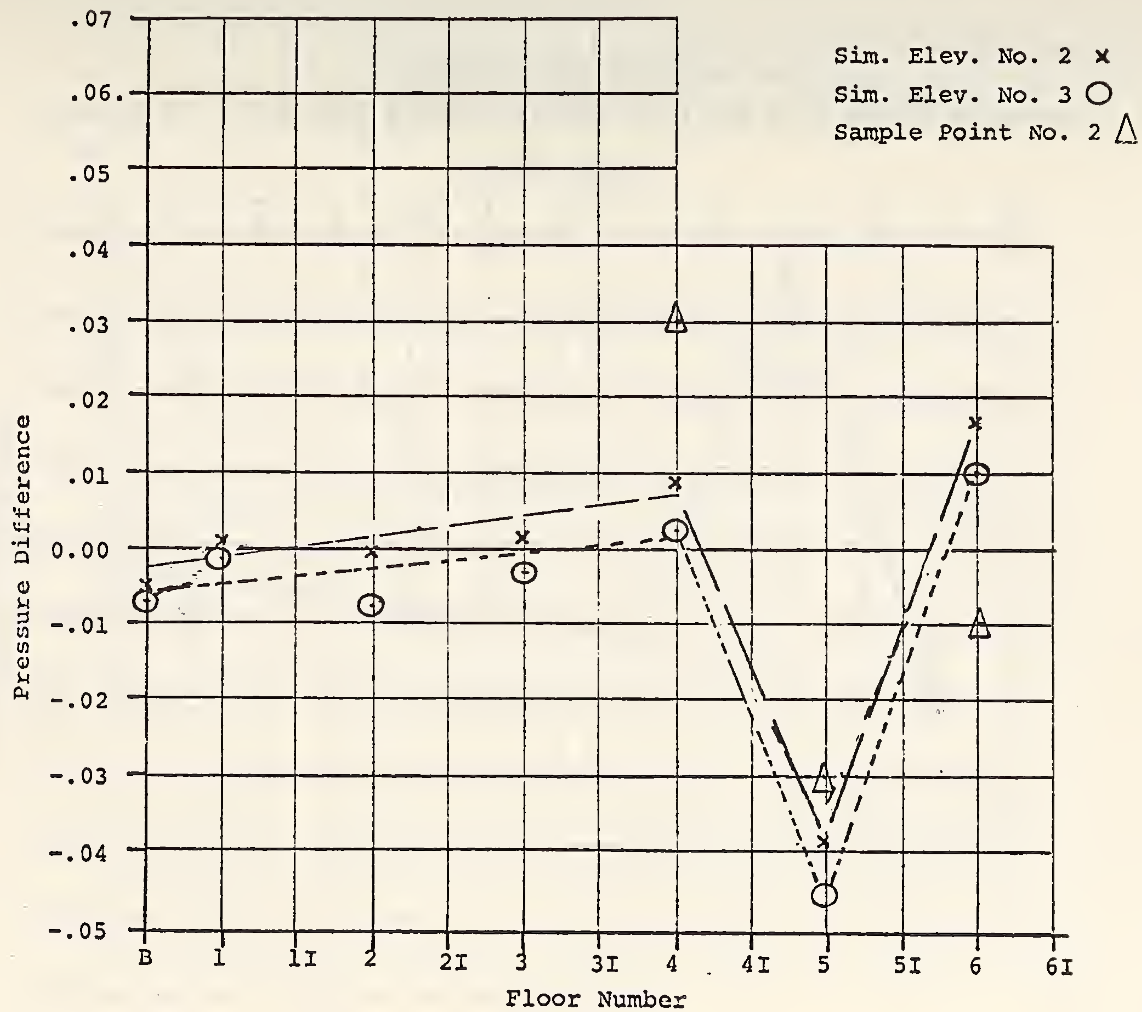

FIGURE 28. SIMULATED ELEVATOR SHAFTS NO. 2 AND 3 VS SAMPLE POINT NO. 2
(PRESSURE TEST CASE NO. 6)

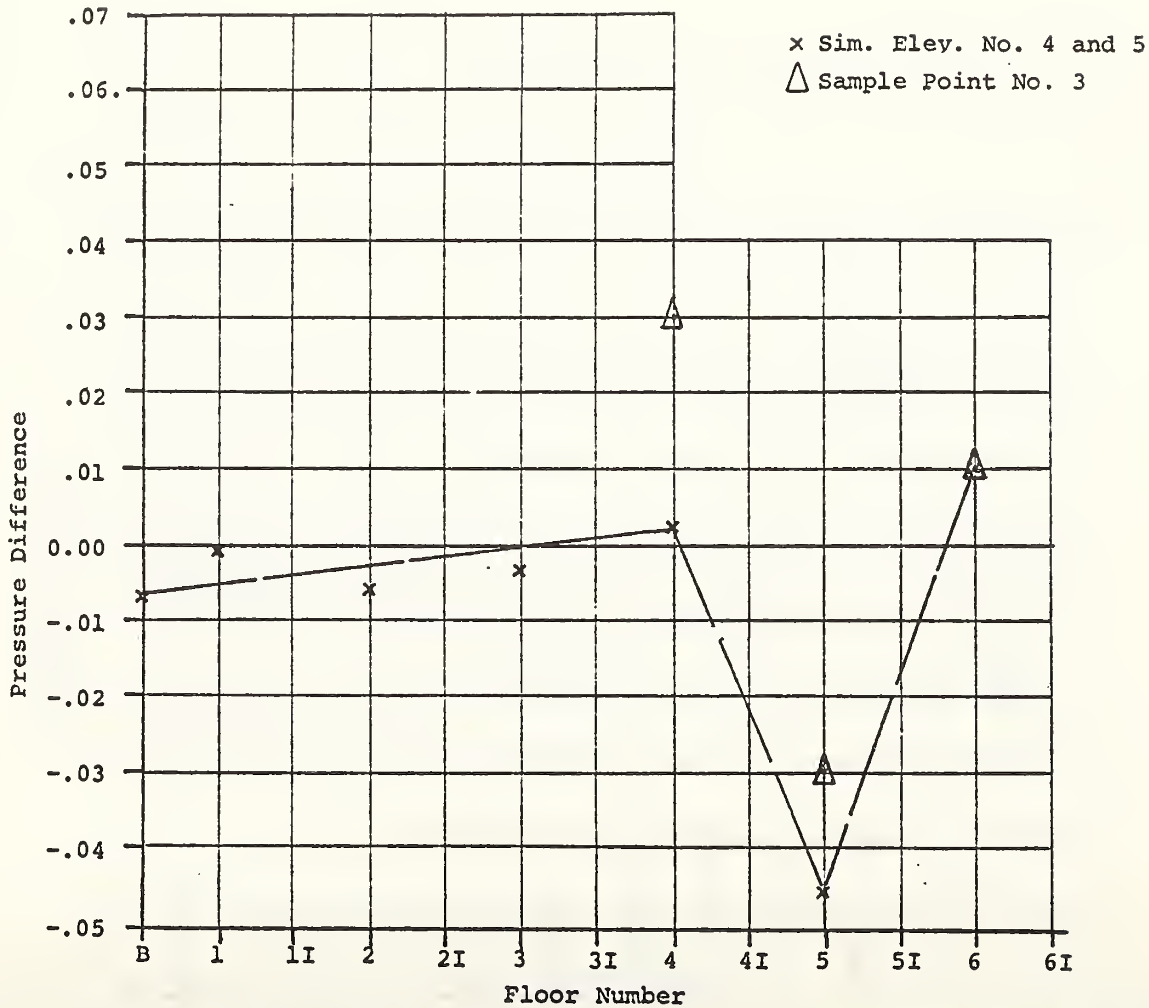

FIGURE 29. SIMULATED ELEVATOR SHAFTS NO. 4 AND 5 VS SAMPLE POINT NO. 3
(PRESSURE TEST CASE NO. 6)

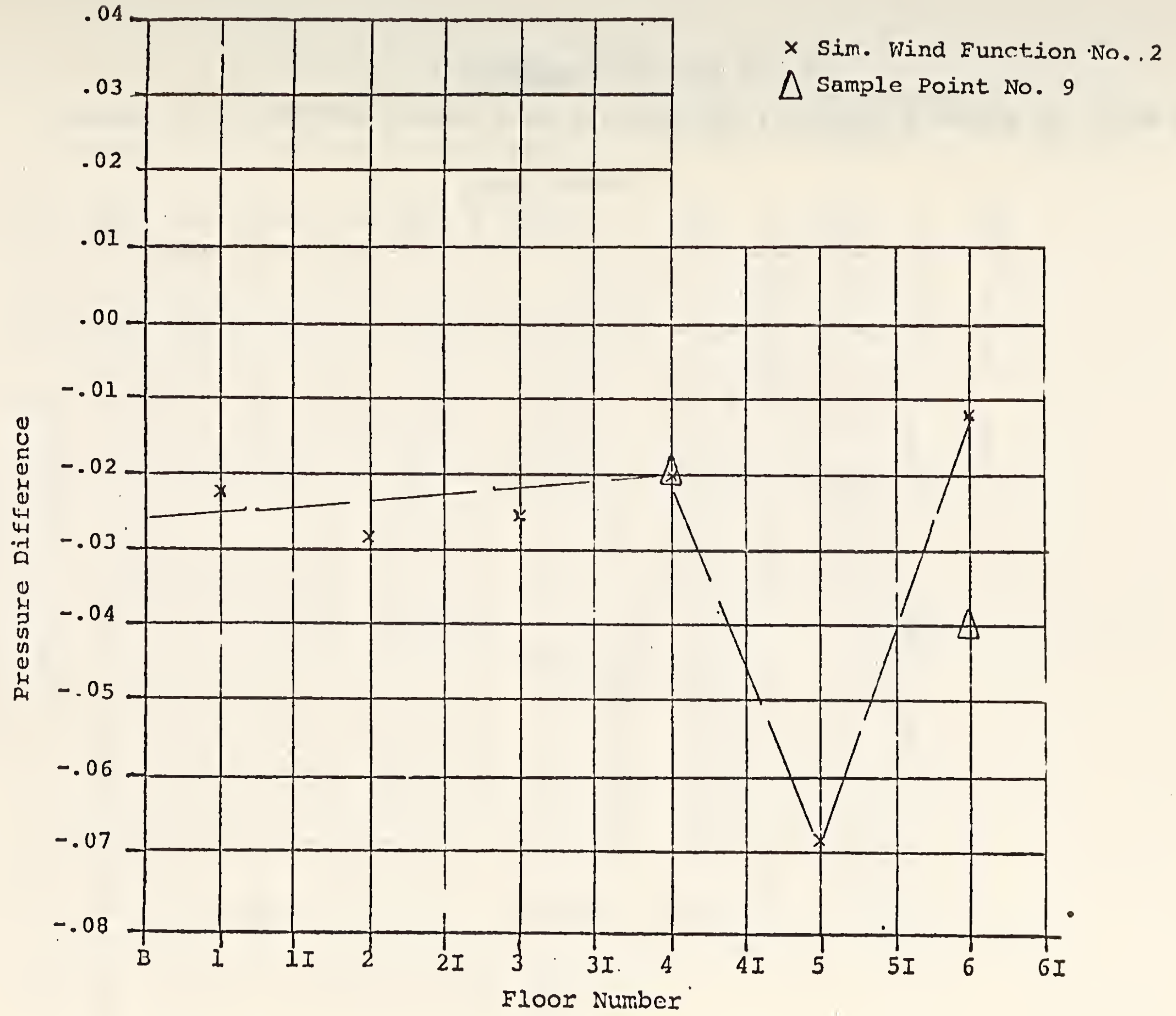

FIGURE 30. SIMULATED OUTSIDE WIND FUNCTION NO. 2 VS SAMPLE POINT NO. 9
(PRESSURE TEST CASE NO. 6)

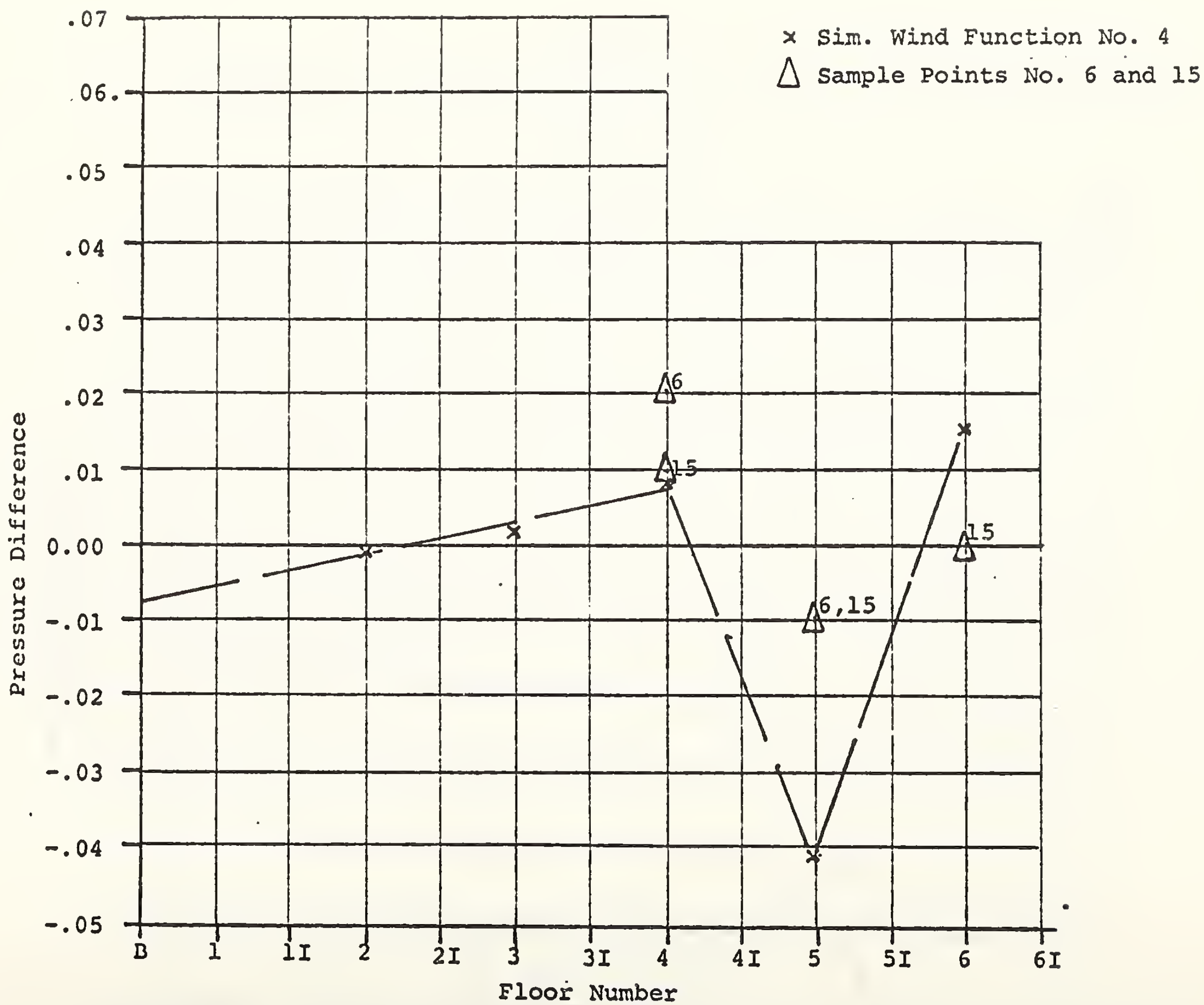

FIGURE 31. SIMULATED OUTSIDE WIND FUNCTION NO. 4 VS SAMPLE POINTS NO. 6 AND 15 (PRESSURE TEST CASE NO. 6)

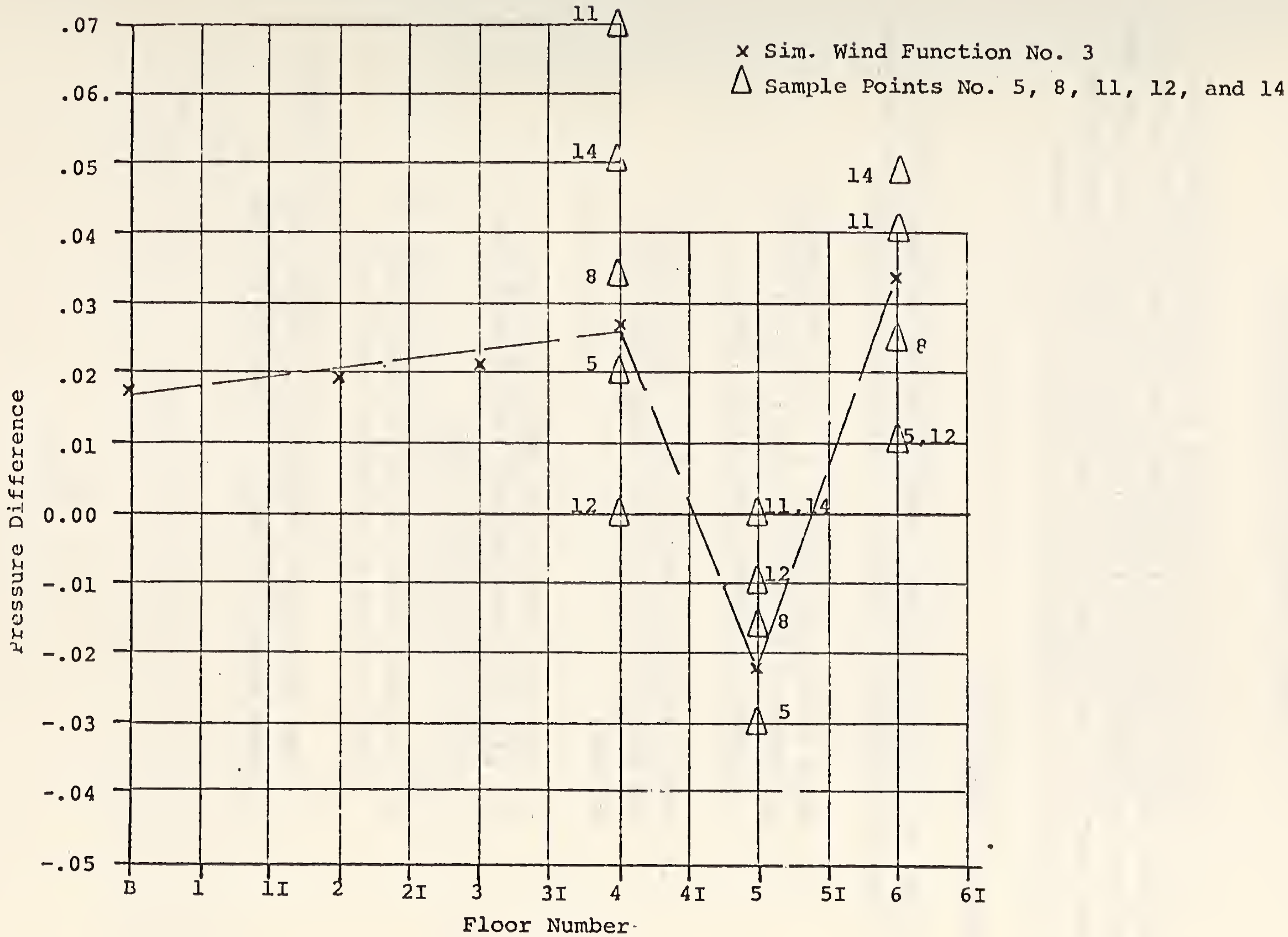

FIGURE 32. SIMULATED OUTSIDE WIND FUNCTION NO. 3 VS SAMPLE POINTS NO. 5, 8, 11, 12, AND 14 (PRESSURE TEST CASE NO. 6)

SMOKE CONCENTRATION SIMULATIONS

Two sets of smoke cases were simulated on the newly developed air movement program coupled to the present smoke concentration program. The first set simulated the field trace gas tests that had been performed earlier. The second set simulated the smoke concentration of the pressure calibration test cases previously discussed.

Trace Gas Simulations

A total of six trace gas tests were available for comparison with the computer simulation results. These tests are defined as follows:

1. Smoke Simulation Test No. 1 - In this case, the HVAC system was in a normal mode with the simulated burn room on the third floor.

2. Smoke Simulation Test No. 2 - In this case, the HVAC system was in a control mode, as follows:

   a. The south wing of the third floor was placed on exhaust only and the burn room was located in this wing.

   b. The east, west, and north wings of the third floor were placed on supply only.

   c. The third floor interstitial exhaust fans were turned off except for the south wing.

d. The balance of the building operated in a normal mode.

3. Smoke Simulation Test No. 3 - In this case, the simulated burn room was placed on the second floor, the second floor interstitial fans were turned off, and the balance of the building remained in a normal mode.

4. Smoke Simulation Test No. 4 - In this case, the simulated burn room was located on the second floor, the second floor was placed on exhaust only, the third floor was placed on supply only, the third floor interstitial fans were turned off, and the balance of the building remained in a normal mode.

5. Smoke Simulation Test No. 5 - This was a smoke decay study with the simulated burn room shut down, the third floor interstitial exhaust fans on, and the HVAC system in a normal mode.

6. Smoke Simulation Test No. 6 - This case was a purging study of the third floor interstitial space with the trace gas released in the interstitial space and the HVAC system in a normal mode.

<u>Computer Simulation of Trace Gas Tests</u>

Since the smoke concentration program did not have the capability to simulate lateral movement of smoke, very few comparisons could be made. Further, no capability presently exists to perform decay and purging simulations which are of interest to designing smoke-controlling HVAC systems. Consequently, cases 5 and 6 and portions of case 3 could not be simulated.

A very important point must be considered when using the present smoke concentration program with the newly developed air movement program. The smoke concentration program does not have the capability to consider all of the infiltration routes provided by the newly developed air movement program. The newly developed air movement program allows a user to select any two of the external wall flows from/to the corridor, the floor above/below flows from/to the corridor and 10 vertical shafts, as a maximum data link to the smoke concentration. This is the maximum configuration allowed by the present smoke concentration program.

For this smoke study of the San Diego VA Hospital, the mass flow data for the six elevator shafts, the shafts adjacent to stairwells 10 and 12, the pneumatic trash/laundry access path, and one stairwell were passed from the newly developed air movement program to the smoke concentration program.

The results of the computer simulations compared to the trace gas tests are presented in Tables 8 through 22.

<u>Smoke Test No. 1</u> - The infiltration rate of smoke from the third floor in the computer simulations of the smoke tests appear to be occurring at too high a rate. The infiltration of the second floor interstitial level in the computer simulation of smoke test 1 may or may not be true. The simulated amount of leakage may be too high. However, no samples were taken in the second floor interstitial level. The infiltration of the trace gas into the fourth floor of the first smoke case probably occurred through a path other than the interstitial spaces, which are usually at a lower pressure level than the occupancy floors. A good possibility is that the trace gas was transported by the elevator cages, since

TABLE 8. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 1 AT 5 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2												
2I		.028		.030		.009						
3	1.0	1.0		.153		.006						
3I	.013	.252				.062						
4	0.00					.052						
4I						.032						
5						.028						
5I						.020						
6						.017						
6I						.013						

TABLE 9. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 1 AT 20 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2												
2I		.074		.171		.035						
3	1.0	1.0		.318		.033						
3I	.013	.621				.221						
4						.217						
4I						.160						
5						.158						
5I						.125						
6						.124						
6I						.101						

TABLE 10. SMOKE SIMULATION COMPARISONS
SMOKE TEST NO. 1 AT 35 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2												
2I		.093		.217		.046						
3	1.0	1.0		.348		.045						
3I	.033	.737				.274						
4	.016					.272						
4I						.203						
5						.203						
5I						.162						
6						.161						
6I						.132						

TABLE 11. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 1 AT 60 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2												
2I		.101		.228		.051						
3	1.0	1.0		.355		.051						
3I	.040	.783				.295						
4	.026					.295						
4I						.221						
5						.221						
5I						.176						
6						.176						
6I						.145						

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TABLE 12. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 1 AT 10 MIN.

Floor	Corridor		Elev. No. 1		Elev. No. 2		Elev. No.3		Elev. No. 4/5		Shafts 8/10	
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1								.004		.003		
1I								.020		.017		
2		.003		.011				.071		.064		
2I		.059		.089		.250		.139		.132		.024
3	1.0	1.0		.423		.555		.2		.197		.020
3I	.006	.368		.012								.124
4	0.0	0.0										.116
4I												.082
5												.078
5I												.060
6	0.0	0.0										.057
6I												.045

TABLE 13. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 2 AT 30 MIN.

Floor	Corridor		Elev. No. 1		Elev. No. 2		Elev. No.3		Elev. No. 4/5		Shafts 8/10	
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B		.001		.001				.056		.047		
1		.007		.003		.004		.135		.123		
1I		.008		.000		.003		.183		.174		
2		.027		.172		.008		.215		.211		
2I		.127		.458		.543		.222		.221		.062
3	1.0	1.0		.808		.730		.225		.224		.060
3I	.086	.477		.071								.199
4	.000	.000		.002								.198
4I												.147
5												.147
5I												.117
6	.000	.000										.117
6I												.096

TABLE 14. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 2 AT 40 MIN.

Floor	Corridor		Elev. No. 1		Elev. No. 2		Elev. No. 3		Elev. No. 4/5		Shafts 8/10	
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B		.003		.003		.001		.111		.099		.002
1		.012		.007		.009		.188		.178		.002
1I		.020		.003		.007		.212		.208		.002
2		.038		.286		.015		.223		.222		.001
2I		.146		.613		.568		.225		.224		.073
3	1.0	1.0		.889		.739		.225		.225		.072
3I	.186	.482		.108								.209
4	.000	.000		.004								.209
4I												.156
5												.155
5I												.124
6	.000	.000										.124
6I												.124

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TABLE 15. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 3 AT 5 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I				.001								
2	1.0	1.0		.157								
2I	.007	.246		.011		.070						
3						.041						
3I						.018						
4						.012						
4I						.007						
5						.005						
5I						.003						
6						.002						
6I						.002						

TABLE 16 . SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 3 AT 15 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I				.004								
2	1.0	1.0		.400								
2I	.080	.503		.050		.239						
3						.214						
3I						.129						
4						.118						
4I						.083						
5						.077						
5I						.058						
6						.055						
6I						.043						

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TABLE 17. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 3 AT 20 MIN.

Floor	Corridor		Elev. No. 2		Shafts 8/10							
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I				.005								
2	1.0	1.0		.494								
2I	.105	.567		.068		.284						
3						.267						
3I						.167						
4						.159						
4I						.115						
5						.111						
5I						.086						
6	.002	.000				.083						
6I						.067						

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TABLE 18. SMOKE SIMULATION COMPARISONS
SMOKE TEST NO. 3 AT 30 MIN.

Floor	Corridor											
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2	*	0.0										
2I		.073										
3												
3I												
4												
4I												
5												
5I												
6												
6I												

*Decay process cannot be simulated in the Smoke Concentration Program at present.

TABLE 19. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 4 AT 5 MIN.

Floor	Corridor		Shafts 8/10									
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2	1.0	1.0										
2I	.006	.231		.065								
3	.000	.000		.038								
3I				.017								
4				.011								
4I				.006								
5				.005								
5I				.003								
6	.000	.000		.002								
6I				.002								

TABLE 20. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 4 AT 15 MIN.

Floor	Corridor		Shafts 8/10									
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2	1.0	1.0										
2I	.012	.530		.245								
3	.000	.000		.217								
3I				.130								
4				.119								
4I				.083								
5				.077								
5I				.058								
6	.000	.000		.055								
6I				.043								

TABLE 21. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 4 AT 25 MIN.

Floor	Corridor		Shafts 8/10									
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2	1.0	1.0										
2I	.006	.695		.350								
3	.000	.000		.334								
3I				.211								
4				.204								
4I				.148								
5				.145								
5I				.113								
6	.000	.000		.111								
6I				.089								

TABLE 22. SMOKE SIMULATION COMPARISONS
SMOKE TEST NO. 4 AT 35 MIN.

Floor												
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I												
2	1.0	1.0										
2I	.006	.787		.487								
3	.000	.000		.400								
3I				.256								
4				.252								
4I				.185								
5				.183								
5I				.145								
6	.000	.000		.144								
6I				.116								

10 of them were in continual operation. However, the computer-simulated leakage shown in elevator shaft no. 2 is a distinct possibility. Leakage was also evidenced back to the corridors from the fourth floor upward in the newly developed air movement program but not by the smoke concentration program. It is the only elevator shaft connecting with the interstitial spaces. Shafts 8 and 10 represent the shafts adjacent to stairwells 10 and 12.

This infiltration of these shafts is possible through small penetrations in the interstitial spaces, which is evidenced in the computer simulation data.

<u>Smoke Test No. 2</u> - The infiltration rates of the computer simulation again appear to be much too high in comparison to the trace gas test results. With the exception of the magnitude of the concentrations, the behavior of the simulated infiltration compared favorably to the trace gas test for those sample points which could be compared. However, the computer simulation evidenced significant infiltration of the elevator shafts and the corridor spaces below the third floor. The elevator shaft infiltration is reasonable, but the corridor infiltration may be due to unrealistic leakage paths in the computer model between floors and the interstitial levels immediately below. The only actual penetrations in this direction are for drain lines, and they are reasonably well sealed. Hence, the infiltration to the simulated floor due to interstitial leaks may not be realistic. The shafts adjacent to stairwells 10 and 12 again reflect smoke infiltration.

<u>Smoke Test No. 3</u> - The computer simulation evidenced the same behavior as reflected in the trace gas test. However, the rates of infiltration are much too high as compared to the

trace gas test. Evidence of the trace gas on the sixth floor in the trace amount at 20 minutes was not found in the computer simulation and was probably due to transport by the 10 elevator cages. Typical infiltration of elevator no. 2 and shafts 8 and 10, as evidenced in previous cases, occurred in the computer simulation again. The decay process from 30 minutes onward could not be simulated in the smoke concentration program, as indicated earlier.

Smoke Test No. 4 - The computer simulation reflected the same behavior for those points which could be compared as did the trace gas test. However, the concentrations were again much too high and were probably due to overly large infiltration rates. Shafts 8 and 10 again reflected the same infiltration characteristics, via entry from the interstitial space. An important point is that these shafts communicate with the wing interstitial spaces via plumbing and electrical conduit penetrations which provide an infiltration path to all interstitial spaces.

The field trace gas test data for smoke test 4 also provided two pressure difference measurements which can be compared to the computer-simulated results. These differences were measured on the second and third floors between the corridor and an elevator shaft. The field data did not specify which elevator shafts were measured. Consequently, Table 23, which reflects a comparison of the measured and computed results, presents the results from each elevator shaft determined by the computer simulation, in comparison with the field data. The comparison is favorable and indicates that the elevator shaft pressures in the computer simulation may have been about .01 inches of water too high in pressure.

TABLE 23. SMOKE TEST NO. 4 - PRESSURE COMPARISONS

Floor	Measured	Computer Simulation				
		Elev. No. 1	Elev. No. 2	Elev. No. 3	Elev. No. 4	Elev. No. 5
2	-.02	-.012	-.006	-.013	-.013	-.013
3	+.02	.031	.037	.030	.030	.030

Note: Minus indicates flow from the corridor to the elevator shaft; plus indicates the converse.

In general, the San Diego VA Hospital is well sealed around cables, conduits, and pipe. However, occasional points of leakage exist because of incomplete sealing at these penetrations. More significantly, there are numerous electrical conduits that exist and that are well sealed at their wall penetrations. However, those conduits are unused. They provide 4- to 6-inch diameter holes through the barriers and are significant paths of infiltration.

The behavior of the computer simulations paralleled the results of the field tests, except in the levels of concentration, and the computer simulation appears suitable for predicting the behavior of smoke in the San Diego VA Hospital.

Computer Simulation of Smoke Movement on Pressure Tests

As indicated earlier, smoke concentrations were also simulated on the computer programs for the pressure test cases. These cases also synthesized various realistic modes of operation under which the building system could exist during a fire.

Pressure test case no. 1, with a burn room on the third floor, was identical to smoke test no. 1 and will not be repeated. However, pressure test case no. 1 was also run with a simulated fire in the first floor interstitial level. At 60 minutes, the only infiltration calculated was into stairwell 12, with concentrations of .007 at the second floor level and .118 at the second floor interstitial level of the stairwell.

Pressure test case no. 2, with a fire on a pressurized floor, the third floor, in this case, demonstrates the infiltration which could occur under such a condition. Table 24 presents the results from the smoke concentration program. As should be expected, the elevator shafts provide the primary infiltration paths to the occupancy floors.

Pressure test case no. 4 simulates a fire on the third floor, with the third and fourth floors in a control mode. Results from the smoke concentration program evidenced no infiltration at 60 minutes to any space represented in the input generated by the newly developed air movement program, as defined above.

TABLE 24. SMOKE SIMULATION COMPARISONS

SMOKE TEST NO. 2 AT 60 MIN.

Floor	Corridor		Elev. No. 1		Elev. No. 2		Elev. No. 3		Elev. No. 4/5		Shafts 8/10	
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B		.011		.461		.006		.356		.346		.010
1		.113		.748		.087		.402		.402		.010
1I		.000		.818		.081		.402		.402		.010
2		.087		.845		.060		.402		.402		.009
2I		.243		.848		.926		.402		.402		.127
3		1.0		.849		.941		.402		.402		.126
3I		.732										.330
4												.330
4I												.247
5												.246
5I												.197
6												.197
6I												.162

Pressure test case no. 5 simulates a fire on the third floor, with the second, third, and fourth floors in a control mode. Results from the smoke concentration program evidenced no infiltration at 60 minutes to any space, in the same manner as pressure test case no. 4, above.

Pressure test case no. 6 simulates a fire on the fifth floor, with the fourth, fifth, and sixth floors in a control mode. Results from the smoke concentration program evidenced no infiltration at 60 minutes to any space, in the same manner as pressure test case no. 4, above.

Simulation of a fire on the third floor, while in a control mode on the fourth, fifth, and sixth floors, was performed as a variation on pressure test case no. 6. With the exception of the shafts adjacent to stairwells 10 and 12, no infiltration of the upper floors above 3I occurred. This is to be expected because of the shielding action of floor 4 in a pressurized mode. Infiltration by two routes was evidenced to the lower floors. Infiltration by floor-to-floor leakage and by elevator shaft no. 2 to the lower floors occurred in the computer simulations. The results of the smoke concentration program are shown in Table 25 for this case.

The results evidenced in the computer-simulated behavior of the smoke were realistic and occurred as expected for the given conditions for these cases.

TABLE 25. SMOKE SIMULATION COMPARISONS
SMOKE TEST NO. 6A AT 60 MIN.

Floor	Corridor		Shafts 8/10									
	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.	Samp.	Sim.
B												
1												
1I				.063								
2		.001		.189								
2I		.102		.190		.052						
3		1.0		.190		.052						
3I		.733				.282						
4						.282						
4I						.211						
5						.211						
5I						.169						
6						.168						
6I						.136						

PARAMETRIC ANALYSIS

The performance of a parametric analysis, unlike a sensitivity analysis, need not be an exhaustive analysis of the effects of incremental variations of each independent variable over an interval of variation. It usually comprises meaningful, i.e., realistic, variations and combinations of variations of significant independent variables. However, its upper limit is equivalent to an exhaustive sensitivity analysis. In the case of a building as extensive as the San Diego VA Hospital, the number of potential variations of state of the building/HVAC system are quite large. Since the primary objective of this effort was to demonstrate the practical application of computer simulation methodology to the design, analysis, and evaluation of smoke control features of large buildings, and since a very limited amount of time and funds could be allocated to this building, it was necessary to define a set of parametric states of the building/HVAC system that were few in number but would clearly fulfill the objectives.

In addition to the above considerations, the investigators responsible for this project have been extremely interested in evaluating the effects of various energy levels and sources which could operate against smoke control measures in buildings. It was felt that, if realistic energy sources and levels could be induced in the simulation and reflect significant effects upon the smoke control measures, then the value of such simulation would be demonstrated.

It was noted during a field trip to the hospital that, during the summer months, there was a prevailing west wind off the Pacific Ocean. The implications of its effect upon the interstitial spaces posed an interesting problem. Consequently, these investigators established two fire scenarios which have realistic sources and spaces according to the nation's statistics on fire sources. These were defined as follows:

1. A fire in the third floor electrical room adjacent to the shaft next to stairwell 9 with subsequent HVAC failures in the third floor. This was followed by a control mode at normal weather conditions.

2. A fire in the third floor interstitial space with subsequent equipment failures in the west wing of the third floor interstitial level. This was followed by a control mode at nominal weather conditions and a control mode with a west wind of 25 mph.

Normal HVAC states were also run with both of the simulated fires. The detailed conditions for the results of the computer simulations are presented in the following material.

Scenario I

The San Diego VA Hospital has electrical and plumbing shafts that exist adjacent to stairwells 9 and 11. Both of these shafts have independent air supply fans on the sixth floor interstitial level. They are vented to the outside periodically down an external wall and have many penetrations at each interstitial level where an electrical room exists. These electrical rooms open directly onto the plumbing and cable shafts. The air supplies mentioned above are actually for these electrical rooms.

An electrical fire is assumed to occur in the electrical room at the third floor interstitial level. Before it is suppressed, it is assumed to destroy sufficient electrical circuitry to cause the third floor interstitial fans, the third floor exhaust fans, and the air conditioning units in the third floor interstitial space to fail. The exhaust fan TF8 for the core in the penthouse was assumed to continue operation.

Three computer simulations were made to evaluate the effect of such a condition with a nominal temperature state and a nominal wind velocity of 11 mph. The first case, Case 1A, simulated the effects of a fire state with the third floor HVAC equipment in a failure mode and the balance of the building's HVAC system operating in a normal mode. The second case, Case 1B, simulated the effects of an HVAC control mode in effect using the remaining systems that would be still operational. The control mode was defined as follows:

1. The third floor and third floor interstitial systems were assumed to remain in a failure state

2. The supply fan to the shaft and the electrical rooms was turned off

3. The entire fourth floor was placed on supply only

4. The entire second floor was placed on supply only

5. All of the second floor interstitial fans were turned off.

To provide a base for comparison, the same fire state was assumed to occur with no failures of the HVAC system in Case 1C.

<u>Case 1A - Failure State of Third Floor HVAC Equipment</u> - The results from the smoke concentration program simulation of the failure state indicated that the smoke from the electrical room fire on the third floor moved downward through shaft no. 9 to the basement level. Since all of the electrical rooms along that shaft open directly onto shaft no. 9, this implies that the smoke detectors below the fire in the lower electrical rooms would also have been activated. Some ambiguities as to exactly where the fire source is located might occur, if heavy dependence is placed upon combustion

product detectors. The heat detectors present in the electrical rooms might prevent such a problem, but they are slow-reacting sensors by nature.

The smoke from the shaft infiltrated the second floor center core interstitial space and the basement corridor. The second floor interstitial smoke then infiltrated shafts 8 and 10. These were the only results directly predictable from the present smoke concentration program. A great deal more significant infiltration actually occurred. In order to trace the flow of smoke more completely, the air flow paths were traced from the results of the newly developed air movement program.

Tracing the flows from the spaces infiltrated according to the smoke concentration program, the results were as follows:

1. The smoke in the center core of the second floor interstitial level infiltrated all of the wings of the second floor interstitial at low levels to the already infiltrated shafts 8 and 10. The balance of the smoke was exhausted to the outside.

2. Fifty percent of the smoke infiltrating the basement corridor was then moved to the office spaces and the balance exhausted to the outside. This was then mostly exhausted. Trace amounts would have infiltrated two stairwells.

3. Shafts 8 and 10 infiltrated the first floor interstitial space and the south wing of all of the interstitial levels above the second floor. These spaces then leaked to adjacent wings and other vertical paths in small amounts. The flow of smoke indicated by the newly developed air movement program under the prescribed failure conditions is

illustrated in Figures 33 through 35. All of the infiltration paths are not shown. Higher order flow paths are generated by the infiltration of the plumbing risers and the stairwells. The infiltration from these spaces is almost entirely into the interstitial spaces above the fourth floor interstitial level.

Analyzing the results of the newly developed air movement program indicated that the third floor was approximately .015 in. of water below normal pressures, with:

1. The west wing providing a large amount of air to the corridor

2. The north and south wings supplying small amounts of air to the corridor

3. The corridor supplying a large amount of air to the east wing, with the balance exhausting through TF-8

4. The elevator shafts .01 to .02 in. of water above the corridor pressures of the third floor and small amounts of air moving from the elevator shafts to the third floor corridor.

The center core of the third floor interstitial space with the north and south wings was fairly static. Most of the air supply was from the third floor and was mostly exhausted by the outside vents. The east wing of the third floor interstitial received significant air from the third floor east wing and exhausted it to the outside. About 100 percent of the air exhausted from the

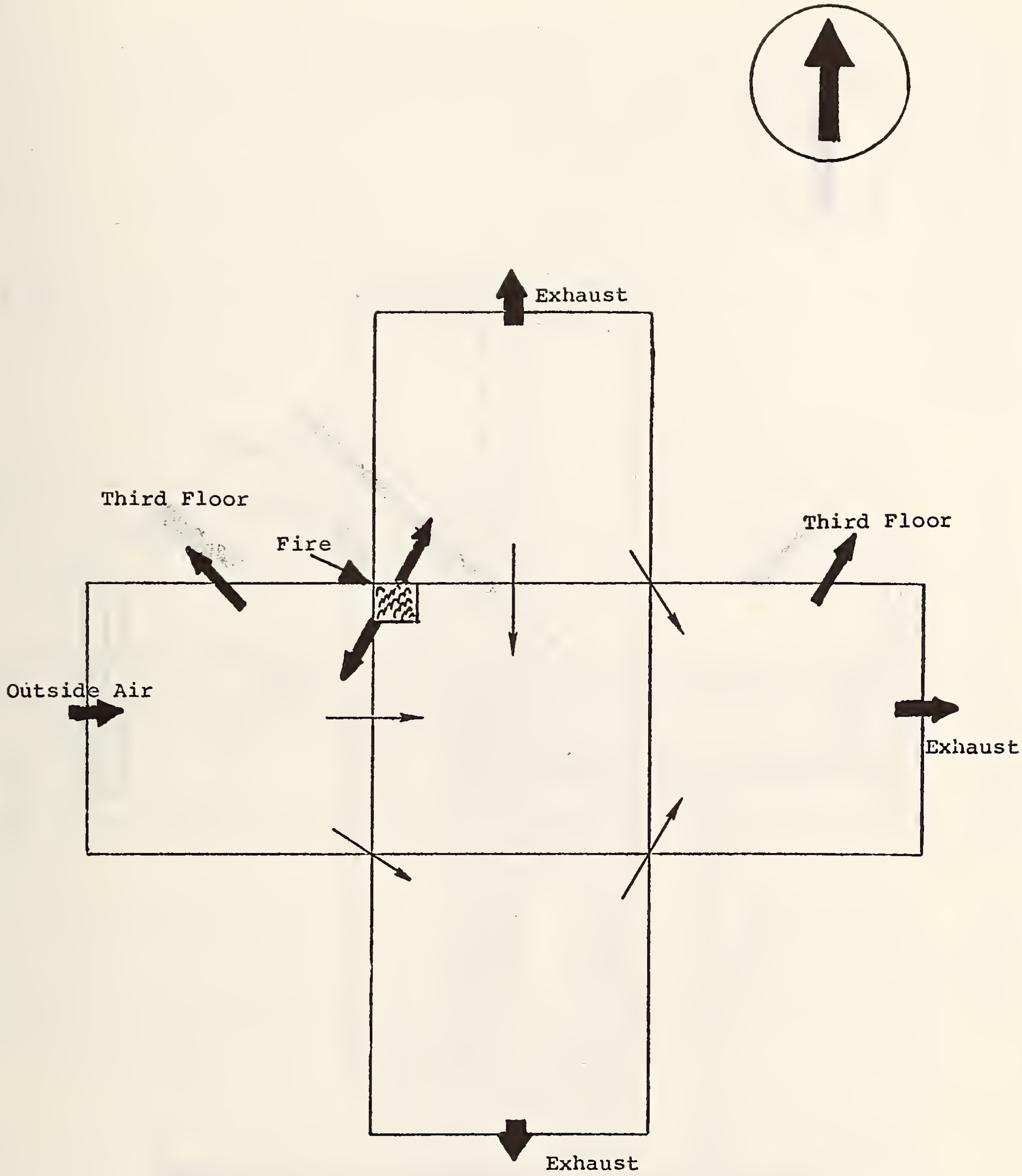

FIGURE 33. PRIMARY SMOKE ROUTES AT THE 3I LEVEL
(CASE 1A)

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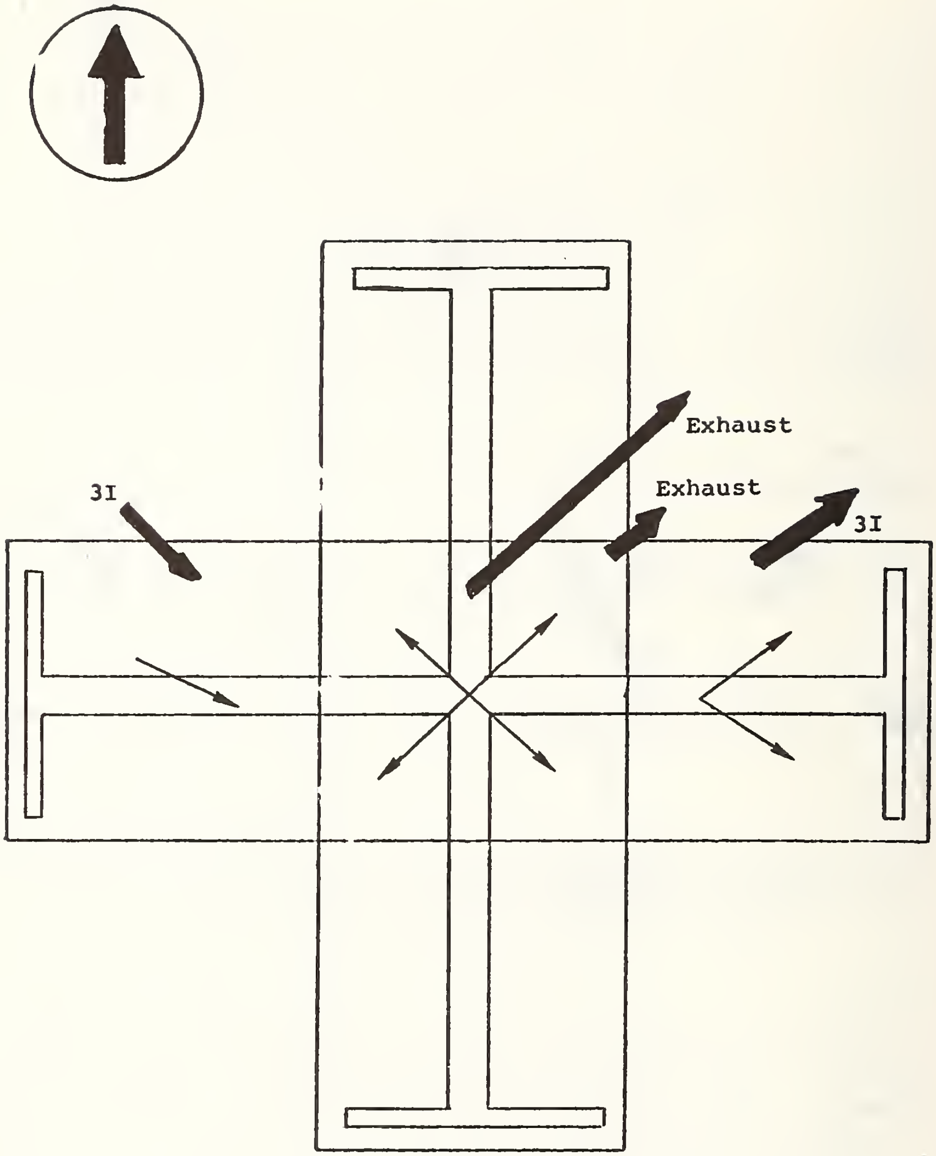
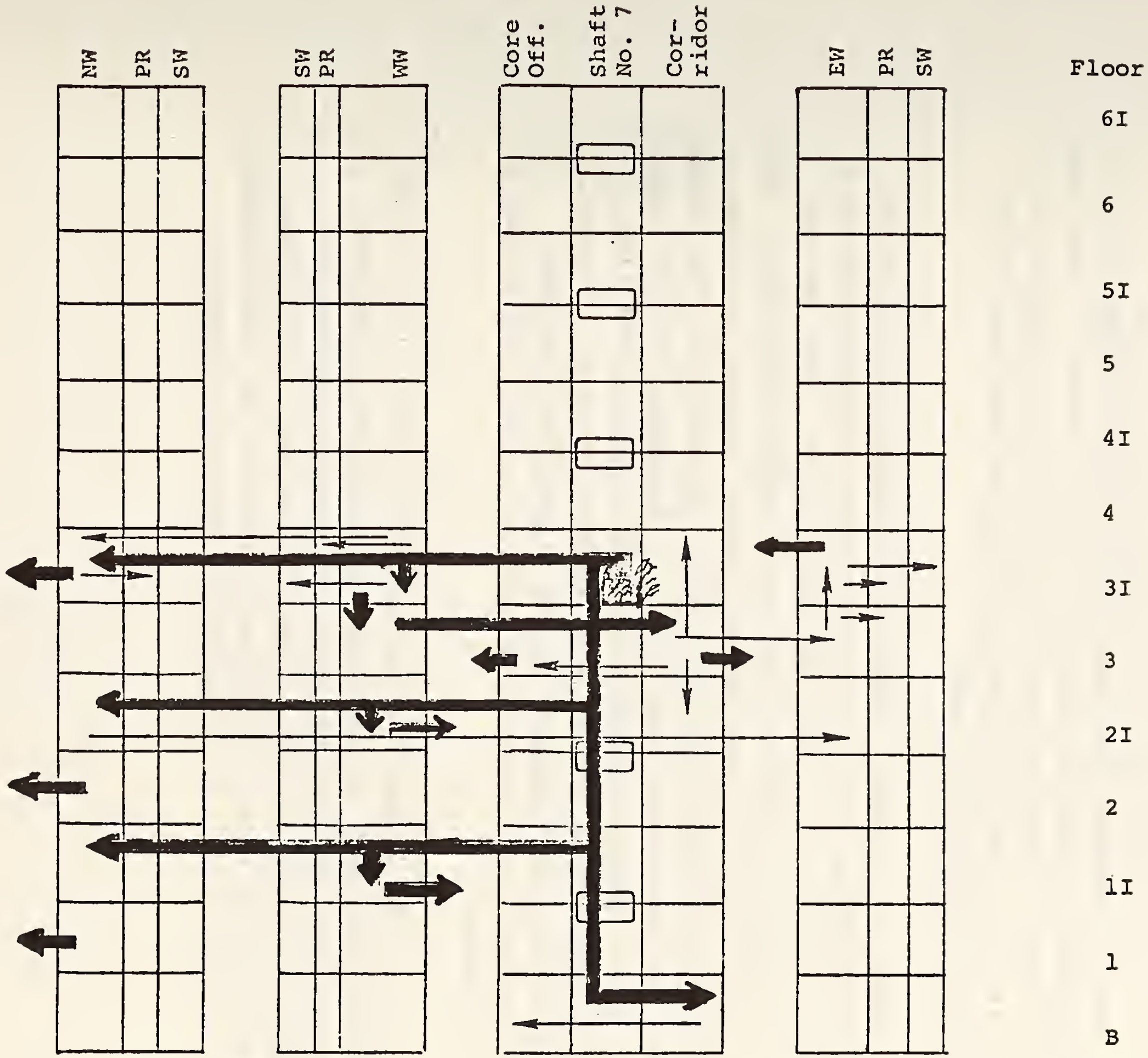


FIGURE 34. PRIMARY SMOKE ROUTES ON THE THIRD FLOOR (CASE 1A)

82



PR = Plumbing Riser(s)
SW = Stairwell(s)
▭ = Electrical Equip. Rm.

FIGURE 35. PRIMARY VERTICAL SMOKE ROUTES
(CASE 1A)

west wing of the third floor interstitial was to the west wing of the third floor. The air supply to the wing of the third floor interstitial space was outside air.

From the fourth floor upward, the building was essentially at a normal state in the corridors and compartment spaces.

This case illustrates the value of the newly developed air movement program in analyzing potential failure states. It also provides a means to analyze evacuation plans, e.g., infiltration of the third floor east wing from a fire in the west wing of the third floor interstitial space.

The assumption of total failure of the equipment of the third floor interstitial level due to the single electrical room fire is not realistic in the case of this building. Only the west and north wing interstitial equipments would probably fail. However, the basic flow behavior would remain the same, with the exception of the east wing third floor infiltration. The third, south, and center core supply fans would probably still be operational and cause exhaustion through the north or west wing interstitial levels, depending on the wind velocity. However, there would also be the possibility of additional equipment failures at higher levels in the west and north wings if such a fire occurred.

Case 1B - Control Mode - The control mode defined above for the given failure state was simulated with this case. The smoke infiltrations predicted by the present smoke concentration program failed to provide a comprehensive view of the effects of this control mode and detailed analysis of the flow predicted by the newly developed air movement program was necessary.

The limited results of the smoke concentration program indicated the following:

1. Infiltration of the first and second interstitial levels from shaft no. 7 occurred.

2. Secondary infiltration of elevator no. 2 from the interstitial spaces occurred.

3. Infiltration of shafts 8 and 10 adjacent to stairwells 10 and 12 occurred.

4. Infiltration of the shaft adjacent to stairwell no. 11 at the lower levels occurred.

In this instance, the smoke infiltration shown by the smoke concentration program did not accurately reflect the flow of smoke from shaft no. 7. An analysis of the air movement simulation data indicated that the smoke flow paths were as shown in Figure 36. The control mode, as simulated, appears to be effective. Although the smoke enters the interstitial spaces and a plumbing riser, it never enters the occupancy floors and always results in being exhausted to the outside.

This case illustrates the value of simulated air movements to analyze the effectiveness of HVAC control of smoke movement. It also illustrates the serious deficiencies existing in the present smoke concentration program and the hazards of employing it in combination with the newly developed air movement program.

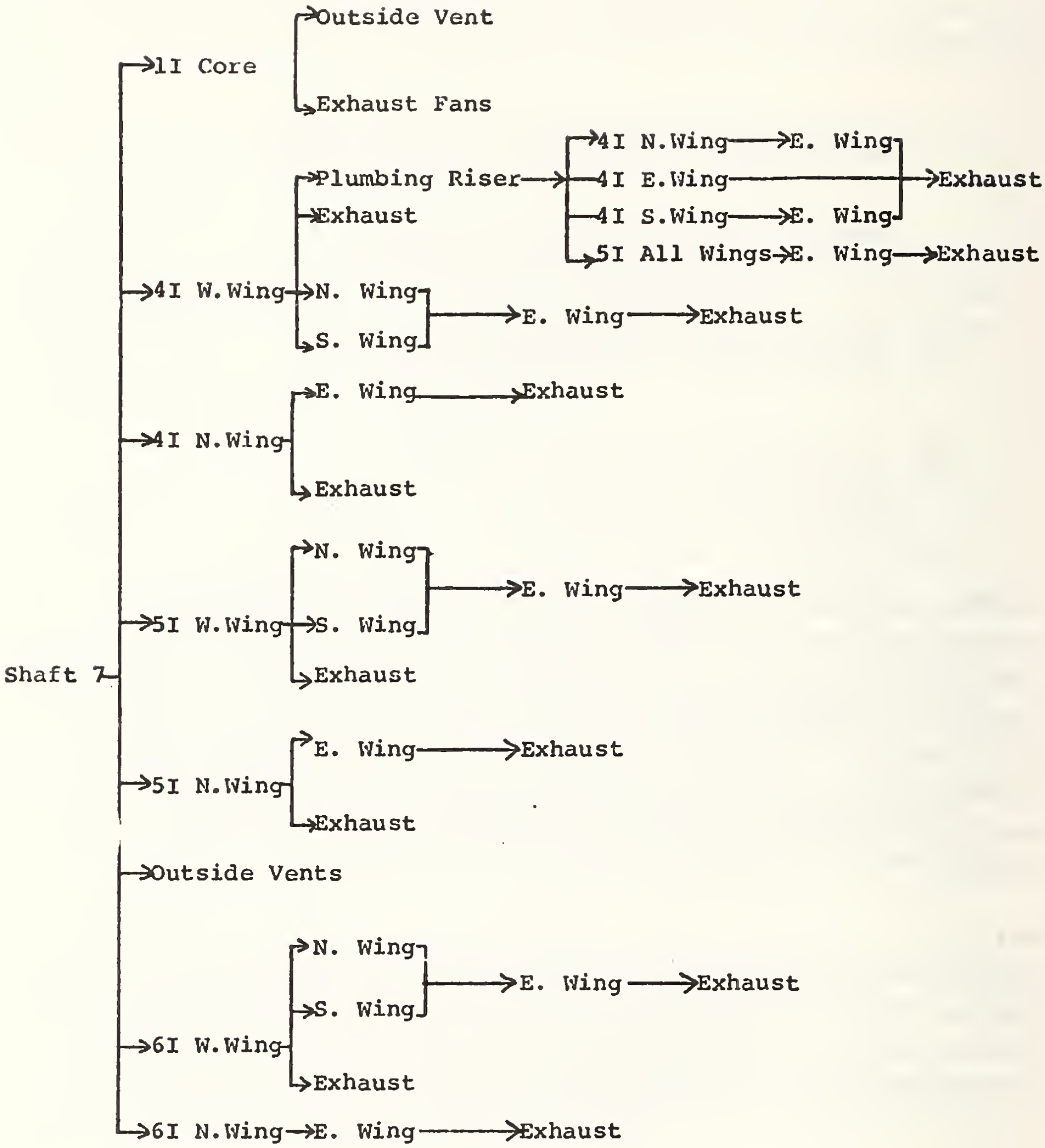


FIGURE 36. SMOKE FLOW IN CONTROL MODE
(CASE 1B)

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Case 1C - No HVAC Failures - This case assumes that the fire exists in the electrical room as for the previous cases and that the HVAC system is in a normal state. The smoke concentration program indicates smoke infiltration as follows:

1. Infiltration of the basement, the first floor interstitial level, and the second floor interstitial level

2. Secondary infiltration of elevator shaft no. 2

3. Infiltration of shafts 8 and 10

4. Infiltration of the shaft next to stairwell 9.

An analysis of the actual flows indicates routes similar to that shown in Figure 36, except for possible infiltration to the basement. The normal state appeared to be almost as effective as the control mode in routing the smoke to exhaust areas for the fire simulated in the electrical room.

Scenario II

In this evaluation, it is assumed that the HVAC equipment failed because of fire in the west wing of the third floor interstitial space. This condition implies the failure of the exhaust fan for the west wing of the third floor interstitial and the supply and exhaust systems for the west wing of the third floor. This failure state was simulated in the first case, Case 1A. A control mode was established in the second case, Case 1B, where:

1. The remainder of the third floor was placed on supply only

2. The remainder of the third floor interstitial exhaust fans were turned off

3. The fourth floor was placed on supply only

4. The second floor interstitial exhaust fans were turned off

5. The second floor was placed on supply only

6. The prevailing west wind was assumed to be at a nominal speed of 11 mph.

The same control mode was also simulated with the west wind at 25 mph for a third case, Case 1C.

A normal mode with the same smoke source was simulated with the wind at a nominal 11 mph for the fourth case, Case 1D.

Case 2A - Failure State of the West Wing HVAC Equipment - The results from the smoke concentration program indicated no infiltration through corridors, vertical shafts, or corridor to corridor. However, tracing the air flows shown by the results of the newly developed air movement program indicates significant air movement from the west wing of the third floor interstitial where the smoke source was assumed to exist. The primary paths of the smoke from the west wing of the third floor interstitial space are illustrated in Figures 37 and 38. The smoke routes to several levels of infiltration are shown in Figure 39. The flow movement indicates significant infiltration of essentially the entire third floor.

Case 2B - Control Mode at Nominal Wind Speed - An analysis of the air movement data generated by the newly developed air movement program indicated that the control mode imposed on the failure state established in Case 2A, as simulated in this case, effectively routes the smoke through non-occupancy spaces. It does, according to the simulation, infiltrate most of the interstitial spaces, but it is either vented or exhausted by exhaust fans to the outside. A few stairwells appear to be infiltrated from the interstitial spaces in relatively small amounts. The smoke routes, to several levels of infiltration, are shown in Figure 40.

The present smoke concentration program does not have the ability to simulate the spaces simulated by the newly developed air movement program. Consequently, it reflected no infiltration of smoke in its results.

Case 2C - Control Mode with a 25-mph West Wind - The same control mode defined earlier for the failure state and simulated in Case 2B was repeated in this case, except that the speed of the west wind was increased to 25 mph. Although a wind of 11 mph did not affect

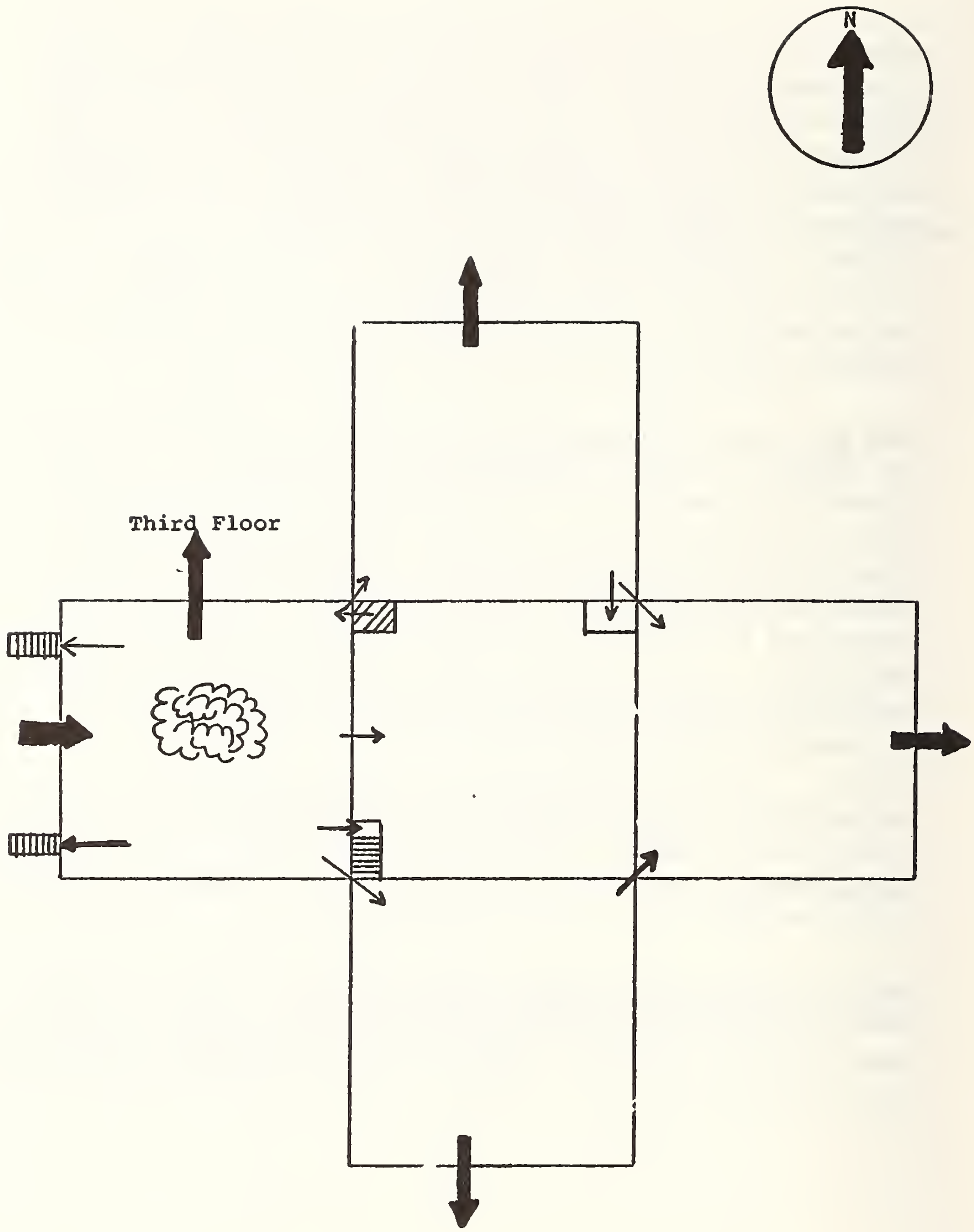

FIGURE 37. PRIMARY SMOKE ROUTES ON THIRD-FLOOR INTERSTITIAL LEVEL

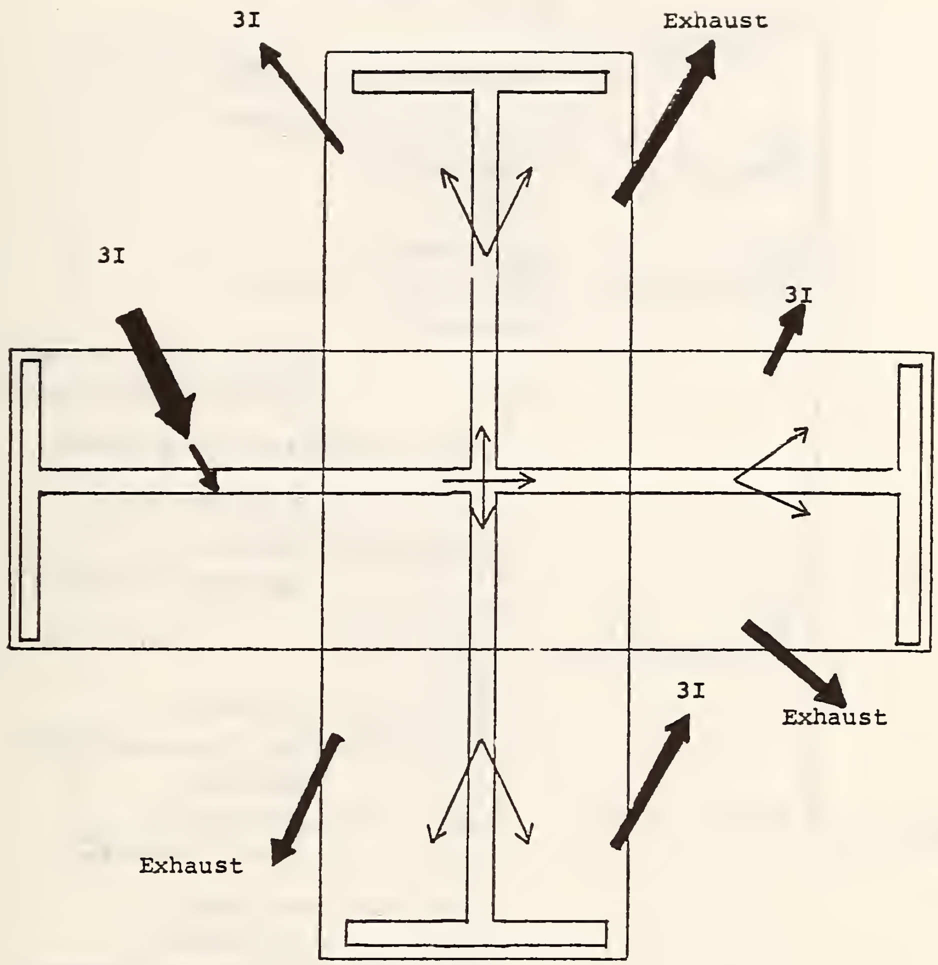

FIGURE 38. PRIMARY SMOKE ROUTES ON THIRD FLOOR

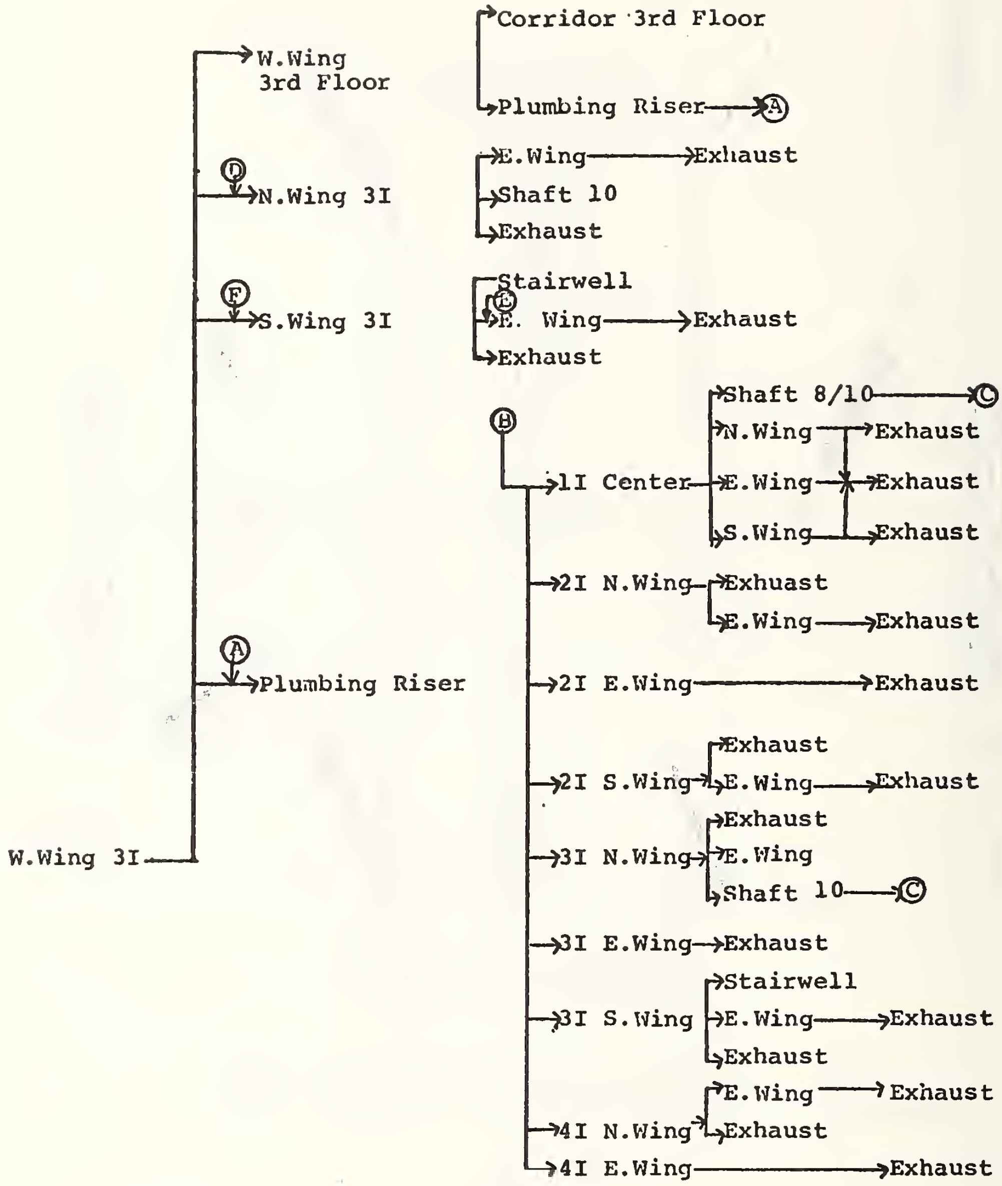

FIGURE 39. SMOKE FLOW PATHS FROM WEST WING 3I

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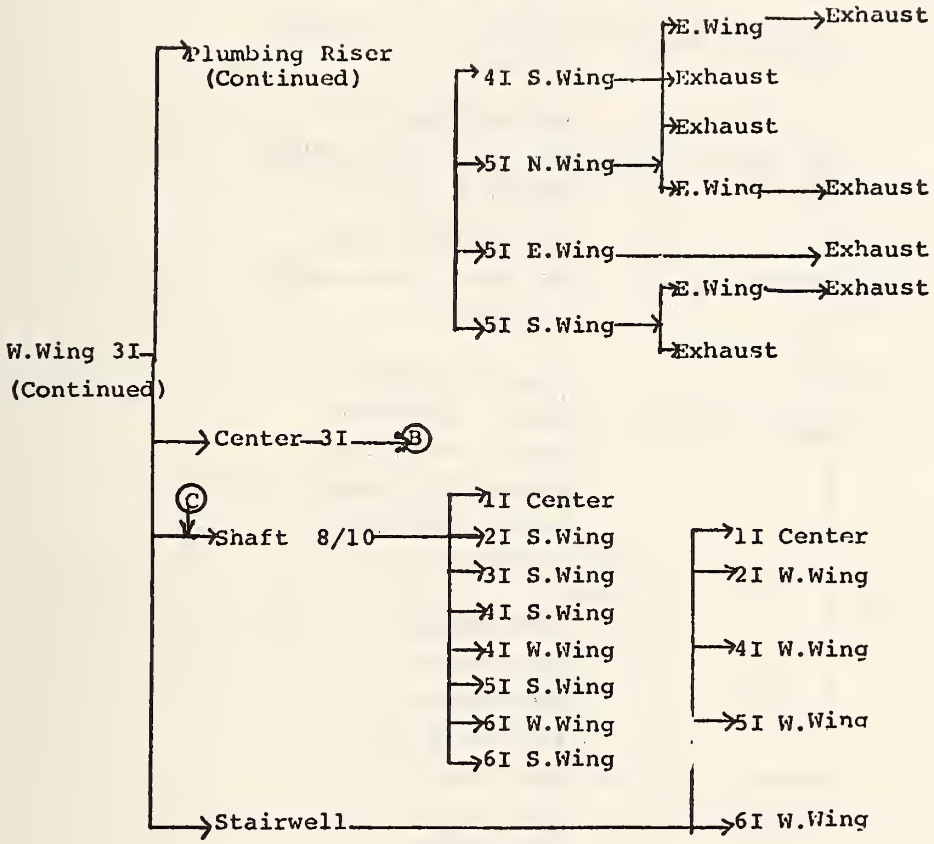

FIGURE 39. SMOKE FLOW PATHS FROM WEST WING 3I (Cont.)

93

- Corridor 3 →
  - N. Wing 3 →
    - Pneumatic System
    - N. Wing 3I → (D)
    - Exhaust
  - E. Wing 3 →
    - Pneumatic System
    - E. Wing 3I → (E)
    - Exhaust
  - S. Wing 3 →
    - Pneumatic System
    - S. Wing 3I → (F)
    - Exhaust
  - Elev. No. 1 →
    - Corr. Basement
    - Corr. 2nd Floor
    - Corr. 4th Floor
    - Corr. 5th Floor
    - Corr. 6th Floor
    - Outside Vent
  - Elev. No. 2 →
    - 1I Center
    - 2I Center
    - 3I Center
    - 4 Corr.
    - 4I Center
    - 5 Corr.
    - 5I Center
    - 6 Corr.
    - 6I Center
  - Exhaust
  - 2I Center
  - 3I Center

FIGURE 39. SMOKE FLOW PATHS FROM WEST WING 3I (Cont.)

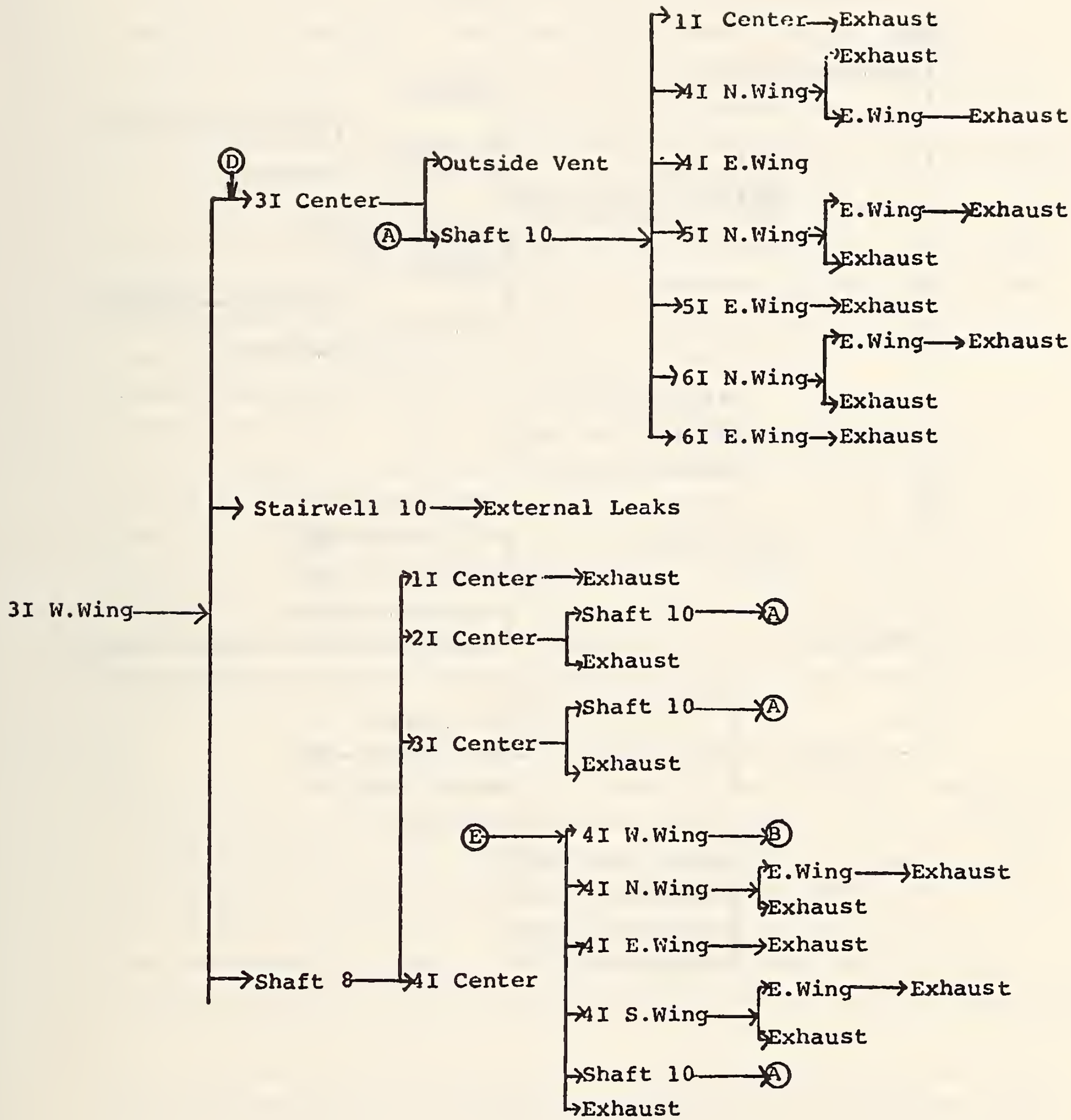

FIGURE 40. INFILTRATION ROUTES UNDER CONTROL MODE (CASE 2B)

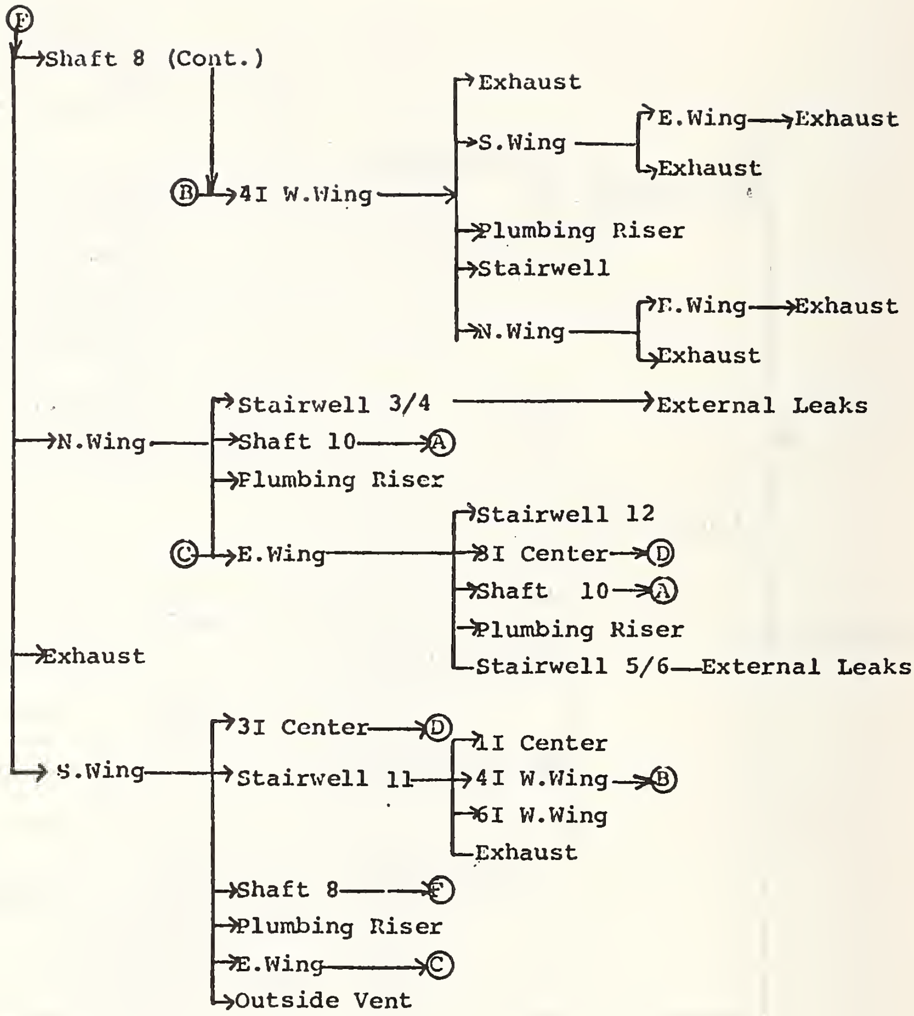

FIGURE 40. INFILTRATION ROUTES UNDER CONTROL MODE (Cont.).

(CASE 2B)

the control mode, as indicated in the results of Case 2B, an analysis of the newly developed air movement program results of this case evidences a serious change in the flow of smoke with a 25-mph west wind. The flow of air into the west wing of the third floor interstitial space was in excess of 4,000 CFM and an increase in pressure in excess of the third floor west wing pressure occurred because of this increased wind velocity. This resulted in a significant infiltration of the west wing of the third floor, as illustrated in Figure 41. Additionally, extensive infiltration of the interstitial spaces and low-level, but extensive, infiltration of stairwells was evidenced, as shown in Figure 42.

This simulation is relevant to the control mode and the failure state synthesized in Scenario I. Similar results would be expected from the control mode used in Scenario I if the wind velocity were increased to 25 mph. It is important to note that the simulation of a 25-mph west wind does not mean that the results evidenced in the computer simulation will actually occur at a wind of 25 mph. It means that, at some wind velocity higher than 11 mph, behavior evidenced in the computer simulation will occur in the real situation.

This case illustrates the need to consider energy levels and sources which may operate against HVAC control techniques under relatively normal conditions, i.e., in relatively low-energy situations, and the need for thorough analysis of smoke control techniques. It also illustrates the potential impact that such conditions would have on evacuation plans. It further illustrates the value of computer simulation techniques in analyzing smoke control techniques.

The conclusions that can be drawn from this case relative to the San Diego VA Hospital are that measures should be considered which prevent the increase of pressure due to external wind pressure if

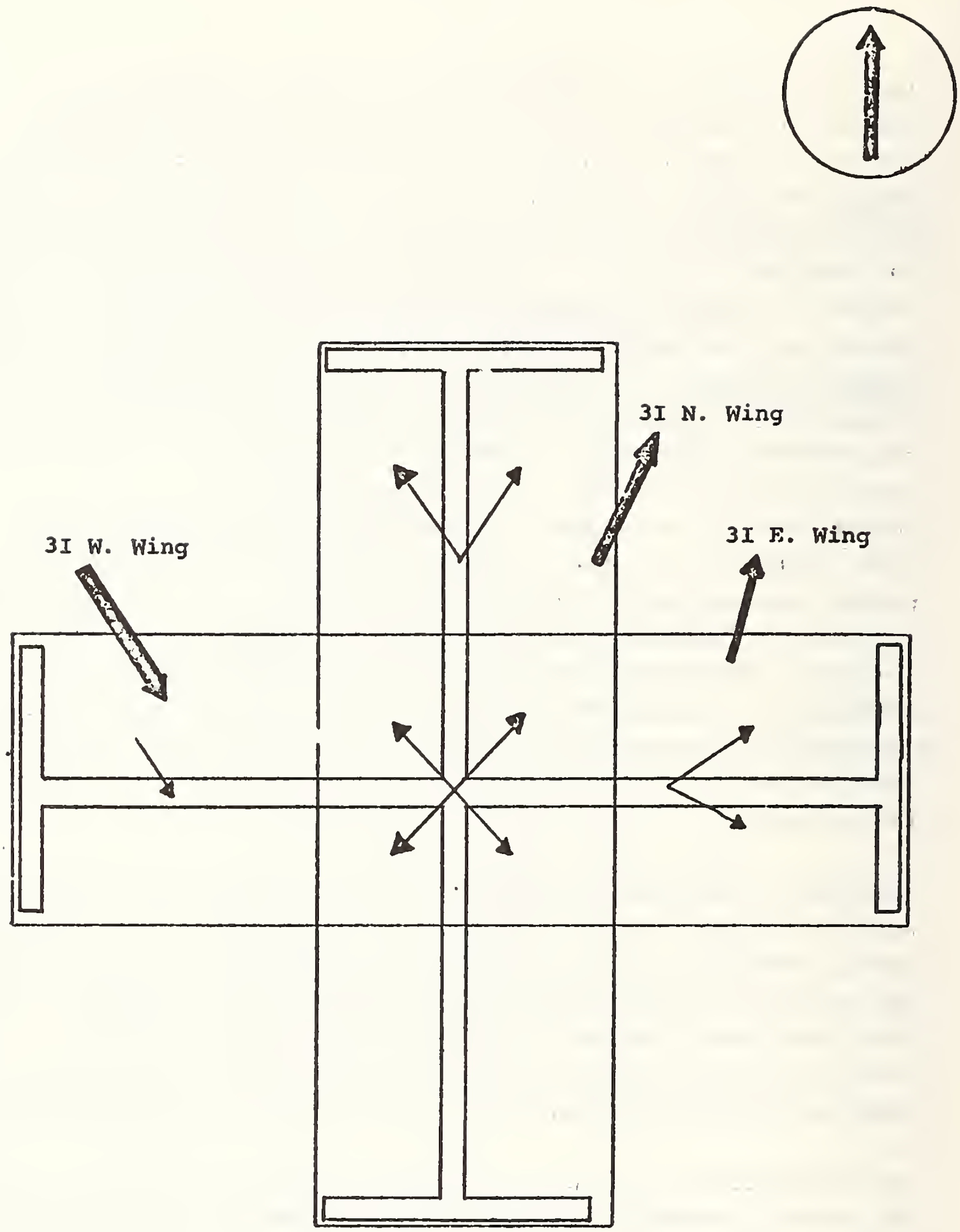

FIGURE 41. THIRD-FLOOR SMOKE ROUTES (CASE 2C)

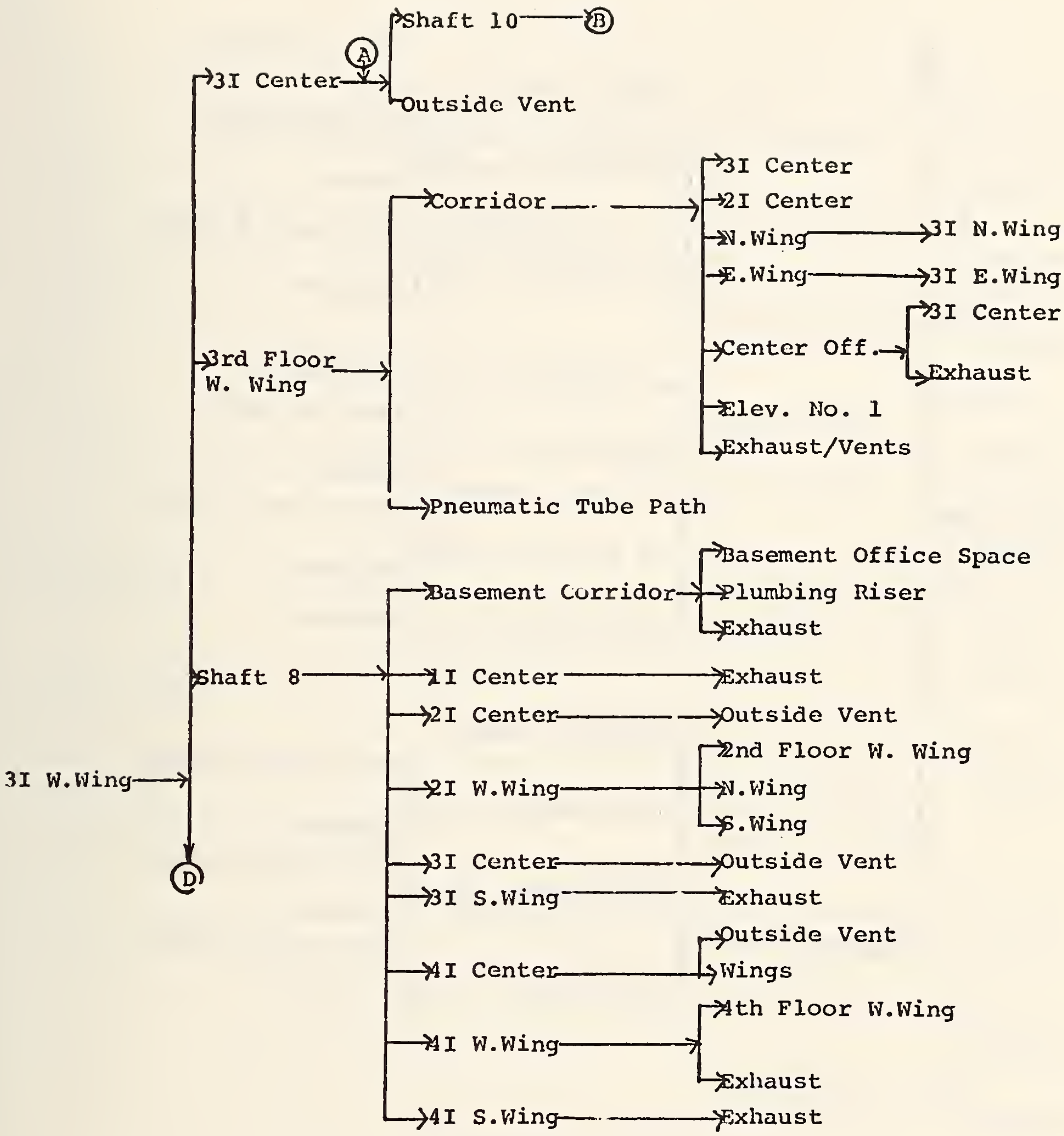

FIGURE 42. INFILTRATION ROUTES UNDER CONTROL MODE (CASE 2C)

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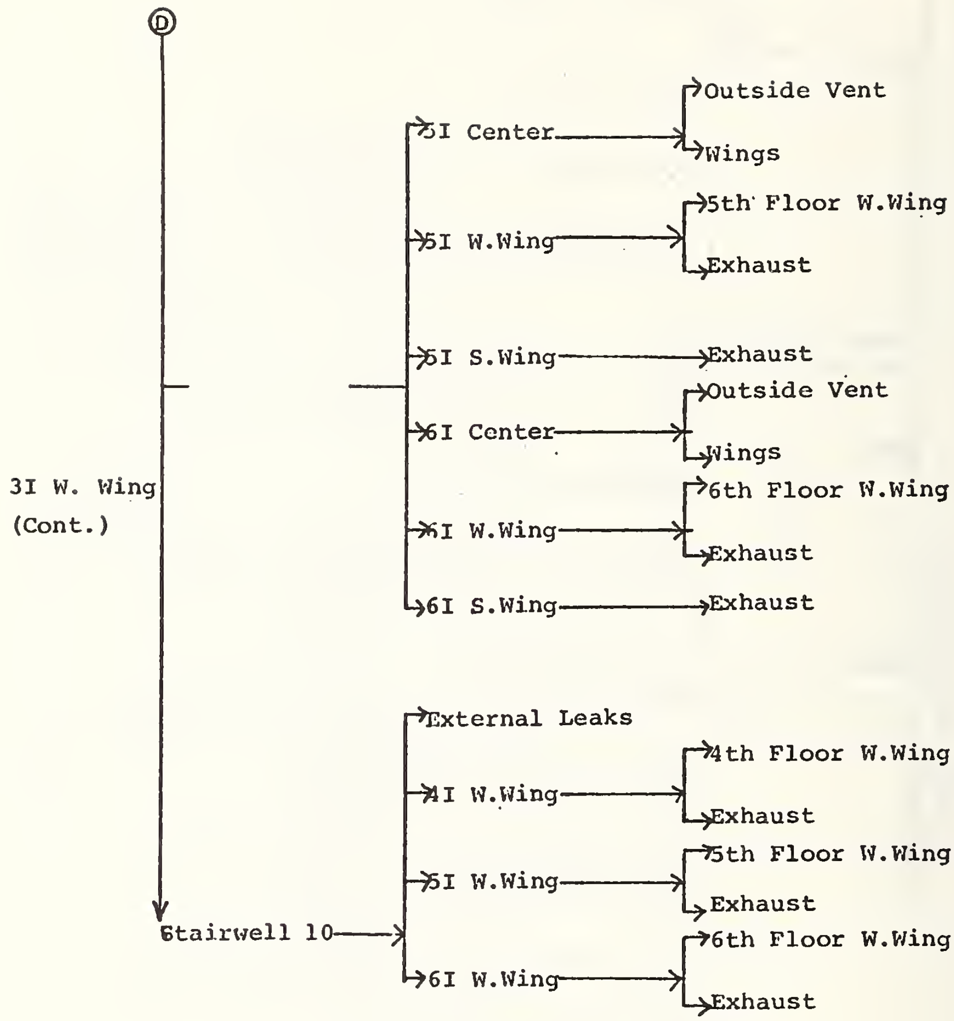

FIGURE 42. INFILTRATION ROUTES UNDER CONTROL MODE (Cont.)
(CASE 2C)

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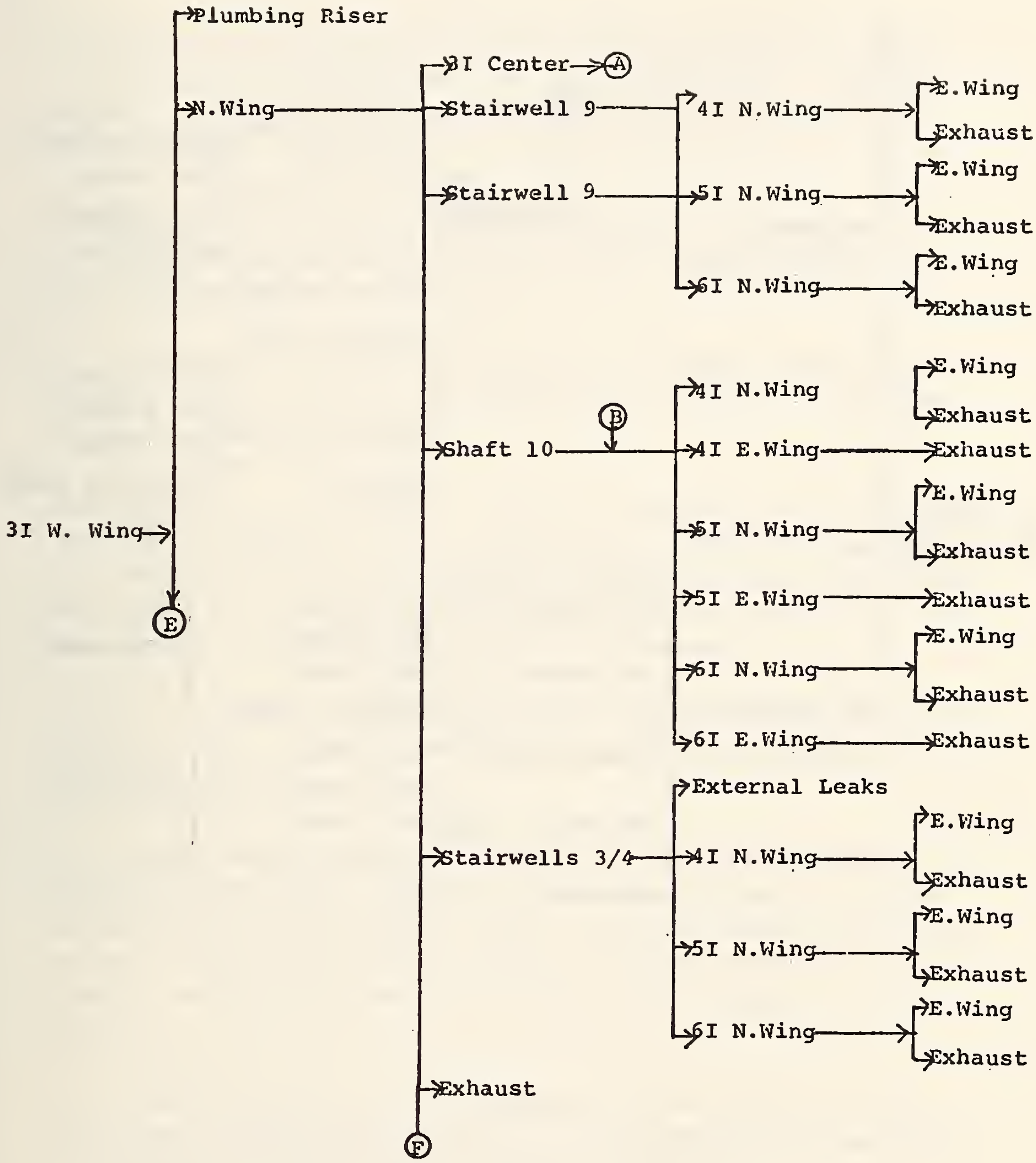

FIGURE 42. INFILTRATION ROUTES UNDER CONTROL MODE (Cont.)
(CASE 2C)

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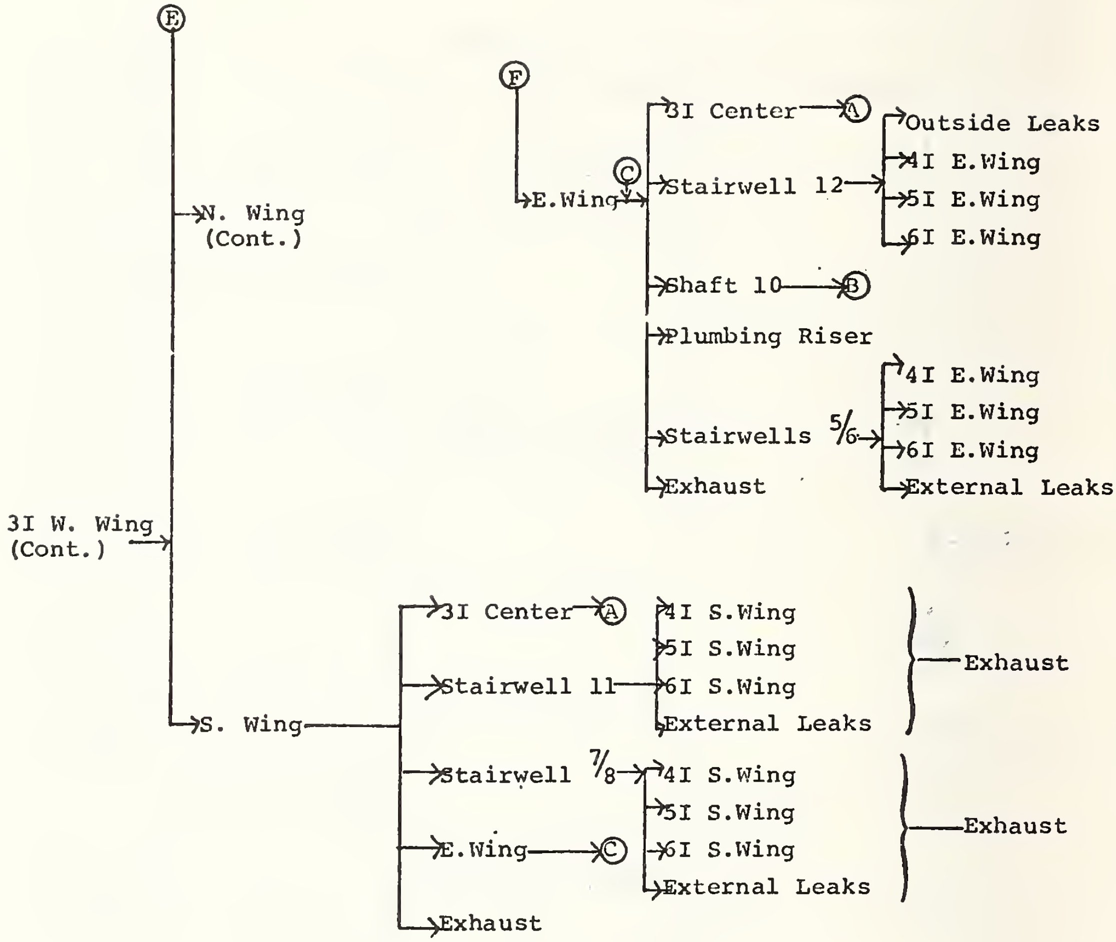

FIGURE 42. INFILTRATION ROUTES UNDER CONTROL MODE (Cont.)
(CASE 2C)

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failure of the interstitial exhaust fans occur. This could be accomplished by dampers over the outside vents which close in case of fire and exhaust fan failure in that space, i.e., each wing or center spaces.

Activation could also be established from wind velocity on the vents of the particular interstitial space suffering from equipment failure and fire.

It is also of importance to note that the present smoke concentration program reflected no infiltration of smoke to any spaces treated in its simulation.

Case 2D - Normal HVAC State - This case simulates the fire condition in the west wing of the third floor interstitial space with the HVAC system in a normal operating state and at a wind velocity of 11 mph, i.e., without a failure state of the equipment in the west wing of the third floor interstitial space.

The results of the smoke concentration program indicate no infiltration, except for shafts 8 and 10, which do not provide paths to occupancy floors.

An analysis of the air flows predicted by the newly developed air movement program also indicates flow to shafts 8 and 10 as well as into the north and south wings of the third floor interstitial space. These two wings then leak to the east wing of the same level. The east wing exhausts all of its air through its exhaust fan.

This case implies that, if no equipment failures occur on the third floor interstitial level, the normal HVAC mode effectively constrains the smoke to the interstitial level.

CONCLUSIONS

Results of the computer simulations for the calibration cases, the trace gas simulations, and the parametric analysis cases indicate that the newly developed air movement program can be used in an effective operational manner satisfactorily.

The only deficiency encountered with the newly developed air movement program was an insufficiency of blower or fan representations. At some time in the future, the program should be modified to allow 50 different fans or blowers.

The use of the present smoke concentration program was essentially valueless. Its limitation to 100 corridors and 10 vertical shafts prevents the consideration of the lateral flows and vertical flows between occupancy spaces. Further, it cannot represent purging or decay processes, i.e., the negative concentration process, or compartment spaces. In determining the smoke flow routes in the parametric analysis cases, it was necessary to manually analyze the flows generated by the newly developed air movement program. Although the routes could be established, estimates of the concentrations which would provide insight into the seriousness of the infiltrations was lacking.

Consequently, the smoke concentration program should be modified to be compatible to the building configurations representable by the newly developed air movement program. Further, that the smoke concentration program should be modified to allow the prescription of an initial smoke concentration state and calculation of a negative or decrementing process to simulate purging and decay of smoke concentrations.

If further simulations of the San Diego VA Hospital are made, the model should be modified to separate the wing corridors from the outer core corridors. This can be accomplished by representing the wing corridors as compartments. The cases simulated in the parametric analysis effort imply that the San Diego VA Hospital offers an extensive base for studying, via computer simulation, the use of HVAC control of smoke under a variety of conditions, particularly energy levels.

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2. G. T. Tamura and J. H. McGuire, "Smoke Movement in High-Rise Buildings," National Research Council, Division of Building Research, Building Digest CBD, 133, Ottawa, 1971.

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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 study was made by the National Bureau of Standards to evaluate the smoke control capabilities of the San Diego Veterans Administration Hospital. A unique feature of the hospital is the presence of independent air-handling units for each floor and each wing. This feature allows the air-handling units to be manipulated for smoke control following the systematic pressurization concept. Systematic pressurization is a means of smoke control whereby a building is divided into either vertical or horizontal compartmented zones such that the air-handling systems are designed to exhaust the immediate fire zone and pressurize the adjacent surrounding zones upon detection of smoke. An experimental technique of smoke simulation and smoke movement measurement was used for the study. The effectiveness of the systematic pressurization smoke control concept is demonstrated by the simulated smoke concentration profiles and pressure measurements.

An extensive series of experiments designed to evaluate the above smoke control concepts were performed by the NBS in cooperation with the VA. Two types of experiments were performed with the building air-handling system operating in normal and various smoke control modes. First, simulated smoke infiltration measurements were obtained by using the sulfur-hexafluoride smoke simulation technique. Second,

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)* Air-handling units; building pressure profile; computer simulation; elevator shaft pressure profiles; parametric analysis; simulated smoke concentration; smoke control; smoke movement; smoke simulation; systematic pressurization.

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ABSTRACT, continued

pressure measurements were obtained across elevator doors, and doors leading from the building central core to each wing. Both SF_6 concentrations and pressure measurements are key indicators of smoke movement in this evaluation. Six basic air-handling test configurations were established and pressure difference data was collected at fifteen locations on each floor measured. At least two floors and more generally three floors were measured for each mode. Each of the six configurations tested are summarized in table 7, and the measured data are summarized in table 8. A total of six smoke simulation experiments were conducted. The results and test conditions for each test are tabulated in tables 1 to 6 inclusively. It is concluded that air-handling systems in the San Diego VA Hospital can be effective in controlling smoke movement if the proper vertical and horizontal systematic pressurization concept as described in this report is applied. This is illustrated in figures 7, 8, 11, and 12.

A computer smoke movement simulation analysis is also presented. Computer calculations compared favorably with field data. Parametric analysis was also performed on smoke control modes for varying environmental and leakage conditions to further study the smoke control uses of the air-handling system and to demonstrate the capability of the computer simulation program.