Toward an Understanding and Prediction of Air Flow in Buildings

by

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Abstract

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This thesis makes two fundamental arguments in the analysis of air flow in buildings:

- buildings are complex three dimensional air flow networks driven by complex air pressure relationships; and
- the key to understanding air flow in buildings is the building air pressure field.

Under standard building analysis, interstitial air flow and interstitial air pressure fields are not often considered and exterior and interior walls, floors, and roof assemblies are either considered as monolithic or having openings resulting in flow across the specific assemblies. Buildings comprise multi-layer envelope assemblies with numerous air gaps or void spaces that are often connected to service chases. As a result, complex three dimensional flow paths and intricate air pressure relationships must be considered.

The standard approaches to analysis concentrate on difficult or impossible to measure parameters – air flows and component leakage areas. This typically results in large inaccuracies in the prediction of building performance. This thesis shows that the building air pressure field is readily measurable, the building air flow field is not. This thesis argues that the building air flow field should be developed from the building air pressure field – not the other way around as in standard building analysis.

By developing the flow field, the leakage areas and the flow relationships from the measured building pressure field, interstitial air pressure fields and resulting interstitial air flows are accounted for. In addition, this approach provides a powerful diagnostic tool for identifying many of the problems related to direct and indirect effects of air flows.

The measured building air pressure field can be used with network analysis to solve the building flow and leakage regime as an alternative to using estimated or measured leakage areas and measured air flows to solve the building air pressure and flow regime. This inverse method of using pressures as inputs rather than leakage areas is calibrated by perturbing both the building and analytical model. The perturbation results in a pressure response unique to the building. This pressure response is used to apportion flows and leakage areas in the network analytical model thereby increasing the accuracy and the range of applicability of the model.

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Nomenclature

A = area (m^2)
A_E = leakage area across exterior of wall assembly (m^2)
A_I = leakage area across interior of wall assembly (m^2)
A_κ = leakage area of known magnitude (m^2)
A_{ij} = leakage area (m^2)
A_l = air leakage area (m^2)
A_w = wall or floor area (m^2)
C = leakage coefficient
C_D = discharge coefficient
C_E = discharge coefficient for exterior of wall assembly
C_I = discharge coefficient for interior of wall assembly
C_k = flow coefficient
C_M = material constant
C_o = fluid resistance coefficient
k = coefficient
n = flow exponent
P = static pressure (Pa)
ΔP = pressure difference (Pa)
ΔP_E = pressure difference across exterior of wall assembly (Pa)
ΔP_I = pressure difference across interior of wall assembly (Pa)
P_t = total pressure (Pa)
P_v = velocity pressure (Pa)
ΔP_{ij} = pressure difference (Pa)
Q = flow rate (L/s)
R_n = leakage area – electrical analogue
R_i^n = pressure ratio
V_{ij} = pressure difference – electrical analogue
x = direction of flow

Greek

β = exponent in leakage function
$\overline{\mu}$ = mean velocity (m/s)
ρ = density of air (kg/m^3)

Outline of Thesis

The introductory chapter presents the context of the work to the field of building physics. This section provides a summary of the entire thesis. It is followed by a discussion on the basis of the thesis research. This section outlines the complexity of modern building assemblies and the resulting three dimensional air flow pathways and an introduction to interstitial air pressure fields.

Chapter II – Air Flow in Buildings contains a critical review of the literature and places it in the context of complex three dimensional air flow networks. The chapter ends in outlining the problem statement. The problem statement sets the stage for the rest of the thesis by arguing the need for alternative analysis approaches.

Chapter III – Air Pressure in Buildings defines the building air pressure field and through the use of examples illustrates the dynamic interaction of the component air pressure fields. HVAC system effects are presented leading to the development of a relational air pressure field model for buildings. The concept of applying the relational model and pressure measurements to existing analytical models in order to tune or calibrate them is introduced.

Chapter IV – Air Pressure Response provides a discussion on the techniques of measuring building air pressure fields and presents experimental work supporting the inverse method of using pressures as inputs rather than leakage areas with existing building analytical models. The experimental work involves a recently constructed detached single family residence and a 25 year old school facility. The chapter ends with a discussion of boundary conditions for the analytical models and the range of applicability of the models.

Chapter V – Practical Applications of the Work presents five case studies illustrating the impact of the work on indoor air quality, smoke and fire spread, durability (moisture), comfort and operating cost (energy).

Chapter VI – Conclusions summarizes the work in the context of air pressure control, design, diagnostics and analysis. Future research is also discussed.

I Introduction

Context of the Work to Building Physics

Air flow in buildings is a complex flow and pressure distribution problem that makes quantification difficult. However, certain parameters have recently become easy to quantify - specifically the air pressure relationships within buildings. These air pressure relationships can be used to develop relational models of the building or portion of the building system under analysis. From these relational models existing analytical models can be "tuned" or calibrated. The sensitivity and complexity of the analytical models are determined by the nature of the problem being studied. For example, the degree of precision can be made to vary between scientific research and engineering practice.

The measured building air pressure field can be used with network analysis to solve the building flow and leakage regime creating an analytical macro model of the building flow and leakage regime. The response of the analytical model can be further tuned by perturbing both the building air pressure field and the analytical model. However, network analysis and perturbation cannot be used to solve the interstitial flow, pressure and leakage regime. Network analysis and perturbation may suggest that such flows exist, but the complexity and workmanship dependence of the interstitial flow, pressure and leakage regime requires direct measurement. In other words, at present, the boundary conditions of the interstitial regime can be defined analytically using the methods outlined in this thesis (the boundary conditions being the building flow, pressure and leakage regime), but the pressures and flows within the interstitial spaces cannot be predicted with certainty using analytical means.

Analytical micro models of interstitial assemblies can be developed and tuned or calibrated by direct field measurements of interstitial air pressures and flows. The micro models can be expanded or incorporated into analytical macro models that address the entire building flow and leakage regime. The effect of the micro flows or interstitial regime on the general building regime can be modeled. In other words it is possible to go from the small to the large analytically. However, it does not appear to be possible to go in the other direction. It does not appear to be possible to generalize the interstitial regimes. They are often purely a local phenomena.

The macro and micro models can both be used in parametric studies to determine the relative significance of a particular factor. Both can be used to determine the effects of flows and pressures. However, both types of models are limited in the extent of their analysis as described above.

Design and diagnostic techniques can be used to avoid problems or to understand problems within the limits of the analysis approach. Design, through an understanding of the relational models, can be used to eliminate, control and understand the development and effects of interstitial air pressure fields and flows. If interstitial air pressure fields are eliminated or conversely deliberately created, expending effort predicting their presence or magnitude becomes unnecessary. In other words, the issue can be designed away. With respect to diagnostics, the interstitial air pressure fields can be measured directly. If they are measured directly predicting their presence or magnitude becomes unnecessary. The key to building design and building analysis is knowing what the critical design issues are or what critical parameters need to be measured.

The current design, construction and analysis process addressing air flow in buildings is largely based on tradition and past experience. Hutcheon (1971) observed: "Tradition has a great weakness in that it deals only with a way of doing something, without any contribution to understanding of why the traditional method works. This being so, it is usually not possible to identify the important factors either in the situation being served or in the arrangement of the solution provided." Hutcheon (1971) concluded: “Rational design is possible only when there is a capability to establish, each time a choice is made, the probability of a particular result." Hutcheon was pointing out the necessity of reducing uncertainty in building performance — the need to establish the probable consequences of design decisions on building performance.

The focus of this thesis is on the predictability and quantification of air flows, air pressures and leakage relationships in buildings.

Basis of Research

The understanding of air flow through and within buildings has assumed that wind forces, thermal effects (stack action), and air movement associated with mechanical cooling, heating and exhaust and other ventilation systems are the dominant factors relating to air pressure relationships and air pressure related building performance.

In principle, this view is correct, though often too basic. Under this view, the wall assemblies, roof assemblies, interior floors and demising walls/partitions are treated either as monolithic or having through-the-assembly openings. Air flow has been assumed to occur across these assemblies, from one side to the other based on the air pressure difference across them, typically through simple leakage areas resulting in one dimensional air flow.

Actually, exterior wall, roof, interior floor and interior wall/partition assemblies are often hollow or multi-layered with numerous air gaps or void spaces and can operate under air pressure regimes (fields) that are largely independent of the air pressures on either side of them. Buildings also contain numerous service chases that provide complex three dimensional linkage among the exterior wall, roof, interior floor and interior wall/partition assembly cavities and void spaces. These interstitial air pressure fields within building assemblies and their linkage to chases and service cavities can lead to lateral flow paths or more intricate three dimensional flow paths that may or may not connect to the interior or exterior spaces that the building assemblies separate.

As a result of these interstitial air pressure fields, direct cross assembly (one-dimensional) air flow does not always hold. To account for the presence of interstitial air pressure fields air flow must be added or subtracted within an assembly, chase or void space. In this manner, continuity of mass and momentum holds across the volume of the assembly or element.

The interstitial air pressure fields often vary with time with complex daily, weekly, seasonal and sometimes random cycles. They are often, but not always, driven by fan forces coupled with duct leakage. Thermal effects, moisture effects and wind forces can also be interstitial air pressure field drivers depending on the linkages of interstitial flow paths. These time variable interstitial air pressure fields help characterize the dynamic characteristics of the pressure response of buildings.

The presence of complex, time dependent interstitial air pressure fields and associated lateral or three dimensional flow paths can lead to complex interactions of the building structure with the mechanical system and climate.

One of the keys to understanding the complex interactions of the building structure with the mechanical system and climate is the pressure response of buildings. Building analysis typically focuses on flows and requires that all flow paths into and out of a control volume be defined. The flow path resistances need to be characterized. Determining all air flow paths and determining the flow path resistances directly, is difficult. As such, estimates of these flow path resistance's are commonly used. These estimates are based on limited field data and laboratory measurements. The literature provides some component values that vary by orders of magnitude and their application is often unable to predict building flow fields (ASHRAE, 1997).

Standard building analysis develops the building pressure field from the flow field. This thesis shows that developing the flow field from the building pressure field is more powerful and permits accounting for interstitial air pressure fields and flows.

To this end this thesis changes the paradigm of analysis: developing the flow field, the leakage areas and the flow relationships from the building pressure field. Determining the characteristics of the building pressure field directly, is considerably easier than determining flow path resistances.

Pressures can be used to predict direction of flows and to develop a relational model. Knowing all the flow paths and their resistances is no longer necessary for most engineering practice. It provides a powerful diagnostic tool for solving many of the problems related to direct and indirect effects of air flows.

It also allows the closing of the gap between the mathematical sophistication of available multi-cell air flow models and the necessary input information defining the building boundary conditions. This approach allows the pressure response of the building to be used to "tune" or calibrate the models extending their range of applicability and accuracy.

II Air Flow in Buildings

Critical Review of the Literature

Controlling heat flow, air flow, moisture flow and solar and other radiation will control the interactions among the physical elements of the building, its occupants and the environment. Of these four, air flow "merits major consideration mainly because of its influence on heat and moisture flow" (Hutcheon, 1953). Air flow carries moisture that impacts a materials long-term performance (serviceability) and structural integrity (durability). Air flow also affects building behavior in a fire (spread of smoke and other toxic gases, supply of oxygen), indoor air quality (distribution of pollutants and location of microbial reservoirs) and thermal energy use. The focus of this thesis is air flow in buildings within this framework.

Historically speaking, the understanding of air flow in buildings may be illustrated with a series of geometric analogues. The geometric analogues presented progress from the simple to the more complex, from two dimensional to three dimensional, from solid to hollow, and from single elements to multiple elements. The geometric analogues are presented in conjunction with a corresponding more traditional visual analogue where appropriate (Figures 2.1 through 2.11).

Two and Three Dimensional Solid Analogues

The first set of figures involve solid two dimensional and three dimensional objects in a flow field (Figure 2.1 and Figure 2.2). They represent wind induced air flows around buildings.

Wind induced air flows around buildings have been studied extensively (Davenport, 1960; Dalgliesh & Schriever, 1962; Davenport & Isyumov, 1967; Davenport & Hui, 1982; Lin, Surry & Inculet, 1995) over the past four decades in Canada and elsewhere. The major focus of these studies has been wind induced structural loading, snow deposition and drift formation and determining the extent of driving forces for rain leakage under wind driven rain conditions. As a result, methods of determining peak wind loads and maximum rain intensity conditions are well developed and accessible to designers and practitioners.

Two and Three Dimensional Single Cell Analogues

The next set of figures involve hollow two dimensional and three dimensional objects (Figure 2.3 and Figure 2.4). These figures represent two different types of analysis. In the first type of analysis, buildings are placed in a flow field and internal wind induced pressures are developed from surface pressures and building envelope leakage areas. This approach is a logical extension of the study of solid two dimensional and three dimensional objects in a flow field. Wind induced internal pressures are commonly studied in this manner (Stathopoulos, Surry & Davenport, 1979; Dalgliesh, 1981).

In the second type of analysis, building envelope leakage areas are determined by inducing interior to exterior pressure differences under controlled supply or exhaust flow conditions and using the envelope leakage areas to develop air change relationships from stack effect, mechanical system and wind drivers. This type of analysis has been the focus of major international effort over the past 30 years and may be considered standard for air flow analysis of building envelopes.

This traditional air flow analysis based on the measurement of building envelope leakage areas relies on two basic flow relationships to describe resulting air flows: flow through orifices and flow through porous media. These relationships are sometimes referred to as “channel flow” and “diffuse flow” respectively (Lux & Brown, 1986). In the two extremes they are referred to as turbulent (flow dominated by inertial effects) and laminar (flow dominated by viscosity effects).

In channel flow and flow through orifices, Bernoulli’s equation is used to develop the basic flow relationship where the rate of flow is proportional to the square root of the pressure difference which is characteristic of turbulent flow (Currie, 1974):

$$Q = A\,C_D\,[\,{}^{2}/_{\rho}\,(\Delta p)\,]^{1/2} \qquad (2 - 1)$$

where
Q = flow rate
A = area
C_D = discharge coefficient
ρ = density of air
Δp = pressure difference

Darcy’s Law (equation 2 - 2) can be used to describe the basic flow relationship through porous media where the rate of flow of a fluid through a porous material is proportional to the pressure differential (Currie, 1974):

$$\bar{\mu} = -\,C_M\,\partial p / \partial x \qquad (2 - 2)$$

where
$\bar{\mu}$ = mean velocity
$\partial p / \partial x$ = pressure gradient
C_M = a material constant
x = direction of flow

The relationship between leakage and pressure in Darcy flow is linear, which is characteristic of laminar flow. Equation 2-2 can be expressed as a linear function of pressure difference (Isaacs & Mills, 1980):

$$Q = f(\Delta p) = k(\Delta p) \qquad (2 - 3)$$

where $k = C_k \rho / \mu$

and where
k = coefficient of permeability
C_k = flow coefficient
μ = viscosity
ρ = density

The value of k depends on the path through the material. It is determined experimentally as it is difficult to predict a value appropriate to a particular set of conditions.

Materials and assemblies are not often homogeneous and rarely exhibit uniform flow characteristics across them. Kronval (1980) and Bumbaru, Jutras and Patenaude (1988) argued that the mode of air flow through a material may be either laminar, turbulent or a combination of both and that the mode may change from laminar to turbulent at several locations within it. They also noted the further complexity of entrance and exit effects. However, they pointed out that the flow relationships could be approximated by a power function and be bounded by varying the exponent between 0.5 (Bernoulli or turbulent flow) and 1.0 (Darcy or laminar flow):

$$Q = C(\Delta p)^n \qquad (2 - 4)$$

where
Q = volume flow rate
C = leakage coefficient
Δp = pressure difference
n = an exponent varying between 0.5 and 1.0

Bumbaru et al. presented the relationships in equation 2-4 graphically in Figure 2.5.

The graphical representation in Figure 2-5 is in contrast with the more typical expression and representation of flow relationships through and within buildings referred to by Nylund (1980) as the basic leakage-pressure relationship (Figure 2.6). Rather than bounding the flows between two diverging flow regimes, Nylund shows a transition of flows from laminar to turbulent. Although Bumbaru et al. were concerned with the flow characteristics of individual materials and Nylund was concerned with the entire building envelope, Kronvall (1980) showed that both views are complimentary.

The complexity of the flow regime across the building assembly was addressed by Kronvall and others (Tamura & Wilson, 1964; Stricker, 1975) by experimentally determining total flows through or within a building at a range of externally imposed controlled pressure differentials and utilizing equation 2-4. Curve fitting was then used to determine the variation of the exponent over the range of pressures.

Nylund and Kronvall both noted that the field work on pressurization of houses yielded leakage curves whose shape varied from house to house but were all bounded by a parabolic curve on the one hand (n = 0.5) and a straight line on the other (n = 1.0). However, Kronvall warned against concluding that the extremes were either complete turbulent flows or complete laminar flows. He pointed out that entrance and exit pressure losses were also a function of the square of the velocity.

Sherman and Grimsrud and others extended this approach of the measurement of the flow-pressure-leakage area relationship to develop infiltration or air change models for energy analysis (Grimsrud, Sherman, Diamond, Condon & Rosenfeld, 1979; Sherman & Grimsrud, 1980; Persily & Linteris, 1983; Sherman, 1987). This extended approach proved to be attractive and useful for predicting long term average values for energy usage and infiltration on an order of magnitude basis in homes without forced air heating and cooling systems. Excellent agreement is reported between predicted and measured air flows for a recently developed single zone model (no interior rooms, doors, single story, no forced air heating or cooling systems) that considers wind, stack and flue effects (Walker and Wilson, 1998).

Unfortunately, the approach has been found to be unsuitable for homes with forced air heating and cooling systems as it does not permit accounting for the changes in interior air pressure regimes arising from duct leakage, interior door closure and the effect of interior partition and floor system compartmentalization (Timusk, 1983; Seskus & Rinella, 1983; Cummings & Tooley, 1988; Cummings & Tooley, 1989; Cummings, Tooley & Moyer, 1990). Significant work on incorporating duct leakage factors into the Sherman-Grimsrud model has recently been done, though with partial success (Palmiter & Bond, 1991; Palmiter, Brown & Bond, 1991; Palmiter, Bond & Sherman, 1991).

Two and Three Dimensional Multi-Cell Analogues

The work discussed to this point has remained focused on a view implied by Figure 2.3 and Figure 2.4. This view represents a single cell air flow model and analysis. The single cell approach can logically be extended to multi-cell analysis as shown in Figure 2.7 and Figure 2.8.

In multi-cell analysis calculations become tedious and complex and reliance on the computational power of computers is necessary. The air flow fields are solved by representing the building and its elements as an analogous electrical network and using an iterative process to calculate pressure differences and resulting flow rates across all of the assembly elements until a certain convergence criterion is met. This approach is the basis of development of multi-cell air flow models used in whole building air flow analysis (Tamura, 1969; Liddament & Allen, 1983; Klote, 1985; Axley & Grot, 1989; Walton, 1989; Walton, 1997; Feustel, 1998).

In multi-cell models used in the study of smoke movement or in determining the transport and dispersion of indoor air contaminants, buildings are represented by a network of spaces or nodes. Steady-state air flows and pressures throughout the building are calculated by solving the air flow network analog. The inputs are the stack effect, the mechanical system air flows and flow leakage areas. The outputs are air flows and pressures. Flows are considered linear functions of pressure difference (Darcy flow) to ease calculation and allow the use of matrix mathematics. A few multi-cell models such as CONTAM96 and COMIS use the power law relationship for flows and pressures. They can also be used to calculate wind induced pressures on building surfaces and their subsequent impact on the air flow network analogue (Walton, 1997; Feustel, 1998)

Feustel (1998) called for improved definition of the variables critical for different building types to develop more accurate input data and, ultimately more accurate models. He identified wind pressure coefficients as a critical factor that needed further study and data on building assembly leakage as another. This was in apparent response to the common divergence of results obtained from modeling compared to those obtained from field measurements.

Multi-cell models require the user to input detailed information relating to building construction assembly leakage. This information is difficult to establish. Flow leakage areas of large openings such as open doors, corridors and open windows can be measured and input accurately. However, leakage areas across interior and exterior wall, floor and roof assemblies are usually estimated in a crude manner. Component building flow leakage areas vary so significantly from building to building due to workmanship that generalizations may not be possible. The 1997 ASHRAE Fundamentals Handbook lists effective leakage areas of components that vary by orders of magnitude within individual categories (ASHRAE, 1997).

Measuring leakage areas is further complicated as they may change with time. There are seasonal effects due to thermal and moisture content induced dimensional changes. Luck & Nelson (1965) examined the variation of infiltration rate with relative humidity in frame buildings. There are also longer term effects as the building and components age. Some effects are gradual and caused by the building wear. Some effects can be abrupt such as where an element or component fails.

It is argued here that the level of detailed input information relating to building construction assembly leakage that multi-cell models require is impossible to obtain with field measurements except for the most basic of building constructions. Fixing leakage areas in multi-cell modeling is presently an “art” based on the best guess of the modeler, rather than a “science” based on field measurement or observation.

The models also require the user to input detailed information describing mechanical systems in the building. Supply and exhaust flows from mechanical systems can be readily determined and input accurately. However, mechanical system characteristics may change with time. Filter resistance changes with time, filters clog, belts and fans wear.

In most models, mechanical system duct leakage is not considered. Even if existing models were modified to account for mechanical system duct leakage, reliable input data is difficult to obtain due to testing limitations imposed by lack of sensitivity and repeatability from pitot tube or hot-wire anemometer traverses and flow hood cumulative error (Lstiburek, 1993).

Thus, it can be argued here, that the difficulties in determining the detailed information relating to mechanical systems in buildings that multi-cell models require, is similar to the difficulties in obtaining building construction assembly leakage areas. Once again, “art” on behalf of the modeler is required.

Two Dimensional Multi-Layer and Multi-Cell Analogues

So far the geometric figures and their corresponding visual analogues have viewed building envelope and interior demising walls and floors as monolithic or homogenous entities with straight-through-the-assembly openings. Real buildings and their components are rarely constructed from homogenous assemblies. Most assemblies are constructed from different materials and often contain interstitial cavities. This leads to complex flow regimes across assemblies. The geometric figure and its corresponding visual analogue presented in Figure 2.9 are representative of such common multi-element, layered, hollow construction for walls, floors and roofs.

The multi-layered complexity of building assemblies was recognized by Nylund (1966) who described the total flow through a building, within a building or through an assembly as a complex combination of Darcy and Bernoulli flows in series and parallel flow combinations. He further postulated that the combination of flows through a building can be modeled by a resistance network of series and parallel flows (Figure 2.10). Nylund (1980) proposed a graphical solution based on a knowledge of the flow-pressure drops characteristic of each component. In Nylund's graphical solution, the pressures or driving forces were first summed and the flows then calculated to take into account the non-linearity of the leakage flows as a function of pressure difference.

Nylund's graphical solution was extended to complex networks describing building assemblies using numerical methods based on analogous work in electrical circuits and electrical admittance (Kronvall, 1980). Kronvall defined air admittance as the inverse of the resistance to air flow of a material or assembly.

Kronvall explored flow paths and flow regimes present in building assemblies and described them as a complicated network of flows through small openings, flows in ducts or interstices and flows in permeable materials.

Kronvall was also concerned with the conditions of transition between laminar and turbulent flow and their dependence on the surface roughness properties of the assembly components. Kronvall (1980) pointed out the lack of tabulated surface roughness factors in the literature (except for flow in ducts and pipes) and subsequently experimentally determined the surface roughness factors for different building materials.

Bumbaru et al. (1988) tested 36 different materials determining air permeance using a method similar to the one developed by Bomberg and Kumaran (1985). They defined the resistance to air flow provided by a material as the reciprocal of the air permeance making air permeance analogous to Kronvall's air admittance. They found the air permeance varied for individual material samples as much as 30 to 50 percent from the average permeance due to the inhomogeneity of the materials tested. However, applying equation 2-4 and curve fitting, they found that the exponent varied between 0.95 to 1.0 and concluded that the flows through the materials were mostly laminar. Based on the laminar flow characteristics of the materials tested, they proposed that air permeance values could be predicted for composite materials using simple series or parallel air flow calculations analogous to simple series or parallel heat gain and heat loss calculations.

Unlike the work by Bumbaru et al. (1988) that provides experimentally determined air permeance values for various building materials, Kronvall (1980) did not publish experimentally determined air permeance/admittance values validating his network based numerical methods solutions to full building assemblies, although the approach appears computationally sound.

Lawton & Quirouette (1991) experimentally determined the air permeance values of critical building assembly details in residential wood frame construction constructed using three different construction methods. Twelve different assemblies were tested. No attempt at comparing the experimentally determined air permeance values with a predictive computational model such as the Kronvall model was made.

The necessity of predetermining all the flow paths and the difficulty in providing all the input values relating to material flow characteristics severely limits the use of such network based numerical air flow models for building assemblies as in the multi-cell models. Where building assemblies are concerned, most researchers are finding it easier to build full scale assemblies and test them empirically rather than attempt to model them numerically.

The graphical, numerical and multi-cell methods for both assemblies and entire buildings considered to this point are based on a "flow-through" mass balance and an assumption that the air pressure profile and flows into and through the building are dependent only on the pressure difference across an assembly. This view holds that pressure differences in and around buildings are caused by wind, air density differences due to temperature differences between the interior and exterior (stack effect), the operation of air consuming devices such as chimneys, and forced-air thermal distribution systems (Wilson, 1961).

Additionally, this view holds that the pressure difference at a location depends on the magnitude of these driving mechanisms as well as the characteristics of the openings in the building envelope (ASHRAE, 1997).

Recent field work only partly supports this view. Work on validation of multi-cell, network based models has been proceeding with limited success. The most promising results pertain to network smoke control models. Recent tests (Said, 1991) in an experimental 10-story fire tower at the National Fire Laboratory of the National Research Council of Canada show good agreement between measured data and predicted data. However, the air pressure drivers occurring under fire conditions are one to two orders of magnitude greater than the air pressure drivers existing under typical operating conditions and it can be argued that extrapolation of fire test results to normal operating air pressure conditions may not be possible. A further limitation of the results arises when the homogeneous nature of the wall and floor assemblies (concrete) that comprise the test fire tower is considered coupled with the lack of service chases, mechanical systems and associated ductwork.

A recent survey of airflow models for multi-zone structures (Feustel & Dieris, 1992) revealed the existence of over 50 multi-zone air flow models. Feustel & Dieris pointed out that although the mathematical sophistication of the various models was impressive, significant work was required on validation of the models under normal operating conditions and recommended the construction of test buildings in which model input parameters could be varied in a controlled manner.

The previous argument relating to the inability to accurately specify building construction assembly leakage and mechanical system leakage for use in multi-cell modeling, is extended here to a more general argument that the sophistication of the air flow models for multi-zone structures far exceeds the sophistication (accuracy) of the inputs or boundary conditions necessary to run the models.

All of the models use similar flow equations for crack flow and are based on the assumption of flow-through mass balance or straight-through the assembly air flow. However, the assumption of flow-through mass balance can be argued by adding or subtracting air flows to the network at intermediate locations such as building interstitial cavities.

Field work indicates air flows into and out of interstitial cavities caused by the leakage of mechanical systems can significantly affect air pressures and building performance questioning the assumption of flow-through mass balance (Harrje, Gadsby & Cromer, 1986; Nelson et al. 1986; Tooley & Moyer, 1988; Lstiburek, 1989; Lstiburek, 1992; Lstiburek, 1993).

Adding or subtracting air flows to the network at intermediate locations can occur with leakage of supply or return systems into or out of interstitial cavities. Supply duct leakage adds air to interstitial cavities leading to pressurization effects. Return duct leakage subtracts air from interstitial cavities leading to depressurization effects. Nelson observed pressurization of floor cavities from supply duct leakage in his infra-red thermography studies of Minnesota houses (Nelson, 1982). Depressurization of floor cavities in houses was reported by Harrje, Gadsby & Cromer due to return system leakage where building cavities such as floor joists (panned floor joists) or stud bays were used as returns (Harrje, Gadsby & Crommer, 1986).

Air flow patterns other than straight-through an assembly air flow have been known to significantly affect building performance. Timusk et al. (1988) examined lateral air flow or “wind washing” and its cooling effect on wood frame building enclosures. In this type of air flow, air enters an assembly interstitial cavity from the exterior driven by wind effects, flows laterally within the assembly and then exits the assembly, often to the exterior. The effect is most pronounced at exterior corners and at soffit assemblies where exterior walls intersect insulated roofs/ceilings.

Burnett & Straube (1995) showed that air flow in the plane of the wall within the interstitial air cavities created by the construction of veneer or screened wall systems significantly affects the moisture performance of the entire assembly. Burnett & Straube identified not only wind effects as drivers for this air flow, but also identified thermal effects and moisture buoyancy effects as air pressure drivers.

Average wind pressures on buildings have been shown to be low (Robinson & Baker, 1975; Burnett & Straube, 1995) and are often of little interest to structural engineers who have been concerned with the wind induced air flow research. Although peak wind loading is a critical design component, as is maximum rain intensity, these values are not representative of typical service life conditions and are usually not relevant for predicting long term performance as it relates to durability and serviceability.

Burnett & Straube (1995) contend that average wind pressures on low rise buildings can be expected to be on the order of 1 Pa with a typical range of 0.1 to 10 Pa. They further concluded that temperature and moisture buoyancy effects, due to their effect on the density of air, can be as significant as wind as drivers for air flow within screened exterior wall cavities and indicated that combined driving pressures within vented cavities (wind, temperature and moisture buoyancy) can be expected to be in the 0.5 to 2 Pa range.

The work by Burnett & Straube implies that small air pressure differences that act for extended periods of time can have a major impact on building performance. Extending the argument further, many of the previously ignored, or not studied, or not considered factors that can produce air pressure effects in the 0.5 to 2 Pa range therefore may have a significant effect on building performance.

As previously stated, a pressure difference across an assembly alone, where interstitial pressures are not considered, is not enough to describe building performance. The interstitial air pressures are usually small and until recently have been beyond measurement. As a result they have not attracted much interest in the research community.

Three Dimensional Multi-Layer and Multi-Cell Analogues

Considering interstitial pressures requires a more complex view that considers three dimensional flow paths and time dependent pressure drivers associated with mechanical systems, wind, stack effects and moisture buoyancy effects even as small as 0.1 to 5 Pa. Figure 2.11 represents this more complex view, extending the view illustrated in Figure 2.8 and Figure 2.9.

Quirouette (1996), in his proposed cavity excitation method of testing rainscreen wall and window systems, recognizes this more complex view. The cavity excitation method determines the leakage characteristics of the pressure equalization chamber and relates them to the volume of the chamber, the vent area and the stiffness of the air barrier system.

When service chases, interior and exterior soffits, complex architectural features and non-simplistic massing are also considered, Figure 2.11 expands into the analogue illustrated in Figure 2.12 where cell connections and interstitial cavity connections are no longer contiguous. Individual cells are often connected to other cells and interstitial cavities, n-cells distant in a manner best described as a three dimensional “snakes & ladders” game with air pressure differentials playing the role of the dice.

Due to the complexity of modern buildings as described in Figure 2.12, air flows in buildings, except within mechanical systems, are difficult to measure. Component leakage areas for building assemblies and for mechanical systems are somewhat easier to measure than air flows, but the limitations of the measurement procedures and the complexity of modern buildings make them impractical to measure except for the most basic of building constructions. However, current technology permits measuring even minute air pressure differences easily.

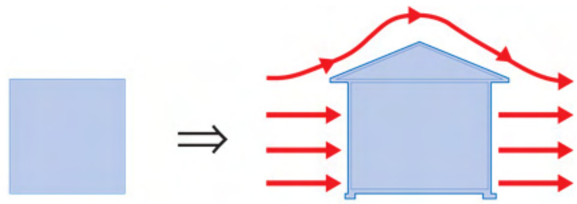


Figure 2.1
Two Dimensional Solid Analogue

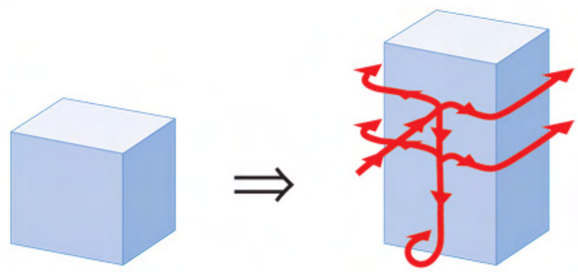


Figure 2.2
Three Dimensional Solid Analogue

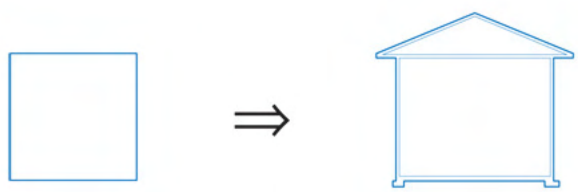


Figure 2.3
Two Dimensional Single Cell Analogue

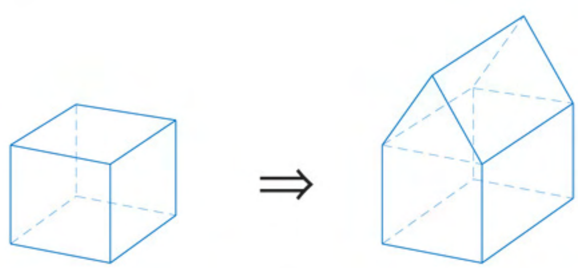


Figure 2.4
Three Dimensional Single Cell Analogue

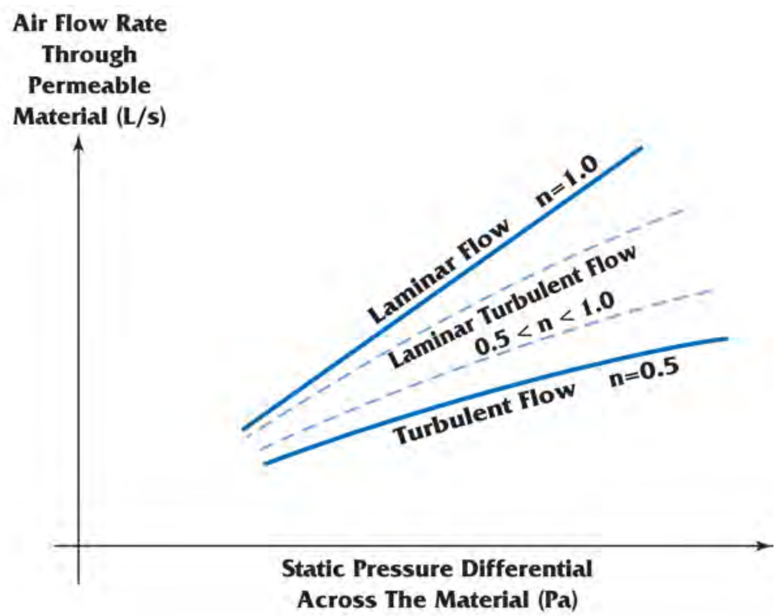


Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)

Q = f (Dp) » k (Dp)^b

Q = air flow, volume/unit of time
D**p** = pressure difference
k = coefficient
b = exponent in approximate leakage function

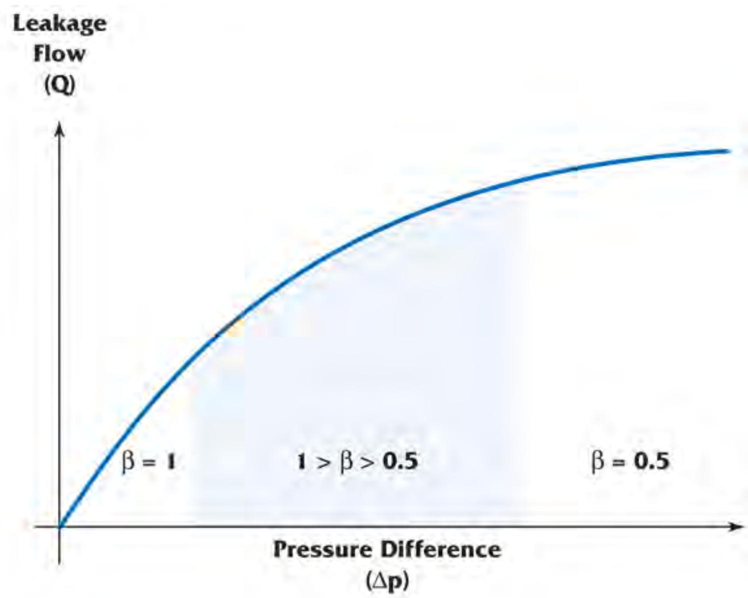


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

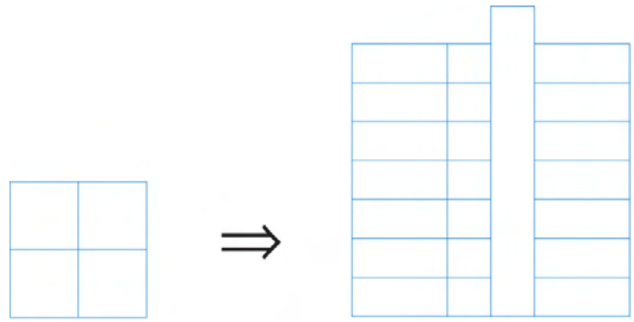


Figure 2.7
Two Dimensional Multi-Cell Analogue

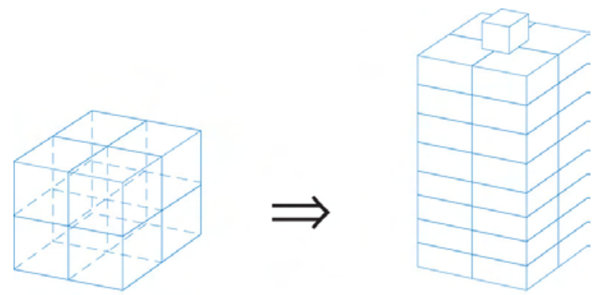


Figure 2.8
Three Dimensional Multi-Cell Analogue

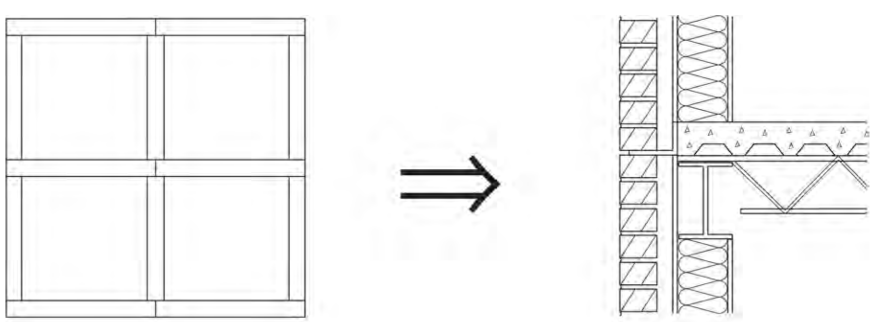
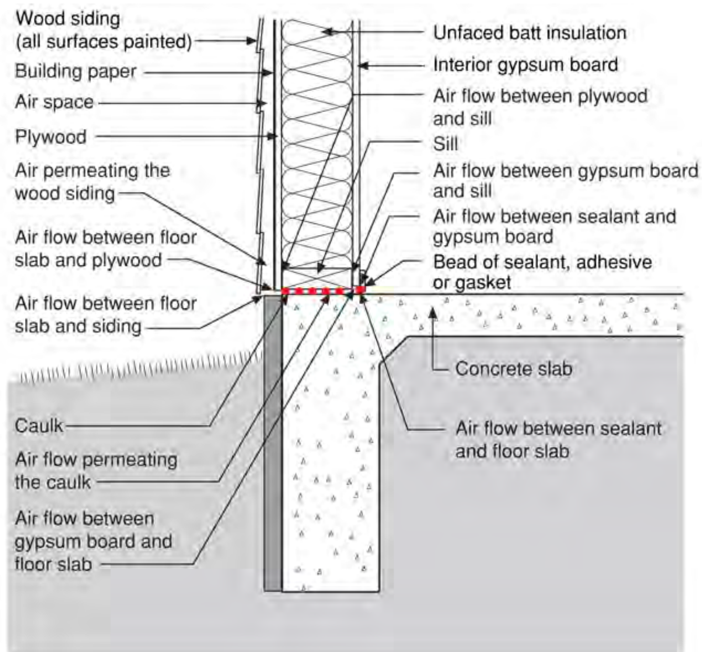
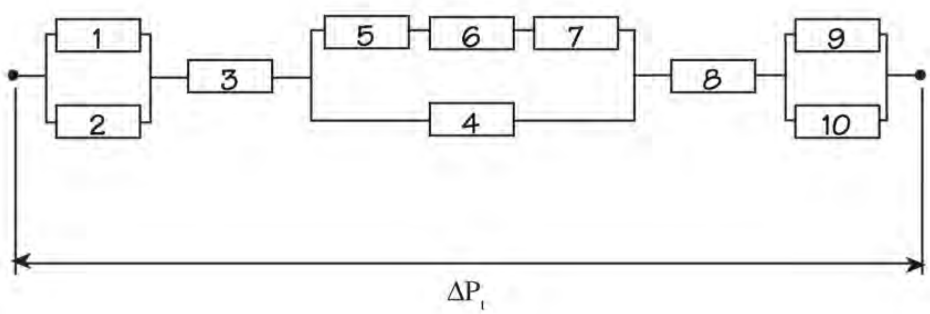


Figure 2.9
Two Dimensional Multi-Layer Multi-Cell Analogue



Possible air flows around sill of a wood-framed house modelled as a resistance network



1. Air permeating the wood-panel cladding
2. Air flow between floor slab and panel
3. Air flow between floor slab and wind protection
4. Air permeating the caulking
5. Air flow between wind protection and sill
6. Air flow bewteen insulation material and sill
7. Air flow between inner lining and sill
8. Air flow between inner lining and floor slab
9. Air flow between fillet and inner lining
10. Air flow between fillet and floor slab

Figure 2.10
Resistance Network
(from Kronvall, 1980)

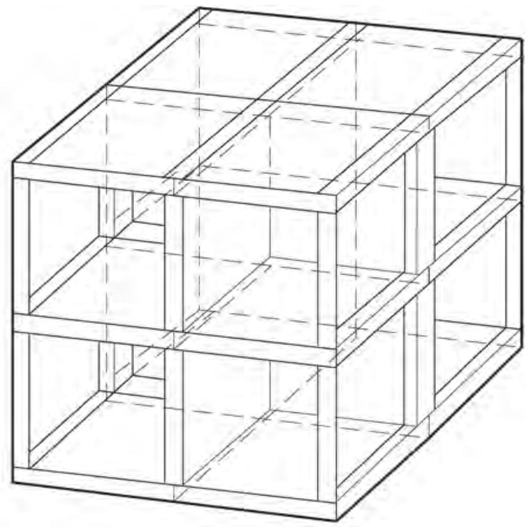


Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue

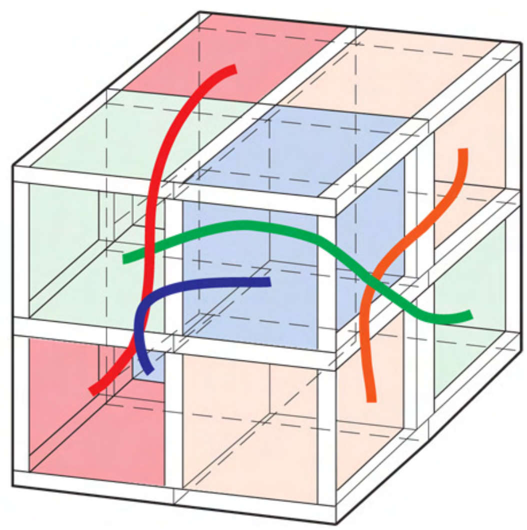


Figure 2.12
Three Dimensional Multi-Layer Multi-Cell Non-Contiguous Analogue

Problem Statement

It is argued that real buildings are multi-layer building envelope assemblies with numerous void spaces connected to service chases that result in complex three dimensional flow paths that are often not contiguous. These flow paths are affected by mechanical system leakage characteristics and operation not just by thermal effects, wind factors, and mechanical system flows.

It is further argued that the existing analytical models used in building analysis are limited in their application and their accuracy due to the level of detailed input information relating to building construction assembly leakage and mechanical systems. The sophistication of the air flow models for multi-zone buildings exceed the sophistication (accuracy) of the boundary conditions necessary to run the models.

In order to address these issues an alternative approach is necessary. This alternative approach still relies on existing analytical models, but uses them in an innovative manner. First relational models of air flow in buildings need to be developed that recognize the complexity of modern buildings. Second, current analytical models need to recognize the limitations of the available information describing buildings and building assemblies or they need to be modified to rely on new information that can readily be obtained within the limits of available technology. Third, limits need to be established on the range of applicability of both the relational models and analytic models.

It is believed that the key to addressing these issues is more completely understanding the air pressure relationships in buildings. Recent advances in technology have made measuring even minute air pressure relationships within buildings practical, low cost and widely available. The applications and implications of these advances in technology will now be addressed.

III Air Pressure in Buildings

Building Air Pressure Field

The building air pressure field (static plus dynamic) - the total air pressure regime within and surrounding the building - involves four contributing air pressure fields:

- exterior field
- interior field
- interstitial field
- air conveyance system field

The exterior field extends from infinity to the exterior skin of the building envelope. The remaining three component fields are inward of the exterior skin of the building envelope except in the special case of ductwork associated with the air conveyance system field that is located to the building exterior.

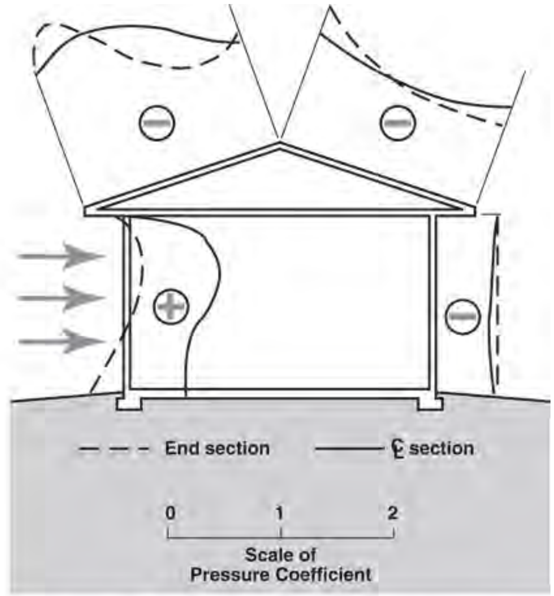
When considering the exterior field, the boundary layer at the building envelope surface is of primary significance in building analysis. The above grade portion of the exterior field is often dominated by wind induced flows (Figure 3.1). The below grade portion of the exterior field is a function of the soil characteristics (air porosity), the footprint of the building, the interaction with the building and time dependent atmospheric pressures in the vicinity of the building (Figure 3.2).

The interior field occurs within spaces such as rooms, corridors, stairwells, and elevator shafts (Figure 3.3) and is dominated by the operation of air conveyance systems, the stack effect and wind. The interior field is bounded by the interstitial air pressure field except in the special case of monolithic, solid, non porous walls, floors and roofs.

The interstitial field occurs within a building cavity such as an exterior or interior wall assembly, roof assembly or floor assembly (Figure 3.4). The interstitial field is bounded by the exterior field and the interior field and is often dominated by the leakage of air conveyance systems and building leakage pathways.

The air conveyance system field occurs within the ductwork of forced-air thermal distribution systems, chimneys, air exhaust and air supply systems (Figure 3.5) and is dominated by the size and capacity of duct work, fans and blowers and temperature differentials. It is bounded by the other three pressure fields.

These air pressure fields are coupled and interact dynamically. The interstitial field provides linkage between the exterior field, the interior field and the air conveyance system field.



Distribution of pressures (+) and suctions (-) on a house with a low-sloped roof with wind perpendicular to eave

Figure 3.1
Exterior Air Pressure Field
(from Hutcheon & Handegord, 1983)

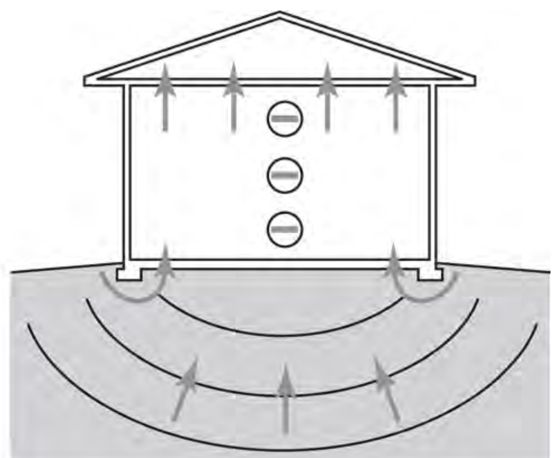


Figure 3.2
Exterior Air Pressure Field Extending Below Grade

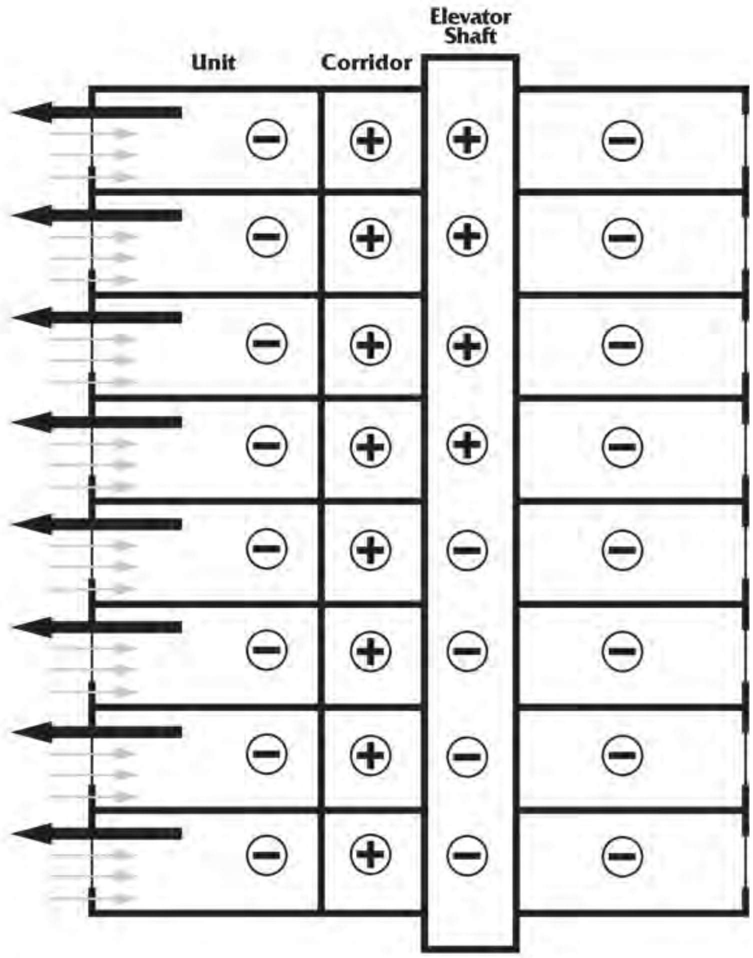


Figure 3.3
Interior Air Pressure Field

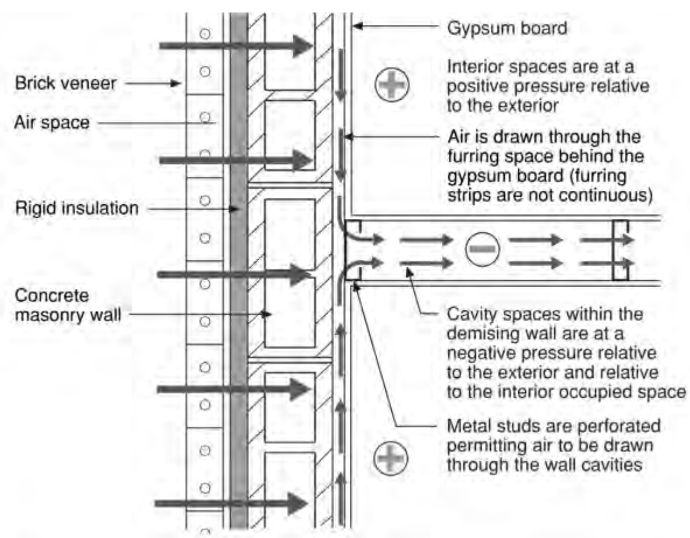


Figure 3.4
Interstitial Air Pressure Field

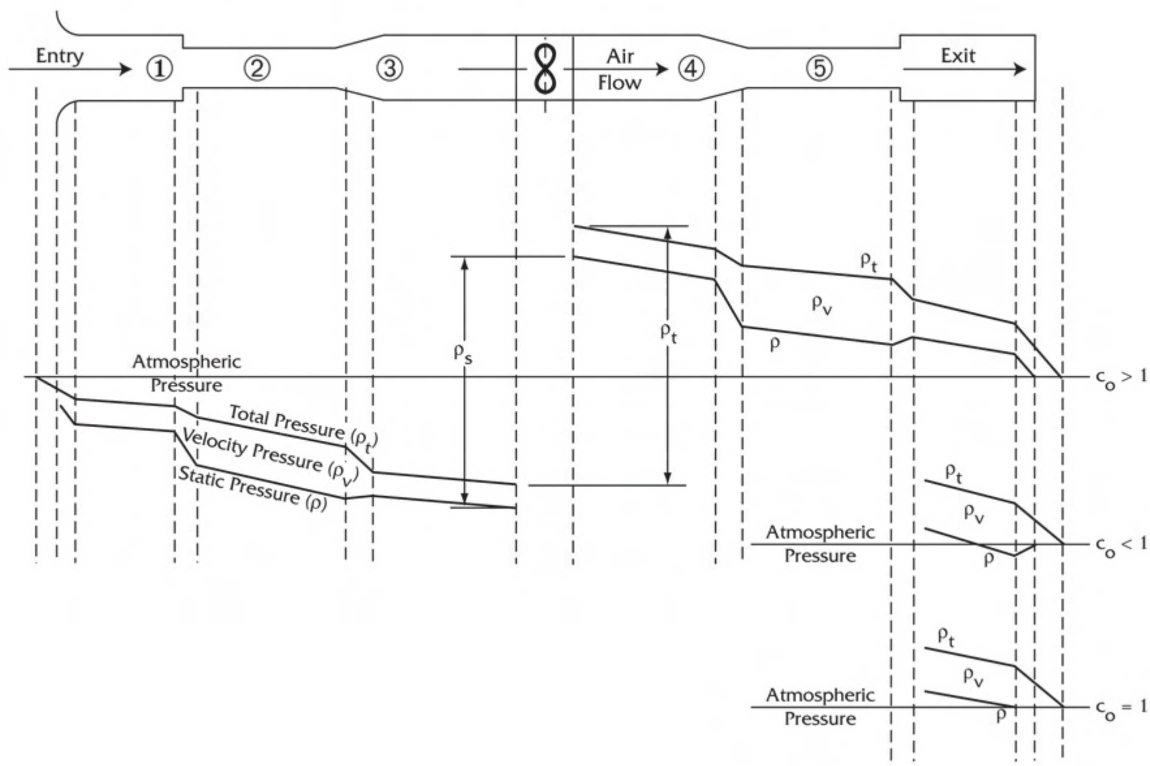


Figure 3.5
Air Conveyance System Air Pressure Field
(from Sauer & Howell, 1990)

Dynamic Interaction of Component Fields

A hotel room/bathroom suite with an exhaust grill, a fan coil unit, corridor make-up air and steel stud demising walls provides a good example of the dynamic interaction of the component fields and the limitations of standard analysis (Figure 3.6).

As is common in hotel construction, a fan coil unit is suspended from the ceiling and enclosed in a gypsum board dropped ceiling enclosure. The dropped ceiling enclosure is designed as a return air plenum. The fan coil unit provides heating and cooling to the hotel room by pulling air from the room through a return grill located at the underside of the dropped ceiling enclosure, conditioning the air, and returning the air through a supply register located in the face of the dropped ceiling enclosure. These units typically supply 1.75 to 2.5 kilowatts of heating and cooling and typically move approximately 100 to 150 L/s of air. Under conventional thinking, this fan coil unit only recirculates air and therefore does not affect the air pressure relationships in the room (Figure 3.7).

Additionally, an exhaust grill is located in the bathroom of each hotel room suite. This exhaust grill is connected to a central exhaust duct extending to a roof top exhaust fan. The roof top exhaust fan often serves several hotel room suites via the central exhaust duct. This exhaust fan often runs continuously, although in some facilities, timer controlled operation occurs. Air which is exhausted from the hotel room/bathroom suite by this exhaust fan is intended to be replaced with make-up air supplied from the corridor. The main HVAC system commonly supplies sufficient conditioned make-up air to the corridor to supply all of the hotel room suites served by the corridor. Make-up air from the corridor is intended to enter the hotel rooms by passing under the door between the room and the corridor. This door is undercut to provide passage of air from the corridor to the room (Figure 3.8).

Design Intent

The design intent usually calls for the hotel room to be pressurized relative to the exterior to control infiltrating hot, humid air during cooling periods, exclude exterior pollutants and minimize drafts during heating periods. Standard practice calls for supplying approximately 15 percent more air to a room than is exhausted to accomplish this. For example, if the exhaust flow out of the bathroom is 25 L/s, the design make-up air to be supplied to the hotel room/bathroom suite through the door undercut is approximately 29 L/s.

Typical Problem and Standard Analysis

Photograph 1 illustrates an increasingly common problem of mold contamination of demising wall assemblies associated with buildings constructed as described in Figure 3.6,

Figure 3.7 and Figure 3.8. In the photograph, the vinyl wall covering has been removed to reveal the extent of mold colonization. The investigation of such a problem is instigated by one or a combination of the following symptoms:

- the room smells;
- the humidity levels within the room are excessive;
- the vinyl wall covering becomes discolored with pink or maroon stains; or
- the gypsum board is soft and water logged.

Using standard analysis, an investigation of the moisture damage in an unoccupied hotel room as presented in Photograph 1 proceeds along the following path:

- The capacity of the fan-coil unit is checked to ensure that it is not oversized. Oversized fan-coils are known to have short duty-cycles. Short duty-cycles are incapable of removing significant quantities of air borne moisture. The fan-coil units are required to have sufficient latent capacity to remove moisture generated by occupants within the hotel rooms due to respiration and to remove moisture entering by vapor diffusion through the building envelope. In this particular example let us assume that the fan-coil unit has been sized correctly.
- The capacity and operation of the central exhaust system is checked against the capacity and operation of the roof-top make-up air unit. Exhaust flow rates are measured with a flow hood and compared to the supply air flow rate (make-up air) provided by the roof-top unit to the corridors. A pitot tube or hot wire anemometer is used to measure supply flow at the roof-top unit. Exhaust fan operation is usually inter-locked with the roof-top make-up air unit. This inter-lock is checked. The intent is to assure that more air is supplied by the roof top unit to the corridors than is exhausted out of the rooms by the central exhaust fans in order to avoid negative air pressures within the hotel rooms with respect to the exterior. This is desirable to control infiltration of exterior humid air and the associated latent load. In this particular example let us assume that positive pressurization is achieved within the hotel room by the operation of the roof-top unit while the central exhaust system is operating. This is verified with a smoke pencil at the exterior window and by summing the measured exhaust flows from the bathroom/suites served by the corridor and comparing this flow to the measured supply air flow to the corridor.
- The intent of the bathroom exhaust flow is to handle odors and moisture generated within the bathroom due to showers and bathing. A smoke

pencil shows that air is pulled into the bathroom under the bathroom door. The quantity of air extracted from the bathroom via the central exhaust system (as measured by a flow hood) is approximately 25 L/s. This matches the design intent and is known by experience to be able to handle normal bathroom moisture loads and odors.

- The relative humidity and temperature in the corridor are measured and recorded as follows: 55 percent relative humidity and 23 degrees C or a dew point temperature of approximately 14 degrees C. This matches the design intent for the roof top unit to supply "neutral temperature air at a neutral relative humidity".
- The exterior relative humidity and temperature are measured and recorded as follows: 60 percent relative humidity and 32 degrees C or a dew point temperature of approximately 24 degrees C. This is an expected condition for August in the location where the hotel is constructed.
- The relative humidity within the hotel room is measured as fluctuating between 65 percent and 75 percent relative humidity. The interior hotel room temperature varies between 23 degrees C and 27 degrees C. This corresponds to dew point temperatures of between 16 degrees C and 20 degrees C. The interior room air moisture levels are unexpectedly high and not explainable. The interior room air moisture levels should match the corridor moisture levels, especially if rooms are unoccupied. Recall that the rooms are at a positive air pressure with respect to the exterior so that infiltration of exterior moisture laden air is eliminated as a moisture source using standard analysis and that vapor diffusion from the exterior through the exterior wall is negligible.
- The possibility of rain water leakage through the building envelope is examined. The possibility of roof leakage is examined. Let us assume that no rain water leakage through wall or roof assemblies is occurring.

At this point the investigation and analysis typically breaks down. More often than not moisture of construction is assumed to be the culprit and the contractor is blamed for not covering the work during construction and preventing rain wetting of the materials. This argument is easily eroded if the hotel is more than a few years old and no explanation what-so-ever is provided.

Non Standard Analysis

Hotel building envelope and interior wall construction is usually steel studs with gypsum board (Figure 3.9). Steel studs are perforated with punched openings to facilitate installation of services. These perforations create a connected wall cavity in both interior and exterior walls. In exterior walls, fiberglass batt insulation is installed. As fiberglass batt insulation provides very small resistance to air flow, the connected wall cavity construction in both interior and exterior walls permits considering these walls as acting as air ducts.

Using non standard analysis, the investigation of the moisture damage in an unoccupied hotel room as presented in Photograph 1 proceeds along the following path:

- The air pressures within the demising walls relative to the exterior are measured with a manometer. Additionally, the air pressure within the room relative to the exterior is measured. The demising wall on one side of the room is measured to be operating under a varying negative air pressure with respect to the exterior between 1 Pa and 2 Pa. This pressure fluctuates based on the opening and closing of the bathroom door. The demising wall on the opposite side of the room varies between a positive air pressure of 1 Pa and a negative air pressure of 1 Pa to the exterior. This pressure fluctuates based on the duty cycle of the fan-coil. The room is measured to have a positive air pressure with respect to the exterior that varies between 1 Pa and 2 Pa based on the duty cycle of the fan-coil.

At this point the investigation is essentially complete. The interpretation of the results follow.

Air Pressure Driver 1: Fan Coil

In the example described in Figure 3.6 and Figure 3.7, the fan coil unit extracts air out of the dropped ceiling assembly because the dropped ceiling enclosure is designed to act as a return plenum. Resistance to air flow is provided by a filter in the return grill creating a negative pressure within the dropped ceiling enclosure relative to its surroundings. However, dropped ceiling enclosures are seldom air tight due to numerous penetrations for controls, power supply, and piping. Additionally, joints and seams in the materials forming the dropped ceiling enclosure are difficult to make airtight.

The dropped ceiling enclosure is connected to the demising wall via the penetrations for controls, power supply, piping and through openings reflective of the prevailing construction practice. The demising wall is further connected to the exterior wall. A negative air pressure field is created in the demising wall relative to the rooms on both sides due to its connection to the dropped ceiling plenum. This negative air pressure field extends to the exterior wall and may or may not be negative with respect to the exterior.

If this air pressure field within the demising wall is also negative with respect to the exterior, it leads to the infiltration of hot humid air during cooling periods and contaminants during other periods through the exterior wall assembly, down the demising wall to the dropped ceiling assembly (Figure 3.10). During cooling periods when this air is cooled due to the cooling of the hotel rooms on both sides of the demising wall, moisture is deposited in the wall cavities leading to mold and microbial contamination.

This negative air pressure field in the interstitial spaces exists only when the fan coil unit is operating and exists despite the positive air pressure in the hotel room created by the air flow from the corridor. This interstitial negative air pressure field is time dependent and is related to the duty cycle of the fan coil unit.

The demising wall acts as an outside air duct supplying outside air to the fan coil. This outside air supply tends to increase the positive air pressure in the room with respect to the exterior. This causes fluctuation in the positive pressure (with respect to the exterior) in the room in synchronization with the duty cycle of the fan-coil. It also leads to elevated levels of air borne moisture within the room.

Air Pressure Driver 2: Central Exhaust

In a similar manner to the fan coil unit induced interstitial demising wall depressurization, leakage of the central exhaust duct located within the plumbing service shaft also leads to the creation of a negative air pressure field relative to the rooms in the opposite demising wall that also extends to the exterior wall. This negative air pressure field exists only when the roof top exhaust fan operates and again exists despite the positive air pressure in the hotel room (Figure 3.11). When the bathroom door is closed, the flow path from the suite to the exhaust grill in the bathroom is interrupted creating a flow resistance resulting in more air to be extracted from the demising wall. This results in increased depressurization within the demising wall on a cycle matched to the opening and closing of the bathroom door.

The negative air pressure field due to the roof top exhaust fan (as modified by bathroom door closure) may or may not be negative with respect to the exterior. If it is negative with respect to the exterior, it will result in the infiltration of exterior air into the demising wall, similar to the fan coil unit example. However, it will not lead to an increase in the levels of air borne moisture within the room since the flow path of this infiltrating air is to the plumbing service shaft and subsequently out of the building via the roof top exhaust fan. This infiltrating air does not enter the rooms on either side of the demising wall.

However, moisture in the infiltrating air is deposited on the gypsum board surfaces enclosing the demising wall interstitial cavity. The deposited moisture migrates by diffusion to the vinyl wall covering/gypsum board interface. Little moisture diffuses through the vinyl wall covering and therefore the room air borne moisture levels are not affected. Unfortunately, the gypsum board and the vinyl wall covering both deteriorate due to the accumulated moisture.

Coupling of Air Pressure Fields

Figures 3.10 and 3.11 illustrate the coupling of the air conveyance system field with the interstitial field and the coupling of the interstitial field to both the exterior field and the interior fields. Standard analysis recognizes the coupling of the air conveyance system field to the exterior and interior fields. A typical example is that of exhaust fans pulling air from bathrooms and discharging it to the exterior. Standard analysis, however, does not recognize the interaction of the air conveyance system field with the interstitial field.

Standard analysis assumes a "flow-through" mass balance and an assumption that the air pressure profile and flows are dependent only on the total pressure difference between the exterior and interior air pressure field. This is clearly not the case in the examples in Figures 3.10 and 3.11 where air flow is extracted at an intermediate location (the demising wall cavity) due to leakage of the dropped ceiling plenum containing the fan coil and due to central exhaust duct leakage. The air extraction from the demising wall cavities leads to replacement air (make-up air) for the demising wall cavities drawn from the exterior as well as from the rooms on both sides of the demising walls.

Standard analysis would assume a positive air pressure with respect to the exterior exists within the demising walls of magnitude somewhere between the interior positive air pressure and the boundary layer air pressure. Time dependent negative air pressures within the demising walls relative to both the boundary layer air pressure and the interior air pressure are completely unexpected and unaccountable with standard analysis.

Photograph 1
Mold Contamination in Hotel Room

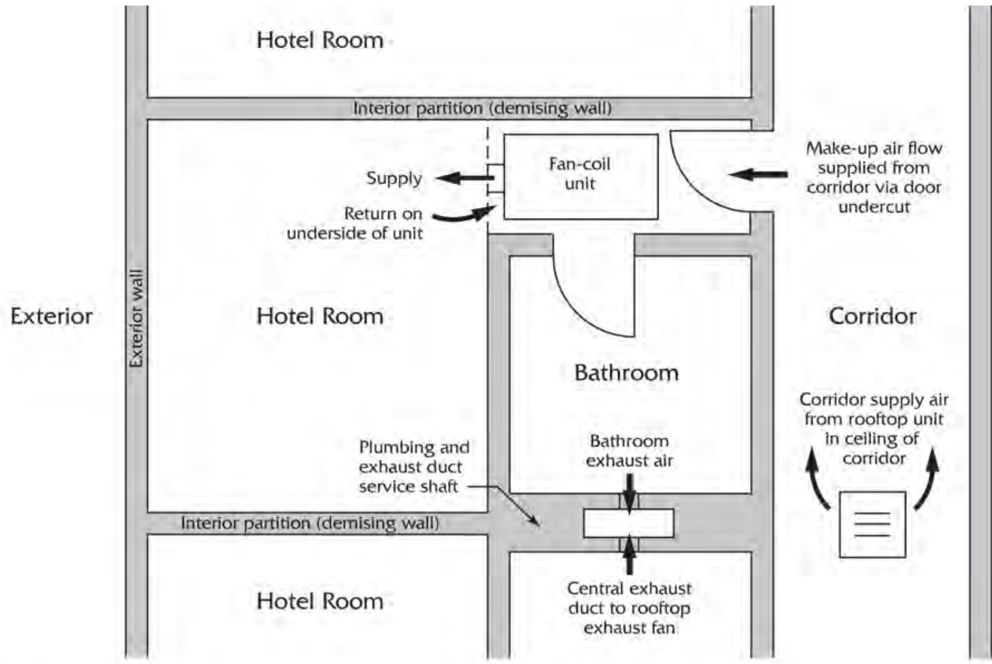


Figure 3.6
Hotel Room/Bath Suite
Plan View

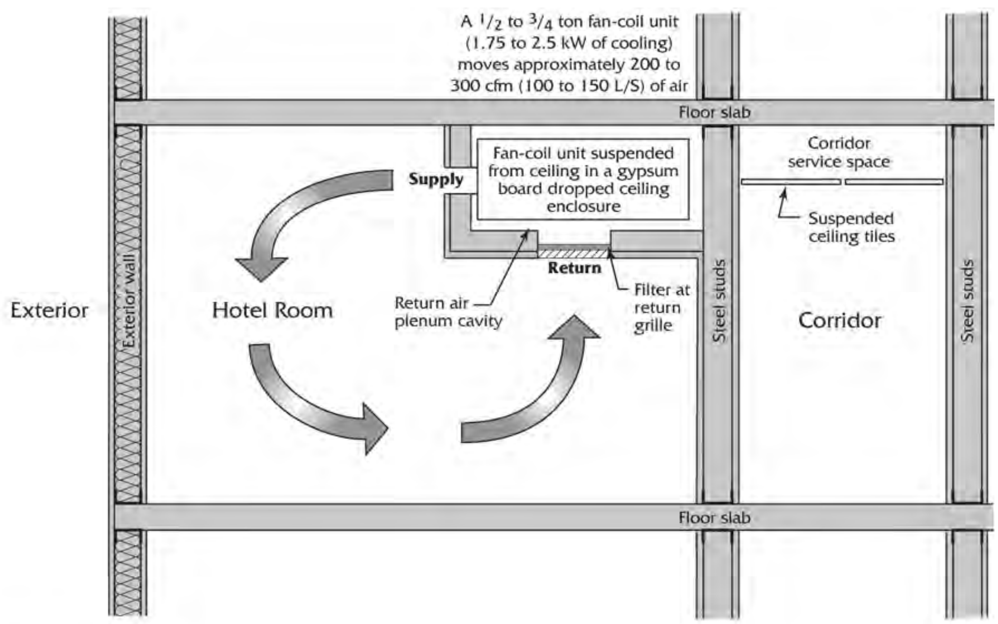


Figure 3.7
Hotel Room/Bath Suite
Section View

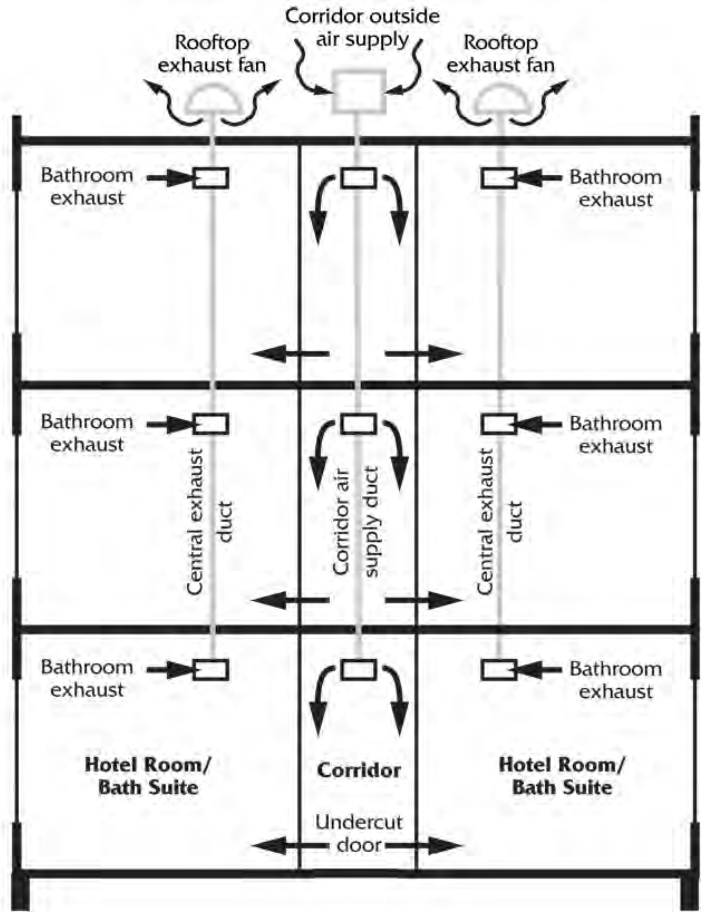


Figure 3.8
Hotel HVAC System
- Air exhausted from bathrooms via central rooftop exhaust fans
- Air supplied from corridors via undercut doors

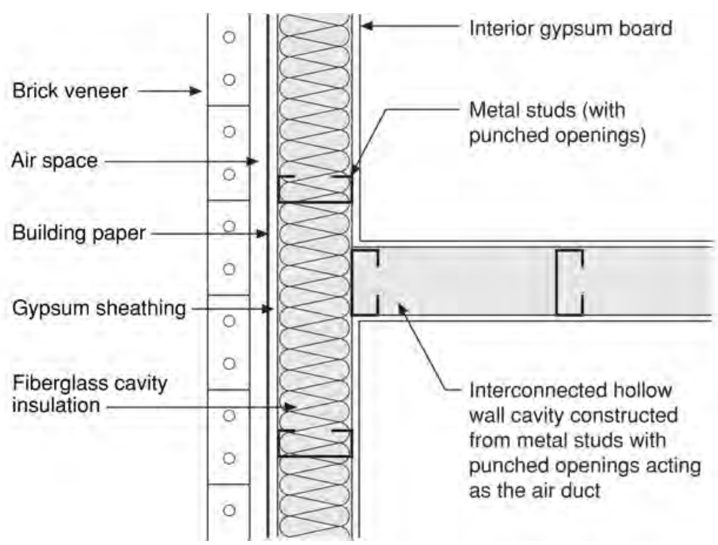


Figure 3.9
Wall Construction Plan View

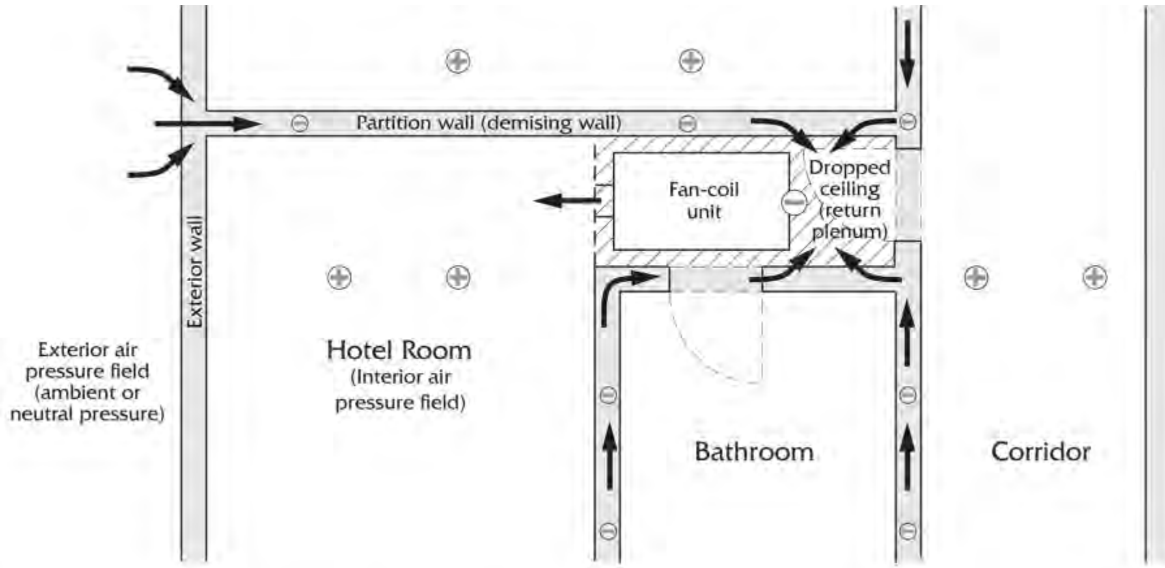


Figure 3.10
Pressure Field Due to Fan-Coil Unit
Plan View

- Room is at positive air pressure relative to exterior-driven air from corridor and air supplied to room from fan-coil unit pulling air from exterior through the demising wall
- Fan-coil unit depressurizes dropped ceiling assembly due to return plenum design
- Demising wall cavity pulled negative due to connection to dropped ceiling return plenum

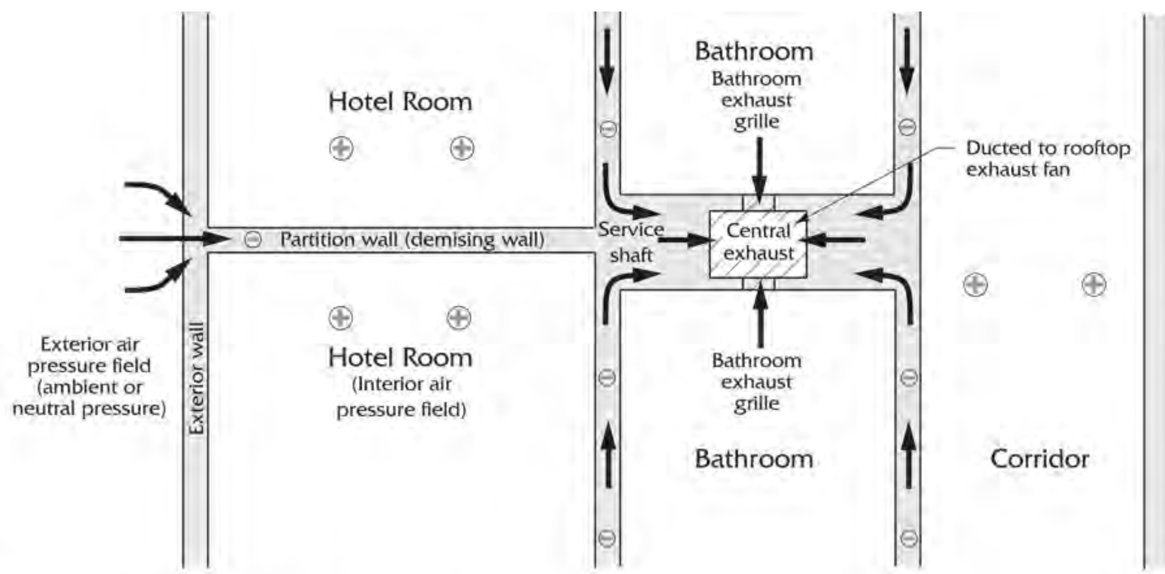


Figure 3.11
Pressure Field Due to Central Exhaust
Plan View

- Leakage of central exhaust duct pulls air out of service shaft depressurizing shaft and demising walls

HVAC System Effects

Under standard air flow analysis it is known that exhaust systems/fans tend to depressurize building enclosures inducing infiltration and supply systems/fans tend to pressurize building enclosures inducing exfiltration.

Also under standard building analysis (typical design assumptions), ducted distribution systems and air handling units in building enclosures have traditionally been thought to not alter interior air pressures. They have been viewed as interior circulation systems which move air from place to place within a building space having a neutral effect on the pressure differences between the interior and exterior of a building enclosure. However, ducted distribution systems (forced air heating and cooling systems) and air handling units often have significant impacts on pressure differences across building assemblies. This impact is primarily due to leakage of the systems and of the air handling units themselves. Imbalance between the supply and exhaust flows due to insufficient or inadequate return paths is also a contributing factor.

Residential Systems

A typical ducted, forced air heating or cooling system can be viewed as two systems: a supply duct system and a return duct system connected together through a fan located within an air handling unit. In buildings in heating climates most supply duct systems and air handling units (furnaces) are normally located in basement spaces (Figure 3.12) whereas in cooling climates most supply duct systems and air handling units (air conditioners) are located either in vented attics or in vented crawl spaces (Figure 3.13).

In buildings with basements, the supply system is usually a relatively "tight" system with supply ducts usually running to every room in the building. The return system is usually a relatively "leaky" system which often utilizes partition wall stud spaces, floor joist space cavities with sheet metal nailed to their lower surfaces and holes cut in floor sheathing with wood blocking as part of the "ducting". Furthermore, there is often only one or two common returns for the whole building. It is rare to find a return register in every room in which a supply register is also located. Even if return registers are matched to supply grills on a room-by-room basis, the return system is often so leaky that it draws only limited return air from the return registers.

A leaky return duct system can draw a significant amount of air from the surrounding air space. Figure 3.14 illustrates the example where much of the return air is drawn from the basement through the leaks in the return system leading to the depressurization of the basement area relative to the exterior and the main level (Timusk, 1983; Nelson et al., 1986; Tooley & Moyer, 1988).

In cooling climates where ductwork and air handlers are often located outside of conditioned spaces in attic spaces and vented, unconditioned, crawl spaces, leaky supply ducts tend to depressurize the conditioned space inducing the infiltration of exterior hot, humid air (Figure 3.15) often creating moisture problems and increasing cooling loads (Tooley & Moyer, 1988).

Leaky supply ducts located in crawl spaces also tend to do the same (Figure 3.16). Leaky return ducts located in attic spaces can also draw hot, humid air into the enclosure as well as leaky return ducts located in crawl spaces which can draw hot humid air, radon and pesticides into the enclosure. Where both leaky supply ducts are located in attics and leaky return ducts are located in crawl spaces, air pressures in the conditioned space may not be significantly effected (Figure 3.17). However, hot, humid air, radon and pesticides can be drawn into the enclosure from the crawl space increasing cooling loads, the probability of moisture related problems and risking occupant health, while cool conditioned air is dumped into the attic space reducing the efficiency of the cooling system.

In addition, in rooms where there is a supply register and no return register, such as bedrooms, pressurization occurs when doors are closed (Figure 3.18). This room pressurization can lead to common area (hallways, living room, etc.) and basement depressurization (Timusk, 1983).

In heating climates where depressurization of the basement space occurs, this can lead to the infiltration of "soil gas" and associated airborne moisture from the humidification of the infiltrating air by the humid ground. Furthermore, radon gas is also likely to be carried along with the moisture in the infiltrating air. Depressurization of the basement space can also lead to the spillage of products of combustion from water heaters and furnaces with standard chimneys.

In heating climates where pressurization of the above grade space (bedrooms) occurs, this can lead to the exfiltration of interior, possibly moisture laden, air. If this airborne moisture condenses within building assemblies it can lead to moisture related problems.

The process of inducing infiltration below grade and exfiltration above grade as a result of the pressure differences created by the forced air system in essence turns the forced air system into a ventilation system providing air change. Unfortunately this air change can lead to infiltration of moisture and radon below grade and the exfiltration of moisture above grade.

These elevated levels of air change as a result of the pressure effects of forced air systems can have significant impacts on energy consumption. Two buildings with identical levels of insulation and leakage openings in the same climate, but with one building with a forced air ducted system and the other building with a radiant system, will have significantly different levels of energy use. The building with the forced air system has much higher energy consumption levels due to the pressure effects of leaky ductwork.

A common example of an air pressure related moisture problem in a cooling climate is where a forced air cooling system air handler is located in a closet/utility room and a large unsealed opening exists between the supply ductwork which is located in the attic space and the ceiling of the closet/utility room where the supply ductwork penetrates the ceiling (Figure 3.19). Return air for the system is drawn from the hot, humid attic space into the utility room through the opening around the ductwork and into the return grill of the air handler. There are cases where the temperature of the building enclosure has actually gone up when the air conditioner/air handler was turned on in similar installations (Tooley & Moyer, 1988). The cooling load increase from the hot, humid air drawn from the attic into the system was actually greater than the capacity of the cooling system. Another serious consequence of leaky air handlers and leaky ductwork is the backdrafting of combustion appliances and possible flame roll-out (Figure 3.20).

One of the most common symptoms of the HVAC system induced air pressure differentials described is the soiling of carpeting. As air moves between rooms, into and out of interstitial cavities, across exterior wall assemblies and between above grade and below grade spaces it migrates under baseboards and under doors. Where carpeting is also present, this moving air is “filtered” by the porous carpet fibers at leaving telltale dark marks at baseboards, under doors and at stair treads. The effect is significantly enhanced where airborne particulates are found in high concentrations such as in smoking occupancies or where aromatic/scented candles are burned. Candles that burn with these types of additives release significant quantities of soot that get filtered at carpet/baseboard intersections, get deposited under doors due to impaction as well as plate out at cold surfaces due to Brownian motion and plastic surfaces due to electrostatic attraction.

Commercial/Institutional Systems

Figure 3.21 illustrates an idealized view of a common commercial/institutional HVAC system. In almost all commercial/institutional HVAC systems, a dropped ceiling or suspended ceiling is used to create a return plenum.

The dropped ceiling is depressurized by air handling units located within the dropped ceiling. The air handling units extract air from the dropped ceiling, condition it (filter, heat or cool the air) and inject it into the occupied zone via a duct distribution system. In other words the supply air is “direct ducted” whereas the return air is pulled up into the dropped ceiling return plenum due to the negative air pressure created within the dropped ceiling by the air handling units extracting air from the dropped ceiling area. To facilitate the return air flow the dropped ceiling is constructed in a deliberately porous manner or return grills are installed to connect the dropped ceiling to the occupied zone.

In this idealized view, interaction of the dropped ceiling return plenum with the exterior walls and roof assembly is not considered. Figure 3.22 illustrates the interactions between dropped ceiling return plenums and exterior wall assemblies and roof assemblies. Air is extracted from roof assemblies, exterior wall cavities, through parapets and though exterior sheathings and building papers via communication with the negative pressure field within the dropped ceiling return plenum created by the operation of the air handling units.

Figure 3.23 illustrates the interactions between air handling units built into exterior walls and the exterior wall assemblies themselves. This is similar to the interaction of an air handling unit in a hotel room/bathroom suite described previously in Figure 3.10. Air is extracted from the exterior wall assembly, drawn into the air handling unit and subsequently injected into the room.

Leakage of exhaust ductwork in chases and their interaction with interior and exterior walls has also been previously described in Figure 3.11.

Measurement of System Leakage

Procedures for leakage testing of HVAC systems have been available for quite some time (SMACNA, 1965; SMACNA, 1967; SMACNA, 1985). Many of these procedures rely on measuring flow at grills and registers and comparing the values to the flow at air handlers. Differences in flow are thereby attributed to leakage in the system between the terminal points (grills and registers) and the air handler. Flow hoods are often used to determine flows at grills and registers and pitot tubes or hot-wire anemometers are used to determine flows at air handlers.

However, significant inaccuracy is introduced with these approaches due to the effects of cumulative error and the sensitivity limitations of flow hoods along with the extreme reliance on the skill of the tester when conducting pitot tube or hot-wire anemometer traverses. Variations in flow measurements of 10 to 20 percent commonly occur using these approaches whereas leakage as low as 3 to 5 percent can have significant effects on building performance (Tooley & Moyer, 1988; Lstiburek, 1993). This was recognized by the industry and new procedures were developed using pressurization methods (SMACNA, 1985). The pressurization methods employed sealing the supply and return grills and pressurizing the system with a variable speed blower. An orifice meter and manometer were used to determine flows at the test blower and pressures created within the duct systems.

The initial pressurization methods were difficult and expensive to conduct and disruptive in the field. It was not until Nelson (1991) developed portable, low cost, convenient and accurate pressurization testing equipment that such testing became practical to conduct in the field.

Due to the difficulties of leakage testing using early pressurization equipment and the complexity and inaccuracy associated with flow hoods, pitot tubes and hot-wire anemometers, much of the work in single family dwellings in the 1980's relied on the "subtraction method" for estimating leakage values. In this approach, a whole house pressurization test is conducted. Supply and return registers and grills are then sealed and a subsequent whole house pressurization test is conducted. The flow rate of the latter is subtracted from the flow rate of the former to obtain an order of magnitude value of system leakage (Robinson & Lambert, 1987).

The subtraction method proved to be a useful tool only in buildings where the majority of the ductwork was located in vented attics or vented crawl spaces. Where ductwork was located within the conditioned spaces, the method could not be used. Only leakage flow rates to the exterior could be quantified. Leakage flow rates to the interior could not be quantified. Additionally, although the approach was relatively "quick and easy", its accuracy was no better than the flow hood, pitot tube, hot-wire anemometer approaches (Cummings, Tooley & Moyer, 1990).

Although the specific duct leakage and air handler leakage values were difficult to determine directly, their effect on the air pressure field could be determined directly with portable, hand held micromanometers.

With respect to measuring leakage of dropped ceiling return plenums or the leakage of air handling units built into exterior walls or soffit assemblies, no practical direct method of measurement exists. However, the effect of the leakage on the air pressure field can be determined directly, again with portable, hand held micromanometers.

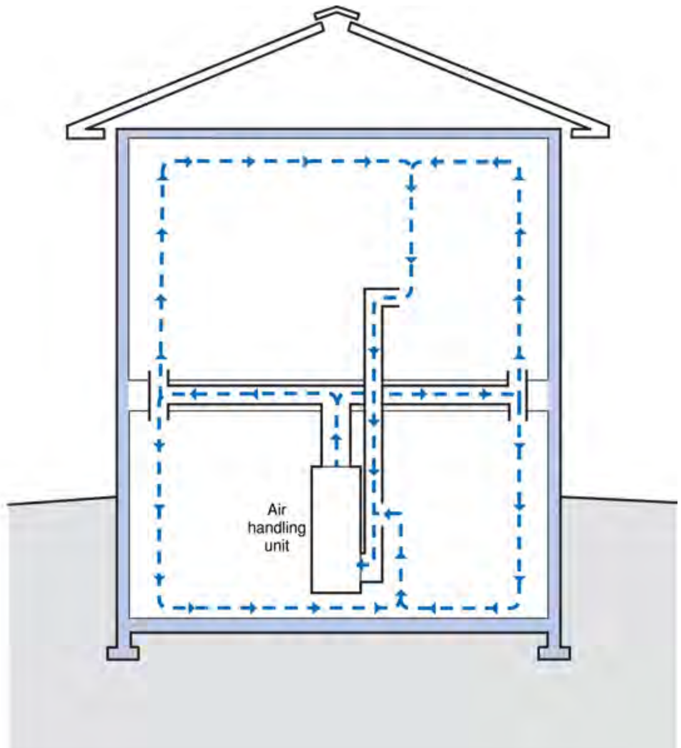


Figure 3.12
Ductwork and Air Handlers in Basements

- No air pressure differences result in a house with an air handler and ductwork located in a basement if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

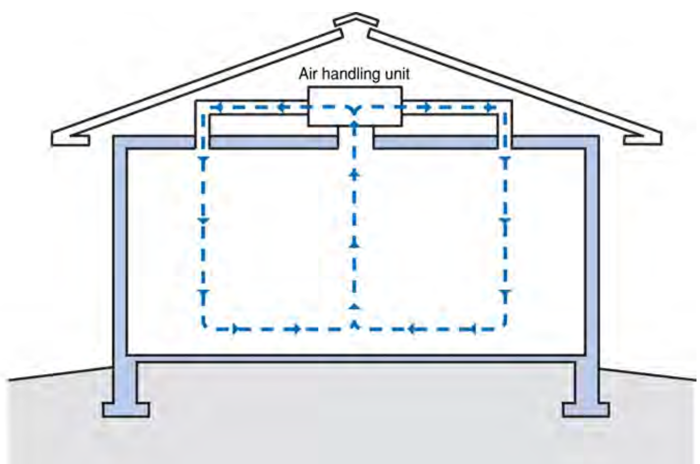


Figure 3.13
Ductwork and Air Handlers in Vented Attics

- No air pressure differences result in a house with an air handler and ductwork located in a vented attic if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

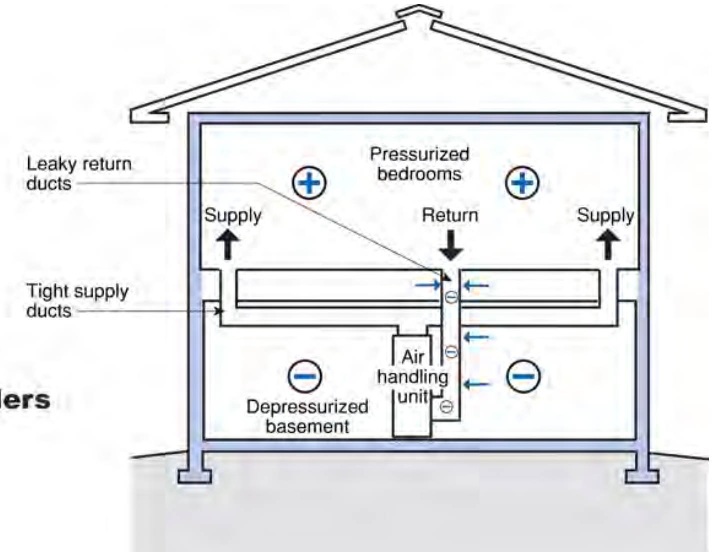


Figure 3.14
Leaky Ductwork and Air Handlers in Basements
- Air pressurization patterns in a house with leaky ductwork in the basement

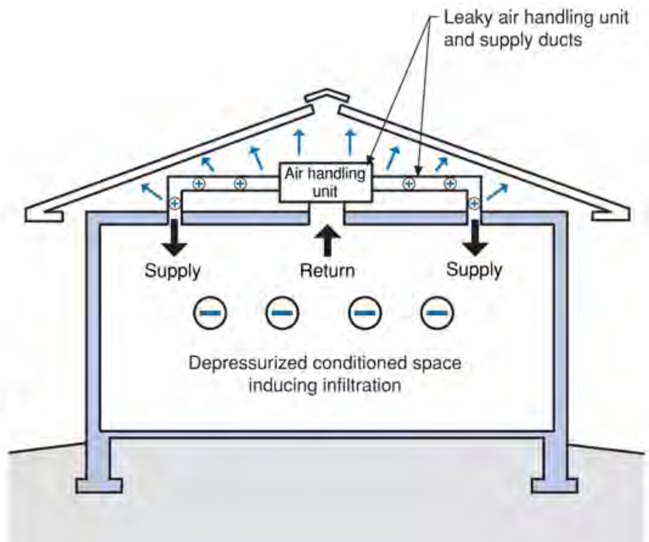


Figure 3.15
Leaky Ductwork and Air Handlers in Vented Attics
- Supply ductwork and air handler leakage is typically 20% or more of the flow through the system

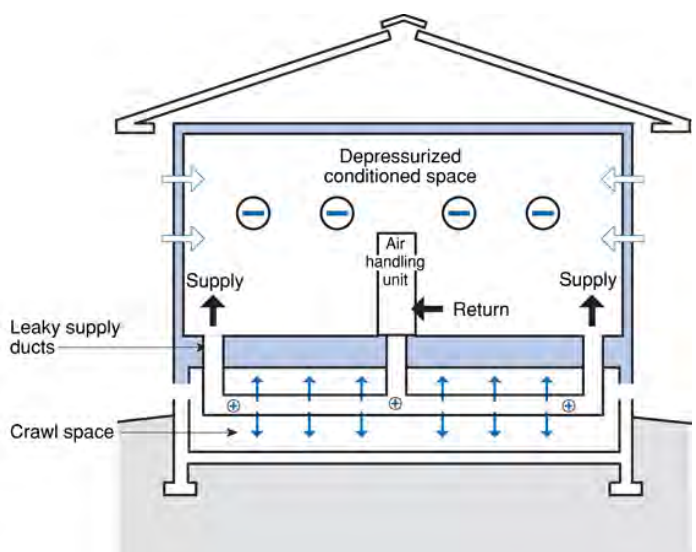


Figure 3.16
Leaky Supply Ductwork in Vented Crawl Space
- Air pressurization pattern with mechanical system ducts in the crawl space

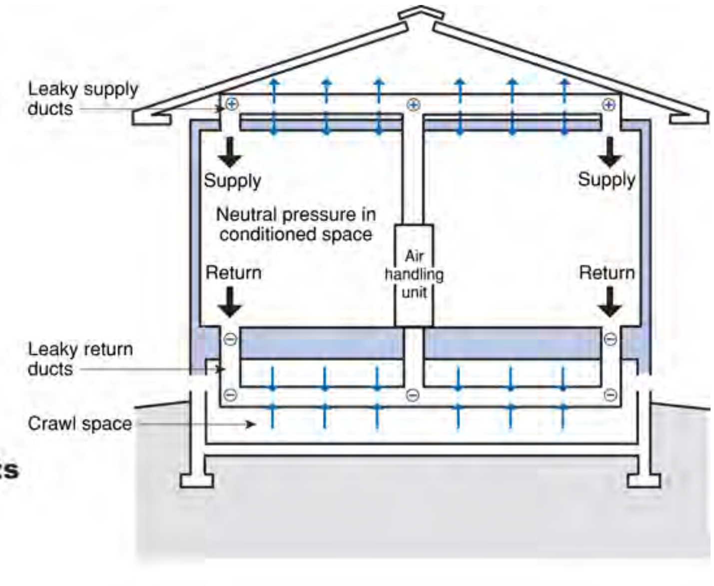
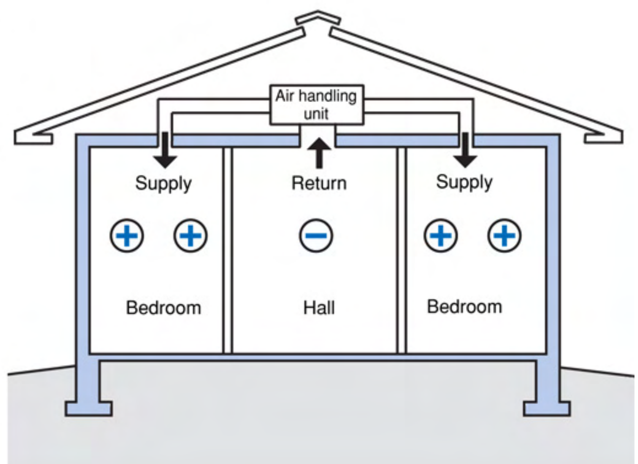


Figure 3.17
Leaky Supply and Return Ducts
- Air pressurization pattern with mechanical system ducts in the attic and crawl space

Figure 3.18
Insufficient Return Air Paths
- Pressurization of bedrooms often occurs if insufficient return pathways are provided; undercutting bedroom doors is usually insufficient; transfer grilles, jump ducts or fully ducted returns may be necessary to prevent pressurization of bedrooms
- Master bedroom suites are often the most pressurized as they typically receive the most supply air
- When bedrooms pressurized, common areas depressurize; this can have serious consequences when fireplaces are located in common areas and subsequently backdraft



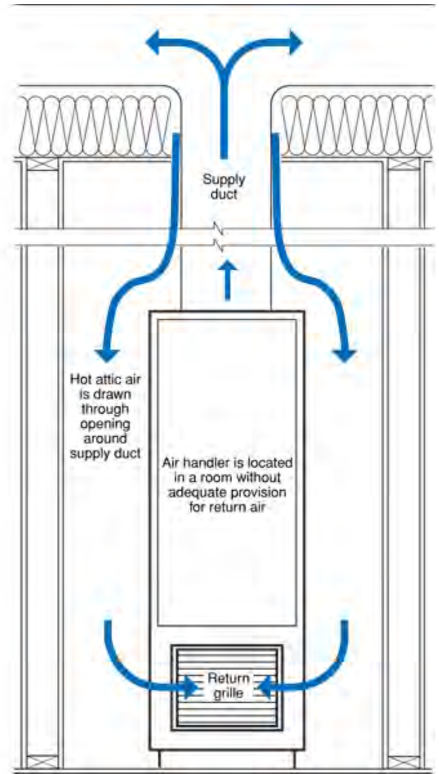


Figure 3.19
Air Handler Closet Depressurization

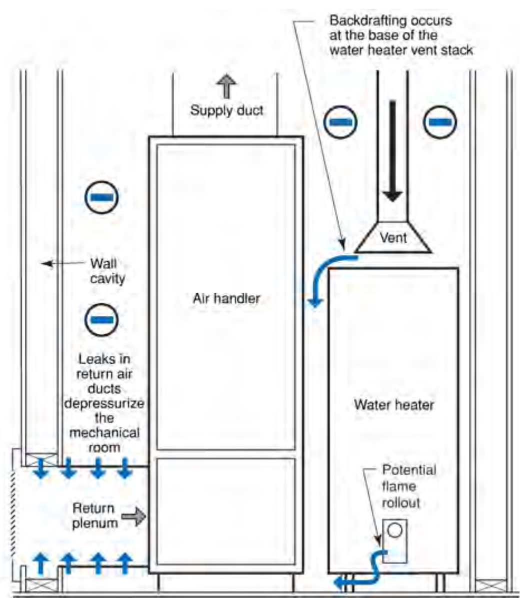


Figure 3.20
Backdrafting in Mechanical Room

- Mechanical room depressurized by return system leakage

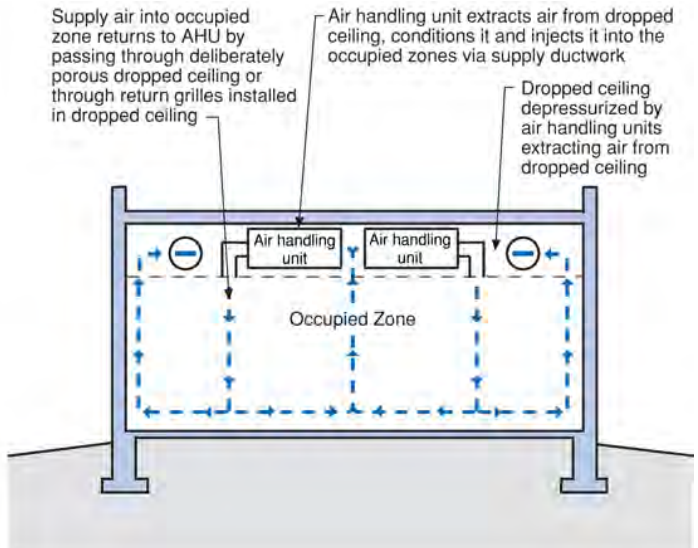
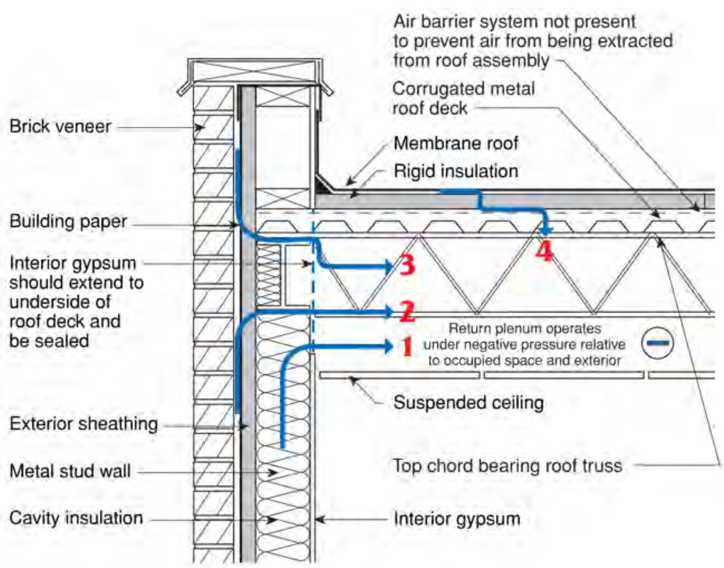


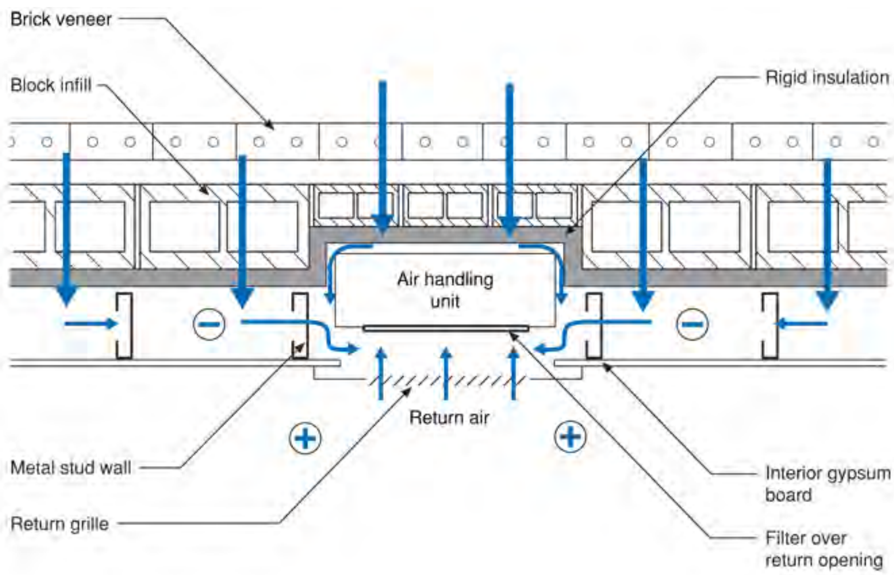
Figure 3.21
Idealized Commercial HVAC System Using a Dropped Ceiling Return Plenum

- Standard analysis assumes no interaction with roof assembly or wall assembly
- Air supplied to the occupied zone is returned to the AHU's via the dropped ceiling return plenum



1. Air is pulled from exterior wall cavity into return plenum since interior gypsum does not extend to underside of roof deck
2. Air is pulled from exterior through gaps in building paper and exterior sheathing
3. Air is pulled from exterior through gaps between corrugated metal roof deck and structural steel
4. Air is pulled from under roof membrane through gaps in rigid insulation and metal roof deck

Figure 3.22
Dropped Ceiling Plenum Connected to Exterior Wall and Roof Assembly



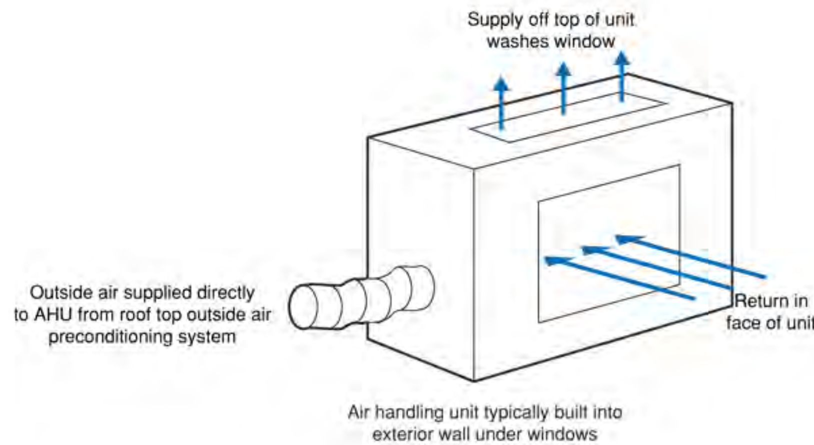


Figure 3.23
AHU Depressurizing Exterior Wall Assembly Plan View

Relational and Analytic Models for Air Flow in Buildings

The significance of these complex, time dependent interstitial air pressure fields and related air flows has not been appreciated or identified for several reasons:

- materials, methods and means of construction have changed;
- the relational model is incomplete; and
- the process of construction is fragmented.

In the past buildings were leaky, not well insulated and the effect of HVAC systems and other air conveyance systems on building pressures was small. The key air pressure relationships defining interstitial air pressures are also small and have until recently been difficult to measure and quantify. Older building structures were more massive with exterior wall assemblies and interior partitions constructed from masonry, masonry back-up and plaster resulting in few or no interstitial connected cavities. More recent construction relies on metal framing, steel studs, gypsum board interior and exterior sheathing resulting in more numerous and larger void spaces, chases and interstitial cavities.

Building design and construction has also become fragmented as a consequence of the increasing specialization and complexity of the technology of construction. Specialization has lead to an abundance of specialists who have tended to focus principally on their own disciplines. In doing so, the system view is often missed. Under these conditions the significance of interstitial air flows and the need for more complete relational models of air flow in buildings is not readily apparent.

Relational Models

Considering interstitial air pressure fields and related air flows and the coupling of mechanical systems to the building envelope and building cavities leads to the development of more complete relational models of air flow in buildings. These relational models of air flow in buildings are based on air pressure relationships rather than on air flow. The relational models identify direction of air flow, but not the quantification of air flow. They can be used to determine the magnitude of the air pressures, but not the leakage areas and therefore not air flows. These relational Air Pressure Field (APF) Models for Buildings can be used to predict and understand the pressure response of buildings. From these relational models, existing analytic models can be tuned or calibrated to provide quantification of flows and leakage areas.

A relational APF model is presented in Figure 3.24 that shows the relationships among the four component fields comprising the building air pressure field. The proposed APF Model involves research on air flows and pressures in buildings that spans this century. The key papers of the component fields are referred to while illustrating their contribution to enhanced understanding (Figure 3.24).

Historical Basis for Relational Model

Coupling of the exterior field and the interior field is a key factor utilized in the design of buildings and cladding systems. Loads for the design of cladding can be found from the algebraic difference between the boundary layer and interior pressures (Davenport, 1960; Dalgliesh & Schriever, 1962; Davenport & Isyumov, 1967; Stathopoulos, Surry & Davenport, 1979; Dalgliesh, 1981; Davenport & Hui, 1982).

Coupling of the interior and exterior fields due to air density differences between the interior and exterior (stack effect) has long been utilized in the ventilation design of process buildings (Barker, 1912; Emswiler, 1926) and in establishing air and smoke flow patterns in high rise buildings (Tamura & Wilson, 1966).

Coupling of the exterior and the interior field has also been extensively studied with respect to wind induced natural infiltration (Swami & Chandra, 1987).

Understanding of the coupling of the exterior and the interstitial fields within exterior wall assemblies forms the basis of pressure equalized rain screen (PER) design for the control of rain entry into walls (Garden, 1963).

The study of wind washing of cavity insulation in exterior wall assemblies further established the link between the exterior field and the interstitial field (Timusk, Seskus & Ary, 1988). The study of ventilation in cladding expanded knowledge about the link between the exterior field and the interstitial field and identified thermal and moisture convection as air pressure drivers (Burnett & Straube, 1995).

Coupling of the interior field, the air conveyance system field and the exterior field was studied extensively because of concerns arising from carbon monoxide poisoning and negative pressures in airtight houses (Steel, 1982). Relationships between building envelope tightness (leakage) and air requirements for chimneys were developed (White, 1983) along with test protocols establishing negative air pressure limits for interior air pressure fields. The pressure limits were related to flow reversals in chimney air conveyance system fields using calibrated fans to alter interior fields in a controlled manner (Timusk, 1983).

Building envelope leakage characteristics using calibrated fans to alter interior air pressure in a controlled manner have been extensively studied (Tamura & Wilson, 1964; Stricker, 1975) leading to the development of leakage-pressure relationships for building envelopes. The work on building envelopes is an extension of leakage-pressure relationships developed for wall assemblies that date to the early part of this century (Larson, 1929).

Door closure and the distribution of supply registers and return grills were determined to be air pressure drivers in the spillage and backdrafting of combustion appliances (Timusk, 1983), thereby identifying the three-way linkage of the interior field, the air conveyance system field and the exterior field. This work was significantly expanded to include duct leakage of ducts in both conditioned and unconditioned spaces (Tooley & Moyer, 1988).

Duct leakage into interstitial spaces was identified as an energy (operating cost) factor (Harrje, Gadsby & Cromer, 1986; Nelson et al., 1986; Tooley & Moyer, 1988) thereby identifying the link between the interior and exterior fields, the air conveyance system field and the interstitial air pressure field.

The linkage between different interstitial fields was subsequently identified as a moisture transport path (Tooley & Moyer, 1989; Lstiburek, 1989) where the air pressure driver for the interstitial field was an HVAC system.

Active control of air pressures within interstitial spaces as a design strategy has been proposed as a viable method of moisture and pollutant control (Handegord, 1989) and forms the basis of dynamic wall strategies for thermal comfort and ventilation (Timusk, 1987).

Rehabilitation techniques using active control of air pressures within building envelope interstitial air spaces are common. Pressurization of roof assembly cavities with exterior air has been successfully used to control the exfiltration of interior moisture laden air in heating climates (Lstiburek, 1988; Quirouette, 1997) as well as active depressurization of sub-slab granular pads to control the infiltration of radon and other soil gases into occupied spaces (Scott, 1979; Acres, 1981). These examples highlight the linkage between interstitial fields, air conveyance system fields, interior and exterior fields that are used in the design process.

Designing the linkage of exterior and interstitial air pressure fields is also typical where the use of powered attic ventilation exhaust fans provide attic air change. This same strategy has also been found to provide incidental linkage to the interior field and subsequent chimney flow reversal. Specifically, the operation of powered attic ventilation exhaust fans has been shown to depressurize conditioned spaces leading to the backdrafting of chimneys and flame roll-out in combustion water heaters (Tooley & Davis, 1994).

Unifying these excellent, though disjoined research papers under the relational APF model as developed in this thesis, enhances prediction and understanding of the pressure response of buildings and of each component field as they interact during the operation of the building.

Analytical Models

The relational model shown in Figure 3.24 can be used to tune or calibrate existing multi-cell analytical models. Figure 3.25 represents an electrical analog of the hotel room described in Figure 3-6. Currents represent the rate of air flows, voltages represent air pressures and resistance's represent air leakage paths. Ambient air pressure under no wind conditions at ground level is considered "ground".

Although this approach has a long history (Nylund, 1966; Nylund, 1980; Kronvall, 1980; Walton, 1989), it is adapted here to consider interstitial spaces and the leakage effects of HVAC systems. In an extension of standard analysis, the nodes represent either rooms or interstitial spaces. In this manner connected compartments such as rooms, exterior wall cavities and interior wall cavities are all considered. Additionally, compartments can also have generators associated with them. The generators represent mechanical system leakage from either ducts, equipment housing or exhaust system service ductwork and chases.

In this manner a mass balance at each node can occur while allowing the introduction or removal of flows at intermediate "nodes". Generators are also used to represent the other "drivers" such as wind, stack and other effects of mechanical systems. Alternating current generators (AC) are used to represent the dynamic effect of wind whereas direct current generators (DC) are used to represent stack effects (temperature differences) and exhaust and supply flows from fans and HVAC systems. The DC generators are used in two different forms, in one form they provide a constant voltage, and in the other form they provide a constant current. This is analogous to representing the stack effect (constant voltage) and an HVAC system flow (constant current).

With this approach standard network analytical models can now be used to address the interstitial air pressure fields and related air flows. The relational model is used to create the nodal grid of the analytical model. Difficulties still exist with respect to determining boundary conditions. However, the relationships between flows, pressures and leakage paths now correspond to actual construction.

In using the modified network analytical models, the issues relating to the level of detailed input information for model boundary conditions can be addressed by changing the focus from difficult to obtain information to easy to obtain information. Specifically, the resistances representing air leakage paths, can be determined by “pressure mapping” a building or portion of a building under imposed known air flows. Under this approach, the pressure response of the building (or portion of building) is measured as a result of the imposed known air flows. These pressures and imposed flows are input into the model and air leakage path resistances are calculated meeting the convergence criterion. The calculated air leakage path resistances are then “fixed”, and the subsequent effect of variable air flows, wind and stack effects modeled.

This differs from standard multi-cell model analysis where the inputs are wind and stack pressures, flow rates relating to the air conveyance systems (currents) and air leakage characteristics (resistance's) of the building components. Outputs are component air flows (currents) and component air pressures (voltages).

The discussed approach avoids the difficulties of predicting component air leakage characteristics since component leakage areas are calculated from air pressures and air flows measured directly. Additionally, the non-linearity typically introduced in multi-cell numerical analysis in dealing with calculating pressures from flows is also avoided since the pressures are measured directly. In practice it is very difficult to isolate the air flows, but it is relatively easy to isolate the air pressures.

Accuracy of the analytical model can be further increased by perturbing the flow field, the leakage field or the pressure field. By determining the effect of the perturbation on the pressure field, the analytical model can be refined or "tuned" to match the response of the building under a similar model based perturbation. In this manner gaps in the information describing the boundary conditions of the model can be filled in.

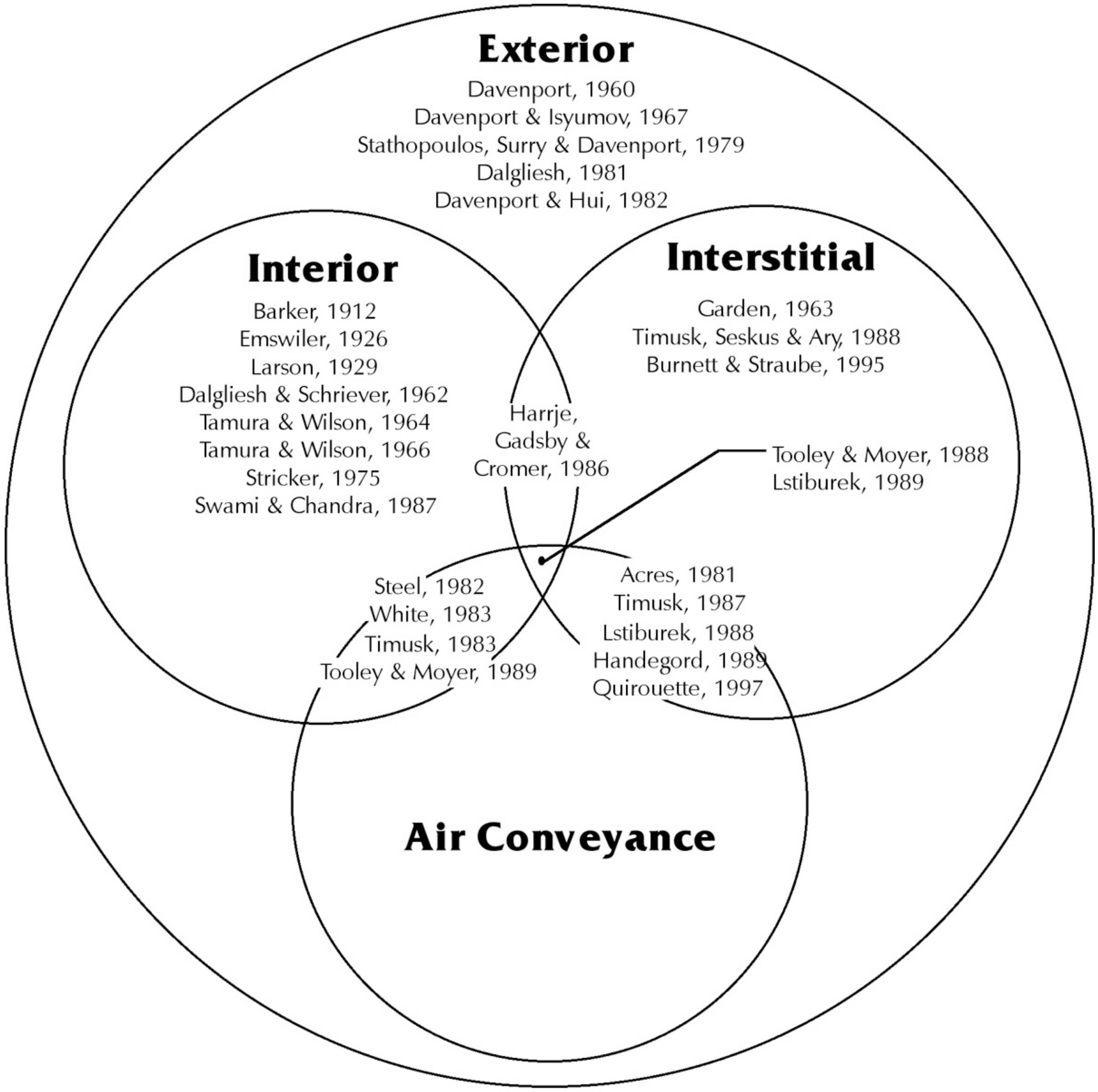
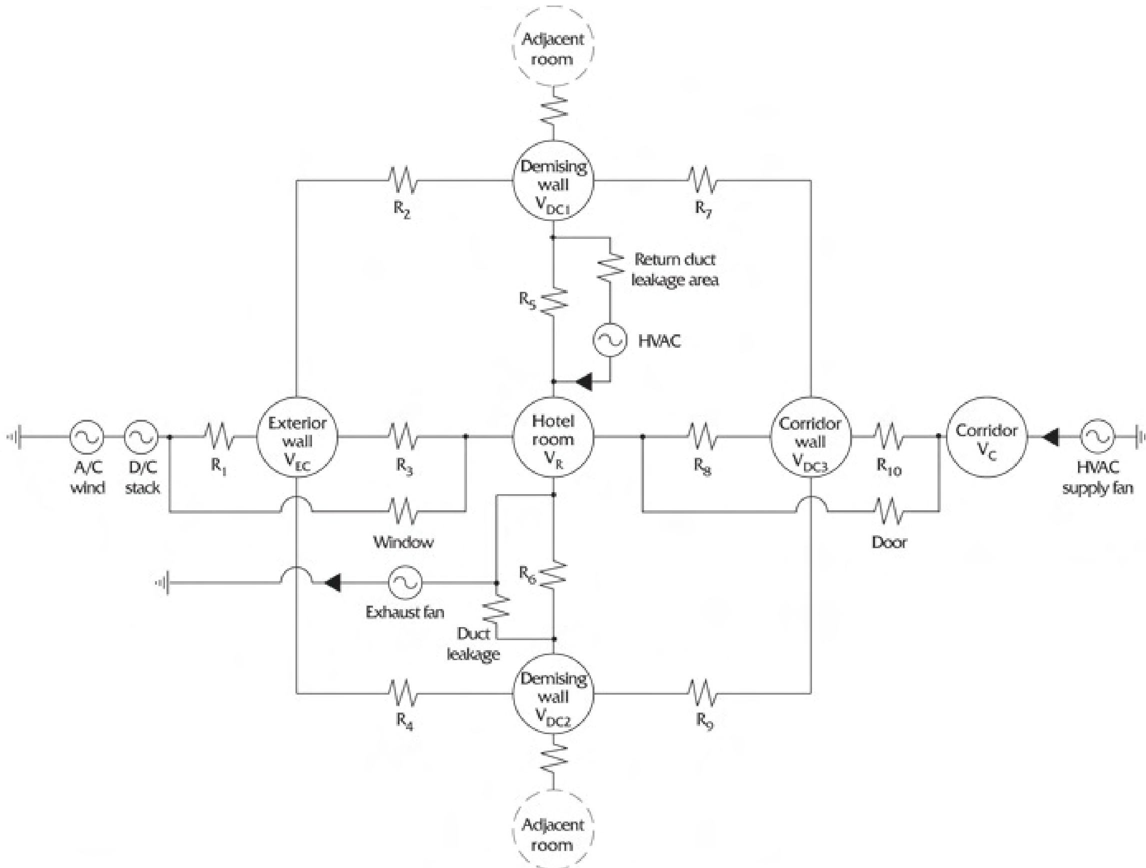


Figure 3.24
Relational Air Pressure Field (APF) Model
- A schematic representation of the relationalAPF model for buildings with reference to the key papers and their contribution



R_1 = Leakage area between ambient and exterior wall cavity

R_2 = Leakage area between exterior wall cavity and demising (partition) wall cavity

R_3 = Leakage area between exterior wall cavity and hotel room

R_4 = Leakage area between exterior wall cavity and demising (partition) wall cavity

R_5 = Leakage area between demising (partition) wall cavity and hotel room

R_6 = Leakage area between demising (partition) wall cavity and hotel room

R_7 = Leakage area between demising (partition) wall cavity and corridor demising wall cavity

R_8 = Leakage area between hotel room and corridor demising wall cavity

R_9 = Leakage area between demising (partition) wall cavity and corridor demising wall cavity

R_{10} = Leakage area between corridor demising wall cavity and corridor

V_{EC} = Pressure in exterior wall

V_R = Pressure in hotel room

V_C = Pressure in corridor

V_{DC1} = Pressure in demising (partition) wall cavity

V_{DC2} = Pressure in demising (partition) wall cavity

V_{DC3} = Pressure in corridor demising wall cavity

Figure 3.25
Electrical Analogue of Hotel Room

IV Air Pressure Response

Measuring Air Pressure Fields

The prevailing air pressure differences in the interstitial and the interior fields are small. Until recently they have been difficult to measure and quantify. Most investigators have relied on smoke tubes to detect air flows. Smoke tubes are extremely sensitive even for small air pressure differences (the author has found them useful with air pressure differences of less than 1 Pa) and can establish the direction of air flow.

Timusk (1983) found that air pressure measurement resolution on the order of 1 Pa was necessary in conducting research on chimney backdrafting and air pressure drivers within houses. Timusk (1987) found that measuring even lower air pressure differences was necessary when testing dynamic wall insulation. Inclined fluid manometers and diaphragm-type magnetic linkage pressure gauges were not sufficiently sensitive for these research needs.

While digital electronic micromanometers with resolution of 0.1 Pa provided the necessary resolution, see Timusk (1983), they were expensive and difficult to obtain. It was not until recently that low cost (less than $1,000) portable digital electronic micromanometers became widely available. With availability, came opportunity for field use unimaginable only years before. Differential air pressure measurements can now be conducted easily, quickly and inexpensively. These breakthroughs in measurement technology set the stage for the enhanced understanding of air pressure drivers in buildings (Tooley & Moyer, 1988; Lstiburek, 1989; Blasnik & Fitzerald, 1992).

Air Pressure Differential Measurements

Figures 4.1 and 4.2 illustrate the use of a digital electronic micromanometer to measure the air pressure difference between the exterior and interior and between the exterior and an interstitial cavity in a demising wall respectively. Photograph 2 shows a digital electronic micromanometer in a typical setup measuring an air pressure difference across a wall assembly.

As it became clear that the linkage between different component air pressure fields is critical for the understanding of building performance, a need for specialized measurement technology became apparent. Moyer developed a six channel digital electronic micromanometer to establish a "pressure map" of a nursing home facility (Lstiburek & Moyer, 1991). The pressure map records the magnitude and direction of the pressure relationships within the facility under a set of specific operating conditions such as the operation of the facility HVAC system or under a given interior to exterior temperature difference. Figure 4.3 and Photograph 3 illustrate the six channel digital electronic micromanometer set up to pressure map the hotel room described in Figure 2.10. The multi-channel manometer is connected to a laptop computer which records and graphically displays the air pressure differentials simultaneously.

Air pressure measurements are often taken relative to the exterior ambient pressure. During initial field research, calm wind conditions (less than 10 kph) were necessary in order to develop an understanding of the building air pressure relationships. Calm wind conditions allow accurate determination of the exterior air pressure field, which can act as a reference for all other pressure measurements.

Measurement protocols evolved with field experience. Manometers with time-averaging capabilities allow accurate determination of the exterior air pressure field even under moderate wind conditions (10 kph to 25 kph). Although it is still desirable to use the exterior ambient as the reference air pressure, in many cases building common areas such as atria, crawlspaces or attics were found to act as reasonable reference air pressures. Wind effects were found to alter the interior to exterior air pressures in accordance with the conventional view. However, in most cases wind effects did not alter the relationships occurring as a result of the coupling of the building envelope and the mechanical systems. Specifically, many of the air pressure relationships occurring among the interstitial field, the interior field and the air conveyance system field were able to be determined under moderate wind effects.

The standard measurement protocol used when testing the hotel room illustrated in Figure 3.6 involves instrumentation shown in Figure 4.3. This protocol involves measurement of air pressures under many possible combinations of building HVAC system operation and building envelope leakage pathways. For example the operation of building air conveyance systems includes various combinations of open and closed interior doorways. The effect of these changes on the building air pressure field is recorded.

Air pressure measurements usually only represent a "snapshot" of the air pressure field. Snapshot air pressure measurements may or may not be representative of the air pressure field of the building. Skill and insight by the investigator conducting measurements are necessary to interpret the snapshot air pressure measurements. Snapshot mapping of building air pressure fields is made more effective if the building HVAC system can be cycled through the various operational conditions (including the effects of door closure). Especially when this is combined with knowledge of the building operational conditions over a daily, weekly and seasonal basis. However, such cycling is not always possible nor under the control of the investigator. Long term air pressure differential monitoring is sometimes necessary and desirable to establish air pressure relationships through the "normal" building operating range.

Building air pressure fields often have daily, weekly and seasonal patterns. For example, most buildings do not operate their HVAC systems at full capacity or at night or over weekends. Additionally, building exhaust fans are often operated on timers. Specialized exhaust fans, such as kitchen range hood exhausts, dryers and spot ventilators operate only as needed. Large differences in air flow induced by HVAC systems also occur between maximum heating and maximum cooling conditions. During "swing" seasonal conditions, economizer operation usually provides the largest air flow rates and the largest air pressure extremes. Additionally, stack effect pressures vary with indoor to outdoor temperature differences further complicating matters.

Figure 4.4 shows the monitoring of air pressure relationships between a hallway and work area in a laboratory facility in New Hampshire over a period of two days. The measurements were taken by connecting a digital micromanometer with an analog output to a stand alone electronic data storage microprocessor. The data storage capacities of the data storage microprocessor allow measurements to be taken over several weeks. Data is downloaded into a laptop computer where data manipulation and analysis can occur.

Figure 4.5 illustrates the use of digital electronic micromanometers to measure the air pressure distribution across the elements of a wall assembly.

Series Pressure Differential

The general relationship between air flow and pressure was shown by Equation 2-4 (see Currie, 1974). Let the leakage coefficient, C, be expressed as:

$$C = C_D A$$

where C_D = discharge coefficient
A = area

$$Q = C_D A (\Delta p)^n \qquad (4 - 1)$$

from Hutcheon & Handegord, 1983

As illustrated in Figure 4.5, the cavity air pressure will be that at which the air flows into and out of the wall cavity are balanced. Assuming no leakage across the floors, that is no leakage out of the top and bottom of the wall cavity, the following holds:

$$Q = C_E A_E \Delta P_E^{\ n} = C_I A_I \Delta P_I^{\ n} \qquad (4 - 2)$$

$$\frac{C_E A_E}{C_I A_I} = \frac{\Delta P_I^{\ n}}{\Delta P_E^{\ n}}$$

$$\cong \frac{A_E}{A_I} = \left(\frac{\Delta P_I}{\Delta P_E}\right)^n$$

$$\cong \left(\frac{A_E}{A_I}\right)^{1/n} = \frac{\Delta P_I}{\Delta P_E}$$

from Hutcheon & Handegord, 1983

where C_E = discharge coefficient for exterior of wall assembly
C_I = discharge coefficient for interior of wall assembly
ΔP_E = pressure difference across exterior of wall assembly
ΔP_I = pressure difference across interior of wall assembly
A_E = leakage area across exterior of wall assembly
A_I = leakage area across interior of wall assembly
n = exponent varying between 0.5 and 1.0

This concept was further developed by Blasnik (1988) and by Blasnik and Fitzerald (1992). The air pressure differences across the wall assembly elements are measured under a given pressure difference. An opening of known size (A_k) is added, and the air pressure differences across the wall assembly elements re-measured. Equation 4-2 is then used as follows to yield the individual leakage areas (Blasnik, 1988):

$$A_E = A_I \left(\frac{\Delta P_{I1}}{\Delta P_{E1}}\right)^n$$

$$A_E + A_k = A_I \left(\frac{\Delta P_{I2}}{\Delta P_{E2}}\right)^n$$

$$\text{Let } \left(\frac{\Delta P_{I1}}{\Delta P_{E1}}\right)^n = R_1^{\ n}$$

$$\text{Let } \left(\frac{\Delta P_{I2}}{\Delta P_{E2}}\right)^n = R_2^{\ n}$$

$$A_E = A_I R_1^{\ n}$$

$$A_E + A_k = A_I R_2^{\ n}$$

$$A_E = A_I R_2^{\ n} - A_k = A_I R_1^{\ n}$$

$$A_I = \frac{A_k}{\left(R_2^{\ n} - R_1^{\ n}\right)}$$

Similarly,

$$A_E = \frac{A_k R_1^{\,n}}{(R_2^{\,n} - R_1^{\,n})}$$

where ΔP_{I1} = initial ΔP across interior of wall assembly

ΔP_{E1} = initial ΔP across exterior of wall assembly

ΔP_{I2} = subsequent ΔP across interior of wall assembly

ΔP_{E2} = subsequent ΔP across exterior of wall assembly

A_k = an opening of known size

Although Blasnik used this approach in determining leakage areas across flat roof attic ceiling assemblies, the approach can be adapted to determine room leakage areas. Consider the following case of a series of rooms served by a corridor (Figure 4.6). Room A is located between Room B and Room C. Each room has an operable window opening to the exterior and a connecting door to the corridor. To simplify matters, let us assume that the floor and ceiling are of slab construction or negligible leakage area.

Initially, the door in Room A is closed and the doors in Room B and Room C are open. The windows in all three rooms are closed. A positive pressure relative to the exterior is induced in the corridor creating a two zone pressure boundary. The pressure differences P_{I1} and P_{E1} are recorded (Figure 4.7). An opening of known size, A_k, is introduced by partially opening the window in Room A. The new pressure P_{I2} and P_{E2} are recorded (Figure 4.8). Equation 4-2 is used as before to determine A_E and A_I.

The process is repeated with a negative pressure relative to the exterior induced in the corridor. In this case, the doors to the corridor for Room B and Room C are closed and the windows in Room B and Room C are wide open creating a different two zone pressure boundary (Figure 4.9). In this case, an opening of known size is introduced in A_{AC} by partially opening the door in Room A. This yields the leakage area of A_{AC}.

Inducing Pressure Differentials and Determining the Pressure Response

The method just described exemplifies an alternative approach of measuring pressures and using them as inputs to determine leakage areas. It is used here in a 3 pressure zone, 2 boundary area example. A more general case for n-pressure zones occurs when the building pressure field is measured and used to determine building leakage areas.

This approach is particularly suitable for buildings with forced air distribution systems that provide heating, cooling and ventilation. In most of these buildings, the supply system extends to each room and is typically more extensive than the return system. By shutting down the return system and blocking the return air paths at the return grills, the supply system can be used to induce a positive pressure field within the building that is readily measured using the techniques previously described. Additionally, test and balance information (or techniques) can be used to yield the flow rates to individual rooms. In this manner, individual supply air flows can be matched to individual room pressures throughout the building yielding a combined pressure and flow map. The pressure and flow map can be used to determine the leakage areas or boundary conditions of the interconnected zones using a multi-cell network model.

Where forced air systems are not present, calibrated fans (e.g. blower door fans) can be used to supply a known air flow inducing a measurable pressure field. This technique can be extended with multiple fans used to simulate the effect of a supply system where corridors and stairwells are used as ducts and risers.

In the general case described, the multi-cell network model matrix equations are not altered. However, an inverse method has been used where pressures are measured inputs to the model and leakage areas are outputs.

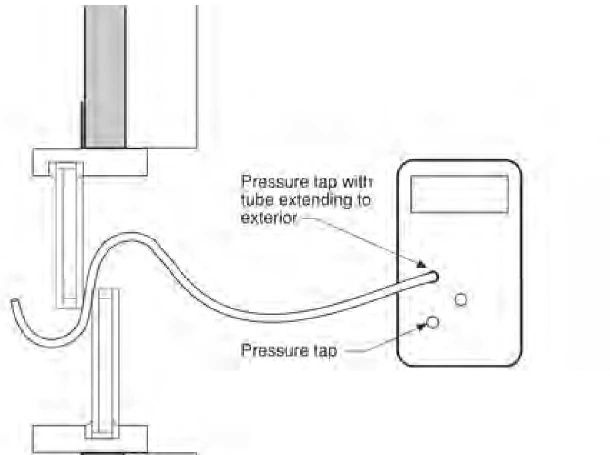


Figure 4.1
Air Pressure Difference Plan View
- Air pressure difference between exterior and interior measured across a window sash with a digital electronic micromanometer (resolution ≈ ± 0.1 Pa)

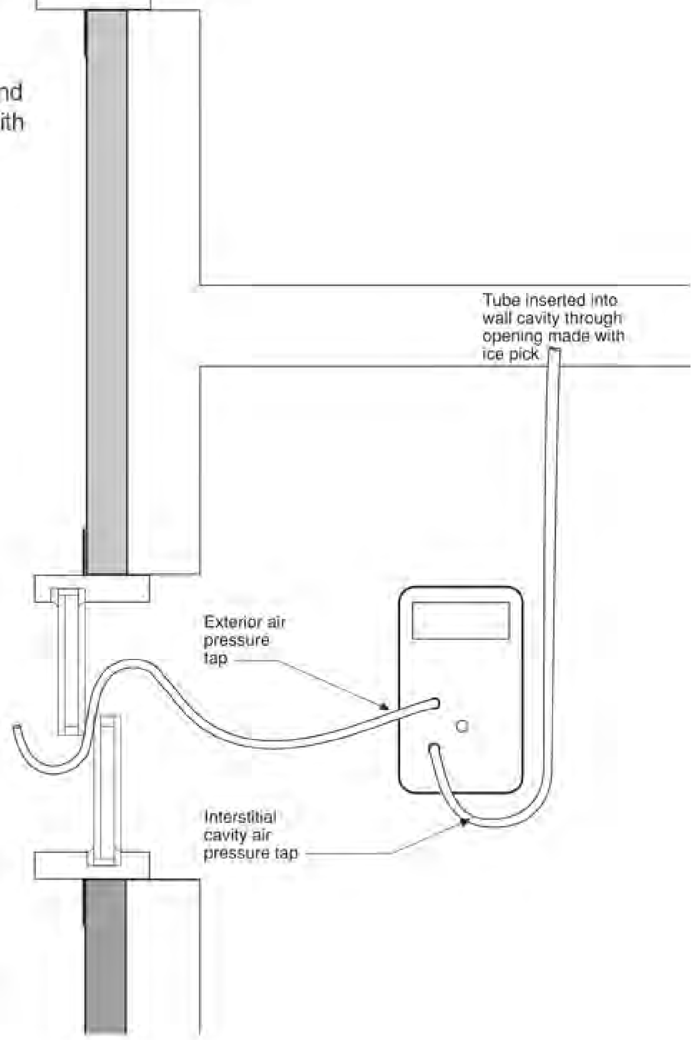


Figure 4.2
Measurement of Air Pressure Difference Plan View
- Measurement of air pressure difference between exterior and interstitial cavity in demising (partition) wall

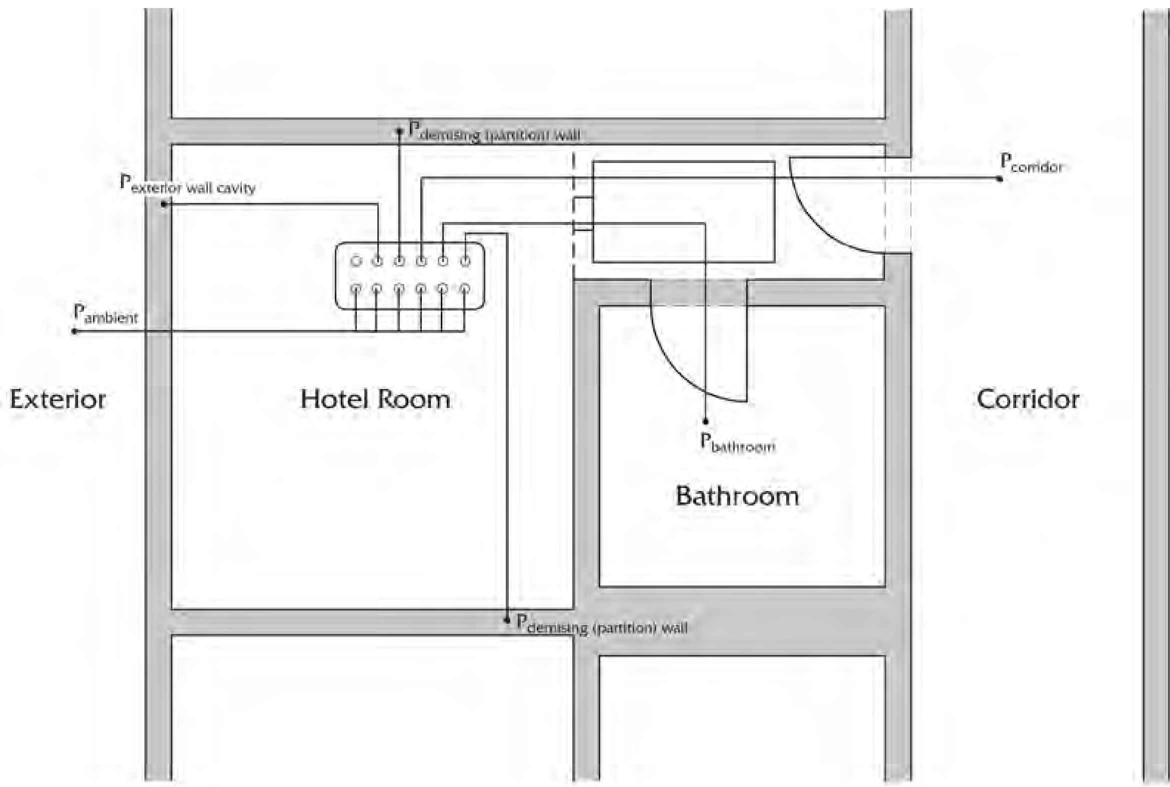
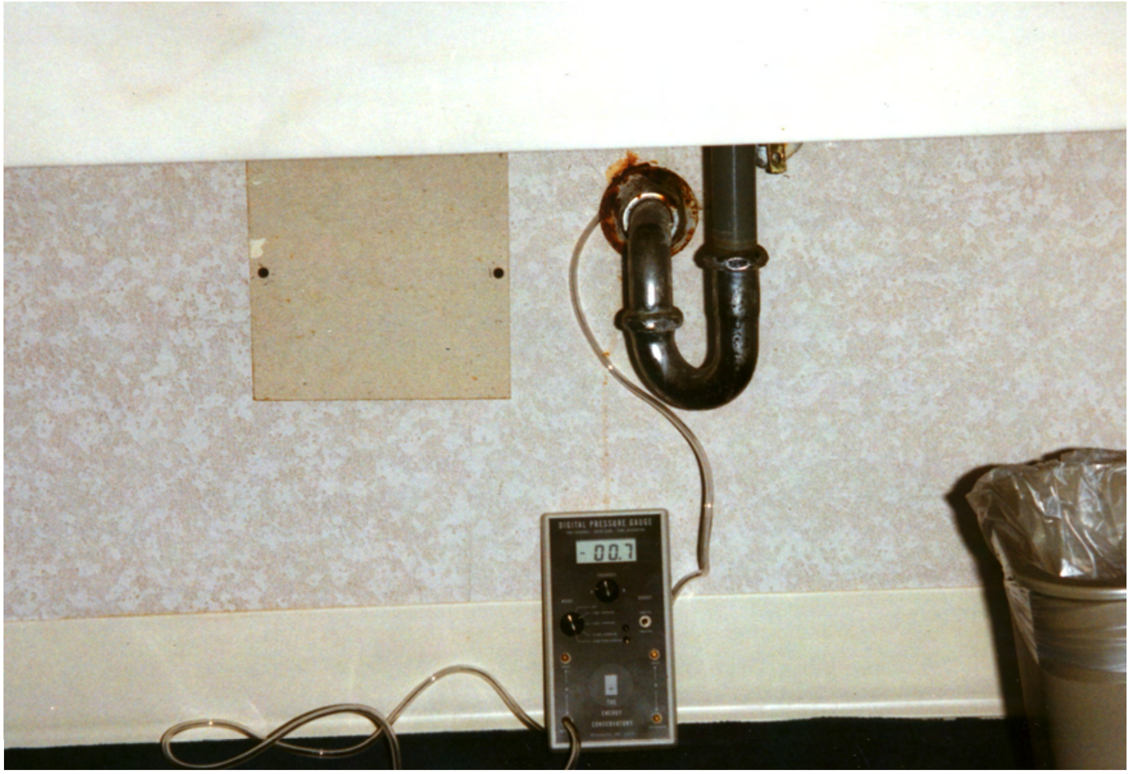


Figure 4.3

Multi-Channel Pressure Measurements

- Six channel micromanometer connected to laptop computer used to map pressure in the hotel room described in Figure 3.6
- All pressures measured relative to exterior air pressure
- Pressure response determined by opening and closing doors, cycling fan-coil, rooftop exhaust and corridor make-up air systems



Photograph 2
Digital Electronic Micromanometer

Photograph 3
Multi-Channel Digital Electronic Micromanometer

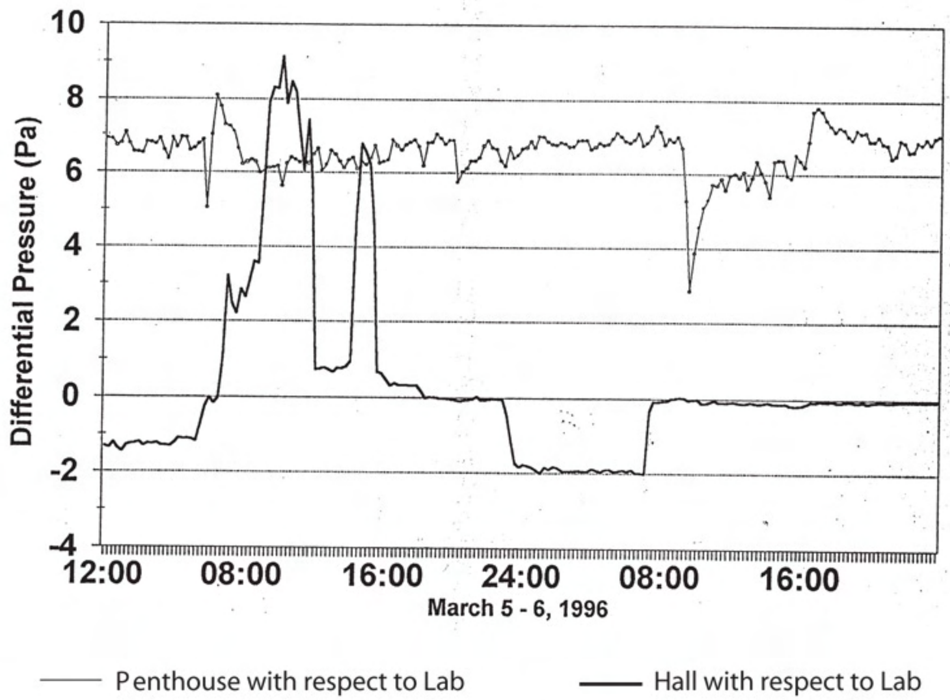


Figure 4.4
Differential Pressure Monitoring in New Hampshire Health and Human Services Building

P_o = outside air pressure

P_I = inside air pressure

P_c = cavity air pressure

A_E = leakage area across exterior of wall assembly

A_I = leakage area across interior of wall assembly

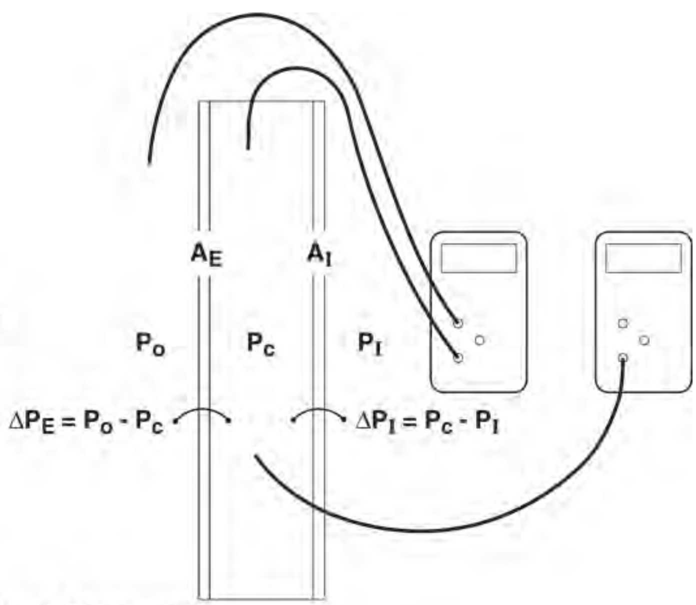


Figure 4.5
Measurement of Series Differential Pressure

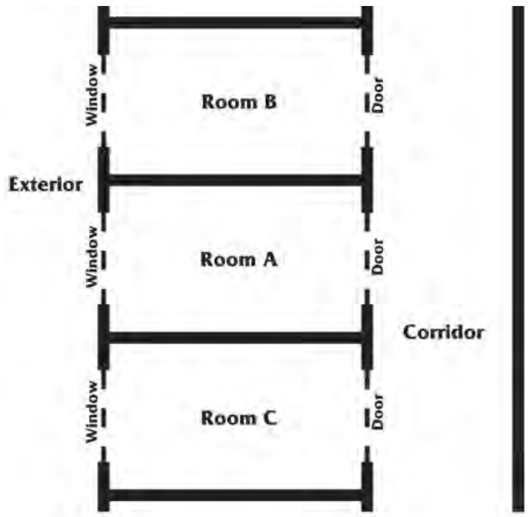
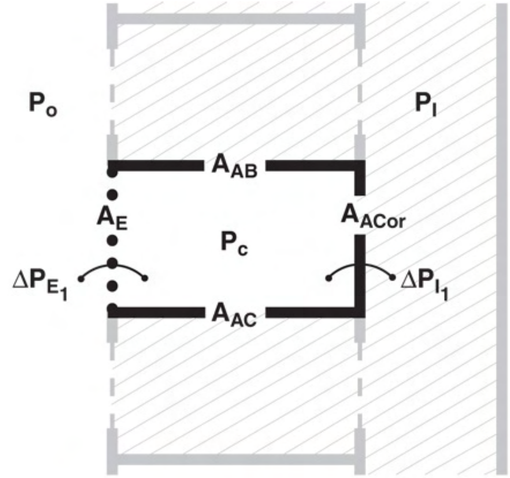


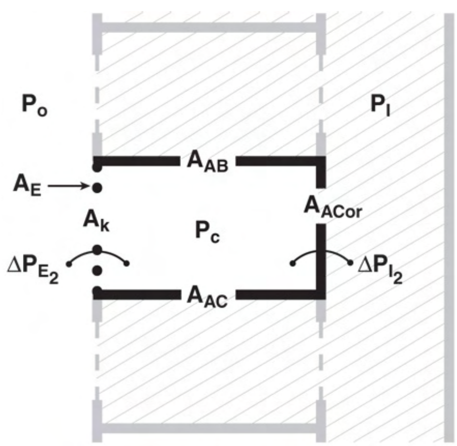
Figure 4.6
Series of Rooms Connected to Corridor



$$A_I = A_{AB} + A_{AC} + A_{ACor}$$

Figure 4.7
Initial Pressure Measurements

- Door to corridor in Room A closed
- Doors to corridor for Rooms B and C are open
- Windows in all rooms closed



$$A_I = A_{AB} + A_{AC} + A_{ACor}$$

Figure 4.8
Subsequent Pressure Measurements

- An opening of known size, A_k, is added to A_E (i.e. window in Room A is opened)

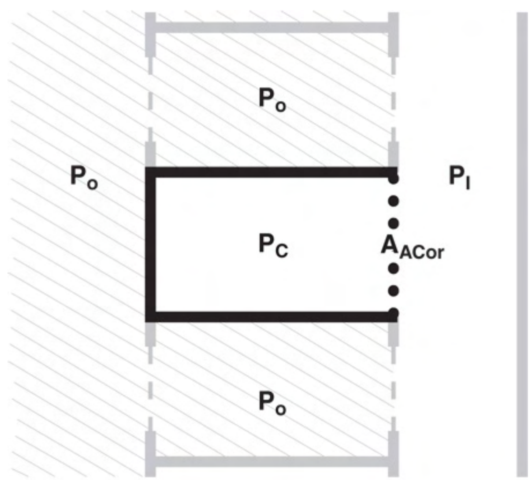


Figure 4.9
Determining Leakage Area A_{ACor}

- Windows in Rooms B and C are opened
- Windows in Room A are closed
- Doors to corridor for all rooms are initially closed; door in Room A subsequently opened

Application of Analytical Models Using New Boundary Conditions

The measured building air pressure field and measured air flows can be used with network analysis to solve the building flow and leakage regime as an alternative to using estimated or measured leakage areas and measured air flows to solve the building air pressure regime and flow regime.

The alternative approach recognizes the limitations of typically available boundary conditions and the difficulty in using existing network analytical models. It relies on using easily quantifiable parameters – the measured air pressure relationships within the building and measured air flows supplied to the building through mechanical systems rather than best guesses, experience or judgement to characterize the component leakage areas. The advantage to this approach is that the standard network model matrix equations are not altered, only the boundary conditions used with the network model matrix equations have been altered.

This inverse method of using pressures as inputs rather than leakage areas is "tuned" or calibrated by perturbing both the building and analytical model. The perturbation involves adding leakage areas of known size or air flows of known magnitude to specific pressure zones. The perturbation results in a pressure response unique to the building. This pressure response is used to apportion flows and leakage areas in the network analytical model thereby increasing the accuracy and the range of applicability of the model.

Experimental work was conducted to test the effectiveness of the approach. Two examples of using the measured building air pressure field and measured air flows with network analysis to solve the building flow and leakage regime are provided. In both cases the buildings and network models are perturbed. The results are compared to detailed measurements of component leakage areas, tabulated component leakage areas found in the literature and the measured building flow regimes obtained using tracer gas analysis.

The first example involves a recently constructed detached single family residence in Minneapolis, MN. The second example involves a 25 year old school facility in Westford, MA.

Single Family Residence – Minneapolis House

To test the effectiveness of using the pressure response of a building to solve the building air flow regime, experimental work was conducted on a single family residence in Minneapolis, MN. Field experimentation was selected over laboratory experimentation, apart from the obvious cost implications, in order to take advantage of the randomness and variability of real buildings.

In the analysis of residential structures several parameters are often readily available or readily determined:

- the total building envelope leakage area (usually determined by a "blower door" test); and
- the individual HVAC system supply and return flows to bedrooms and other areas of the house (usually determined with a flow hood).

What is often very difficult to obtain or determine are the following:

- the leakage area of individual zones or spaces; and
- the air flow within and across individual zones or spaces.

However, all this information is necessary in order to take advantage of the powerful capabilities of available multi-cell network analytical models. The experimental work used the pressure response approach, the perturbation of the building pressure field, to determine this often difficult to obtain information and compared the results with information obtained in a more traditional manner – namely tracer gas testing.

In the field experiment, the house pressure field was perturbed as follows:

- air flows of known magnitude were imposed using the house HVAC system; and
- leakage areas of known magnitude were added by opening windows.

The pressure response of each of the two perturbations was recorded. The pressure response of one type of perturbation was used to "tune" a network analytical model. The "tuning" involved apportioning the network analytical model leakage areas until the network analytical model pressure response matched the field measurements. Once tuned using this back calculation approach, the network analytical model was perturbed using the other perturbation approach. The response of the model perturbed in this manner was compared to the actual house response due to a similar type of perturbation.

Additionally, as part of the field experimental work, two types of tracer gas testing were conducted. The results of the field tracer gas testing were compared with predicted tracer gas results of the previously "tuned" network analytical model.

The intent was to show that different methods of perturbation give similar results in the apportioning of leakage areas and subsequently to show that the apportioning of network analytical model leakage areas using pressure field perturbation provides good agreement with tracer gas testing results.

Finally, the perturbation approach to apportioning network analytical model leakage areas was compared with results obtained using tabulated values for leakage areas found in the literature.

Experimental Work – Minneapolis House

The single family residence in question was constructed in 1998 in a commuter suburb of the twin cities of Minneapolis and St. Paul, MN (Photograph 4). It is a two story wood frame structure constructed over a cast concrete basement foundation. The floor plan is presented in Figure 4.10. The residence can be represented by the six zone relational model presented in Figure 4.11.

The exterior walls are constructed of 38 mm by 140 mm studs insulated with fiberglass cavity insulation. The exterior sheathing consists of 25 mm fiberboard. The exterior cladding is vinyl siding. No housewrap or exterior building paper is present. An interior polyethylene air flow retarder/vapor diffusion retarder is installed under 12 mm interior gypsum sheathing. The floor system for the main floor and for the second floor is structural oriented stand board over engineered wood joists. The basement floor is a concrete slab cast over sheet polyethylene and crushed stone.

Eight exterior air pressure taps were installed. Pressure taps were located high and low on each of the four exterior walls immediately beneath the vinyl siding. The low taps were located approximately 1.5 m above grade and the high taps were located approximately 5 m above grade. Additionally, a pressure tap was installed within the vented attic space. The exterior air pressure reference was established by extending tubing to the four sides of the residence at grade level and connecting the tubing to a pressure averaging chamber.

Winds during the time of air pressure field testing were intermittent, causing pressure fluctuations at the surface of the building envelope ±10 Pa. Interior temperatures varied between 19 and 21 degrees C. Exterior temperatures were minus 15 degrees C.

A representative plot of these exterior air pressures during the time of testing is presented in Figure 4.12. Note that the attic air pressure difference relative to the interior common area remains extremely stable. Experience has shown that under moderate wind conditions (10 kph to 25 kph) well vented attic spaces often make for a good reference pressure when exterior surface pressures fluctuate excessively and the use of numerous exterior pressure taps and a pressure averaging chamber is impractical.

A standard depressurization test, yielding a building leakage curve as described in Figure 4.13, was conducted. During this test all interior doors were open. This test quantifies the leakage area of the building envelope (the exterior walls, insulated ceiling, the walls separating the garage from the interior conditioned space, basement walls and basement slab).

The building was perturbed by adding a single flow of known magnitude to the common area zone creating differential pressures across the six zones. The perturbation was accomplished by conducting a modified depressurization test. During this test, the doors connecting the individual zones were closed and the duct distribution supply and return system sealed while air was extracted from the common area. An exhaust flow of 475 L/s was imposed on the common area of the residence. The resulting pressure field as recorded is presented in Figure 4.14 and Figure 4.15.

A six zone analytical model was created using a standard network model, CONTAM96 (Walton, 1997). CONTAM96 is a resistance based network model developed by the National Institute for Standards and Technology (NIST). The analytical model was configured to the relational model presented in Figure 4.11.

Using information from the standard depressurization test and a manual iterative (trial and error) process, the leakage areas in the CONTAM96 analytical model were apportioned until reasonable agreement occurred between the pressure field recorded in Figure 4.15 due to the perturbation resulting from adding an exhaust flow of 475 L/s to the common area and the pressure field output from the CONTAM96 analytical model subjected to the same exhaust flow (Figure 4.16). The details describing this “tuned” or calibrated CONTAM96 analytical model are contained in Appendix A.

The results are compared in Table 4.1. Note that the greatest variation exists with respect to the southeast bedroom. This was initially believed to be due to the limits of either the manual iterative process or some unidentified pathway in the building.

The pressure response of the residence was then used to test the pressure response of the “tuned” analytical model. The pressure field in the residence was perturbed two different ways to create a pressure response:

- air flows of known magnitude were imposed on individual zones and the resulting air pressure field recorded; and
- leakage areas of known magnitude were introduced to individual zones and the resulting air pressure field recorded.

The “tuned” CONTAM96 analytical model (as configured in Figure 4.16 and described in Appendix A) was similarly perturbed and the pressure response of the model compared with the actual building pressure response.

Imposed Air Flows – Minneapolis House

Air flows of known magnitude were imposed on individual zones by using the house furnace and supply duct system. Bedroom doors were closed and return ducts in the bedrooms were sealed. The basement door was left open. Air was pushed into the bedrooms from the common area by the operation of the furnace fan. Supply flows were measured using a calibrated fan (a “duct blaster”) and the resulting air pressure field, the building pressure response, was recorded (Figure 4.17).

Similar air flows were imposed on the tuned CONTAM96 analytical model (as previously configured in Figure 4.16 and described in Appendix A). The model pressure response is recorded in Figure 4.18. The results are compared in Table 4.2. The actual pressure response of the building and the pressure response of the model “trend” in the same manner and show excellent agreement except for the southeast bedroom.

Imposed Leakage Areas – Minneapolis House

Exterior windows were opened and closed under conditions where the common area was depressurized with an exhaust flow that varied between 465 L/s and 475 L/s. The bedroom doors and the basement door were closed and the supply and return ducts were sealed. Exterior windows in individual zones were opened and closed on a 15 second cycle (closed 15 seconds, open 15 seconds) for four cycles each. The varying pressure field within the house and varying exhaust flows were continuously recorded (10 readings per second) using a multi-channel digital micromanometer (Energy Conservatory Multi-Channel Mircromanometer) and plotted (Figure 4.19 through Figure 4.30). The values from the plots are summarized in Table 4.3.

Figure 4.21, Figure 4.24, Figure 4.27 and Figure 4.30 show the variation in flow through the exhaust fan as individual windows are opened and closed. The fan controls were not adjusted during the opening and closing of the exterior windows. However, the resistance to flow was affected due to the varying of the leakage areas. The flow through the fan modulated in phase with the opening and closing of the individual window openings as did the common area pressure (“house pressure”). The variation in house pressure due to the opening and closing of the individual windows is seen in Figure 4.19, Figure 4.22, Figure 4.25 and Figure 4.28. Exhaust fan flows and common area pressures hovered around 465 L/s and minus 56 Pa when individual windows were closed. The values changed to 475 L/s and minus 44 Pa when individual windows were open.

Examination of the plots indicate that the building pressure field - when window openings were closed - remained stable throughout the window opening and closing test sequence.

Figure 4.20, Figure 4.23, Figure 4.26 and Figure 4.29 show the dynamic response of the building pressure field responding to the opening and closing of individual bedroom windows. The magnitude of the specific responses to the individual window openings can be found in Table 4.3.

Table 4.4 contains the results of the dynamic response of the tuned CONTAM96 analytical model (as previously configured in Figure 4.16 and described in Appendix A). Table 4.5 compares the tuned analytical model pressure field variations with the actual field measurements. Note that the dynamic pressure response of the building and the dynamic pressure response of the tuned model trend in the same manner and show good agreement. Again, the largest variation occurs with respect to the southeast bedroom.

A "standard" CONTAM96 analytical model was constructed using the field measured building envelope leakage area. The analytical model was configured to the relational model presented in Figure 4.11. Internal leakage areas were obtained from tabulated results contained in the literature (ASHRAE, 1997). The envelope leakage area was apportioned as per common convention (ceiling 1/3, above grade walls 1/3 and basement 1/3). A 25 mm undercut was assumed for all interior doors. Leakage areas for interior partitions and floors were specified as follows:

$$A_l/A_w = 0.00011 \text{ @ } 75 \text{ Pa with the } C_D = 0.65 \qquad (4\text{-}3)$$

see ASHRAE, 1997

where A_l = air leakage area
A_w = wall or floor area
C_D = discharge coefficient

The details describing this "standard" model are contained in Appendix B.

This standard CONTAM96 analytical model (Figure 4.31) was run with a similar exhaust flow and similar configuration to the Minneapolis house as described in Figure 4.15 and the tuned CONTAM96 analytical model described in Figure 4.16.

Table 4.6 contains a comparison of the actual measured data from the house and the data derived from both the standard model and the tuned model. The standard model shows significant variations from actual measured data and the tuned model.

Tracer Gas Testing – Minneapolis House

Two tracer gas tests were conducted. Sulfur hexafluoride (SF6) was the tracer gas. The gas analyzer was programmed to measure SF6 concentrations at approximately two minute intervals at six locations: basement, first floor, northwest bedroom, southwest bedroom, southeast bedroom and the northeast bedroom. This first test was conducted with the house interior doors closed and furnace shut down. The return system and supply system ductwork was sealed. Exterior wind pressures and temperatures were measured.

Interior temperatures were maintained with portable electric resistance heaters. The heaters were computer controlled to hold temperatures constant to within 0.5 C degrees. The results are recorded in Figure 4.32.

The tuned CONTAM96 analytical model (as previously configured in Figure 4.16 and described in Appendix A), using the tracer gas decay module, was run under similar wind pressure and temperature conditions as the actual first tracer gas test. The results are presented in Figure 4.33.

The standard CONTAM96 analytical model (as described in Appendix B) was run under similar wind pressure and temperature conditions as the first tracer gas test. The results are presented in Figure 4.34.

Table 4.7 compares the results of Figure 4.32, Figure 4.33 and Figure 4.34 after a 3 hour decay period. Reasonable agreement among the actual air change measurements and the two model predictions occurs. The largest divergence occurs with the standard CONTAM96 analytical model predictions with respect to the basement air change.

The second tracer gas test was conducted with the interior doors closed and the furnace fan operating on a 20 minute on – 40 minute off duty cycle. Interior temperatures were again maintained with portable electric resistance heaters. The results are recorded in Figure 4.35. The tuned CONTAM96 analytical model and the standard CONTAM96 analytical model were also run under similar conditions. The results are presented in Figure 4.36 and Figure 4.37 respectively.

Table 4.8 compares the results of Figure 4.35, Figure 4.36 and Figure 4.37 after a 4 hour decay period. Again the results provide reasonable agreement between predictions and actual measurements. However, divergence is noted between actual air change and the predicted air change of both models for the southeast bedroom and particularly between the standard model and the actual basement air change.

After the analysis of the data from the tuned analytical model, specifically the curious response of the southeast bedroom from both an air pressure response perspective and tracer gas air change perspective, the Minneapolis house was subject to an exhaustive physical examination. A construction defect was subsequently identified that connected the southeast bedroom to the floor cavity, service chaseway containing the return air duct and garage through a return system leak and incomplete floor cavity draftstopping. It is hypothesized that such a pathway could affect the pressure response and air change of the southeast bedroom during the perturbation testing in the manner the measured data suggests.

Operation of the furnace was found to depressurize the floor cavity 0.5 Pa relative to the common area, and the service chaseway containing the return air duct was found to be depressurized 9 Pa relative to the common area above the second floor draftstopping and 2 Pa relative to the common area below the second floor draftstopping.

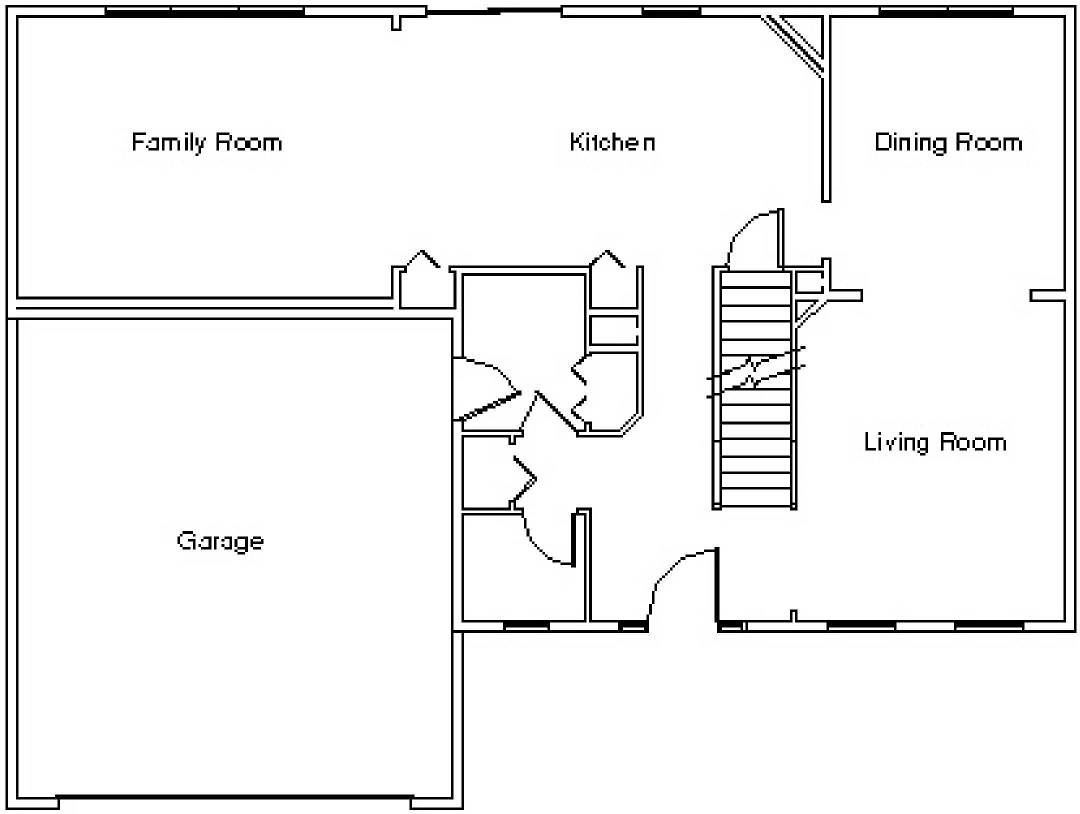
Unfortunately, simultaneous interstitial cavity pressure measurements were not taken during the perturbation testing that would enable verification of this hypothesis. Additionally, the complex flow pathway described exceeds the current modeling capabilities of COMTAM96 with respect to iterative "tuning" to allocate leakage areas along complex flow pathways. In other words, the manual trial and error leakage apportioning approach used in this thesis was found to be impractical to test this hypothesis. However, a computerized apportioning approach meeting a convergence criteria is believed to be both practical and likely to explain the observed phenomena. It remains a subject of future work and a logical next step in furthering the applicability of the approaches presented in this thesis.

It is significant to note that the network analysis used with the perturbation testing to establish boundary conditions suggested the existence of the interstitial flow, pressure and leakage regime that the depressurization of the floor cavity and service chaseway represents – but confirmation required direct measurement.

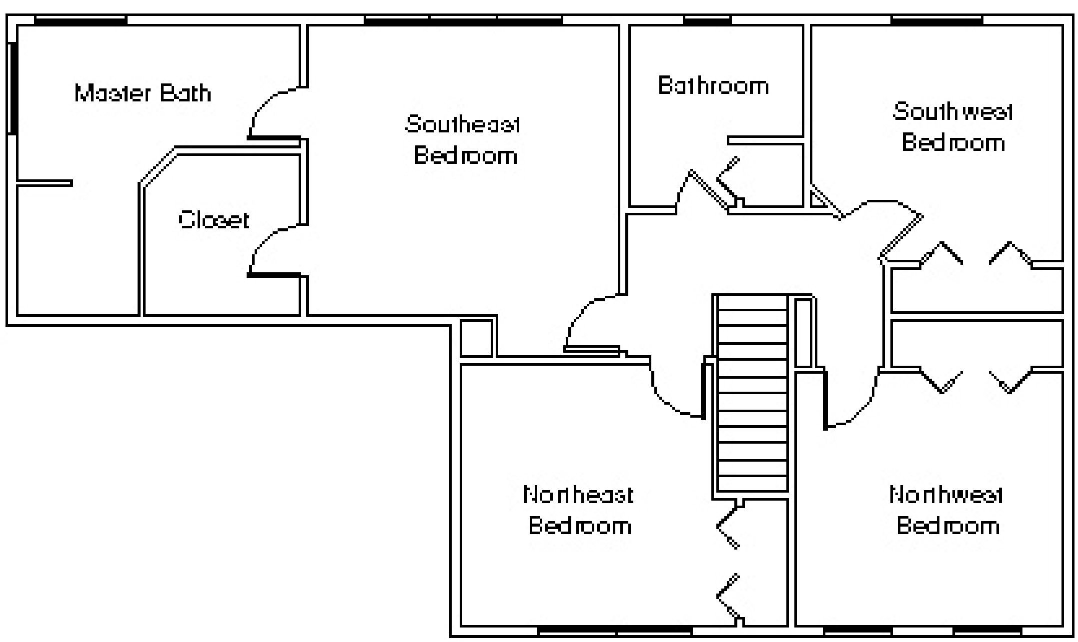
It is also significant to note that the direct measurement was done with the furnace running – in other words the furnace provided a "local" perturbation that was detected by the air pressure differential measurement instrumentation – the digital micromanometer.

Photograph 4

Minneapolis House



First Floor Plan



Second Floor Plan

Figure 4.10

Minneapolis House
Floor Plan

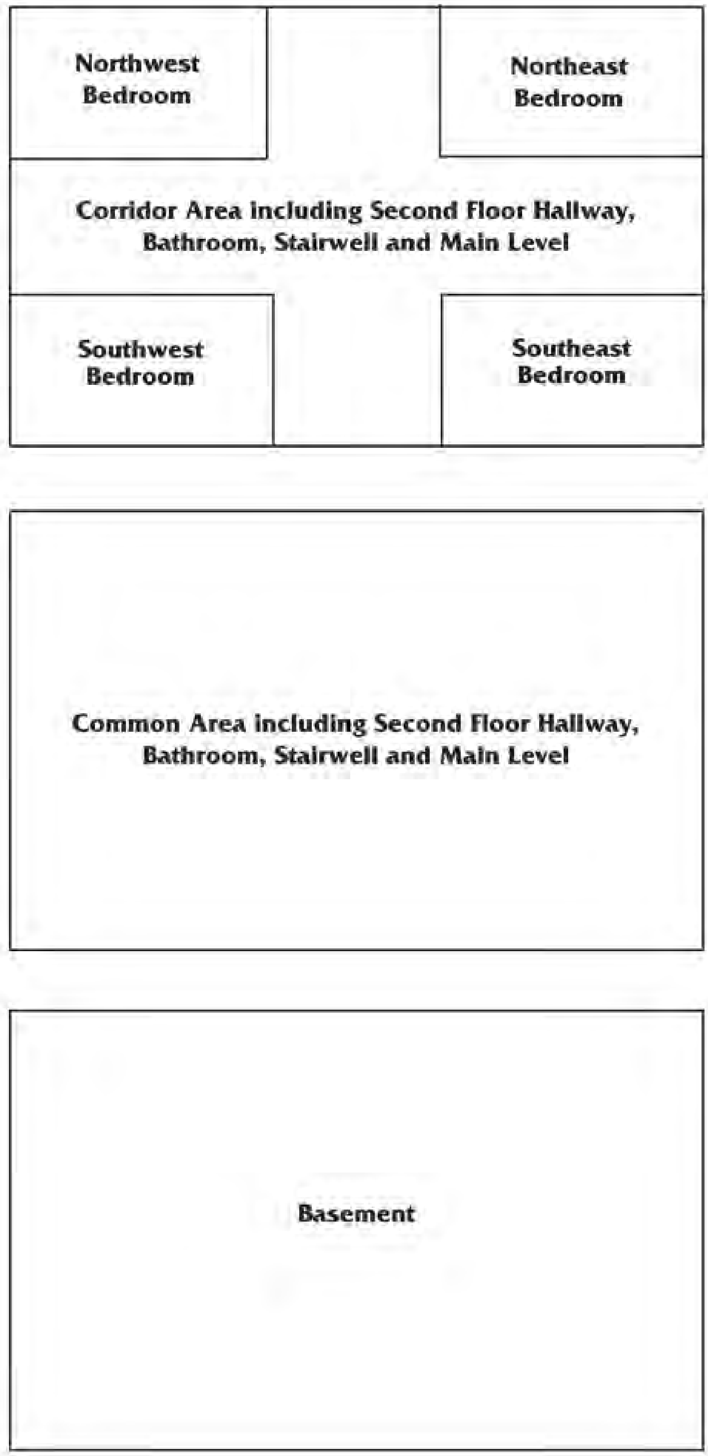


Figure 4.11
Minneapolis House
Six Zone Relational Model

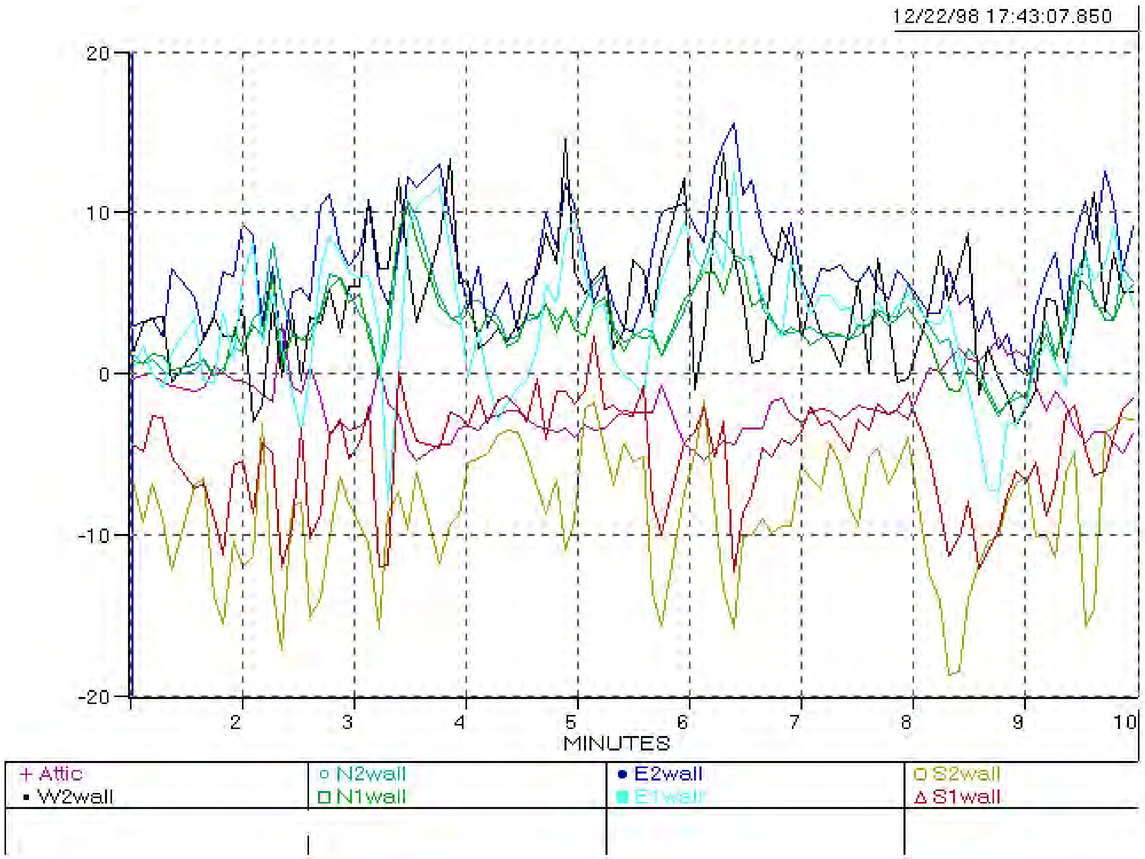


Figure 4.12

Representative Exterior Air Pressures (Pa)

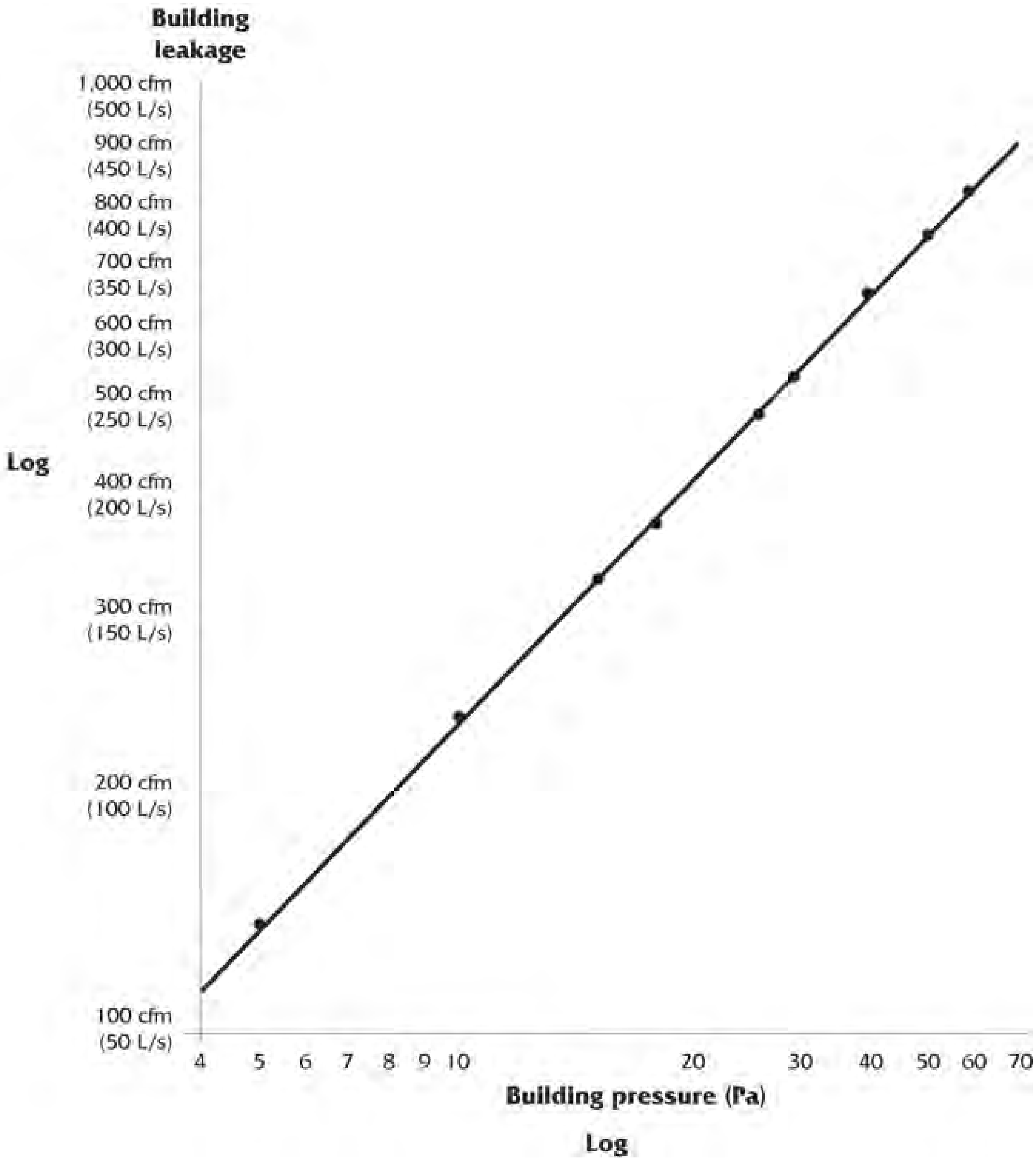


Figure 4.13

**Minneapolis House
Building Leakage Curve**

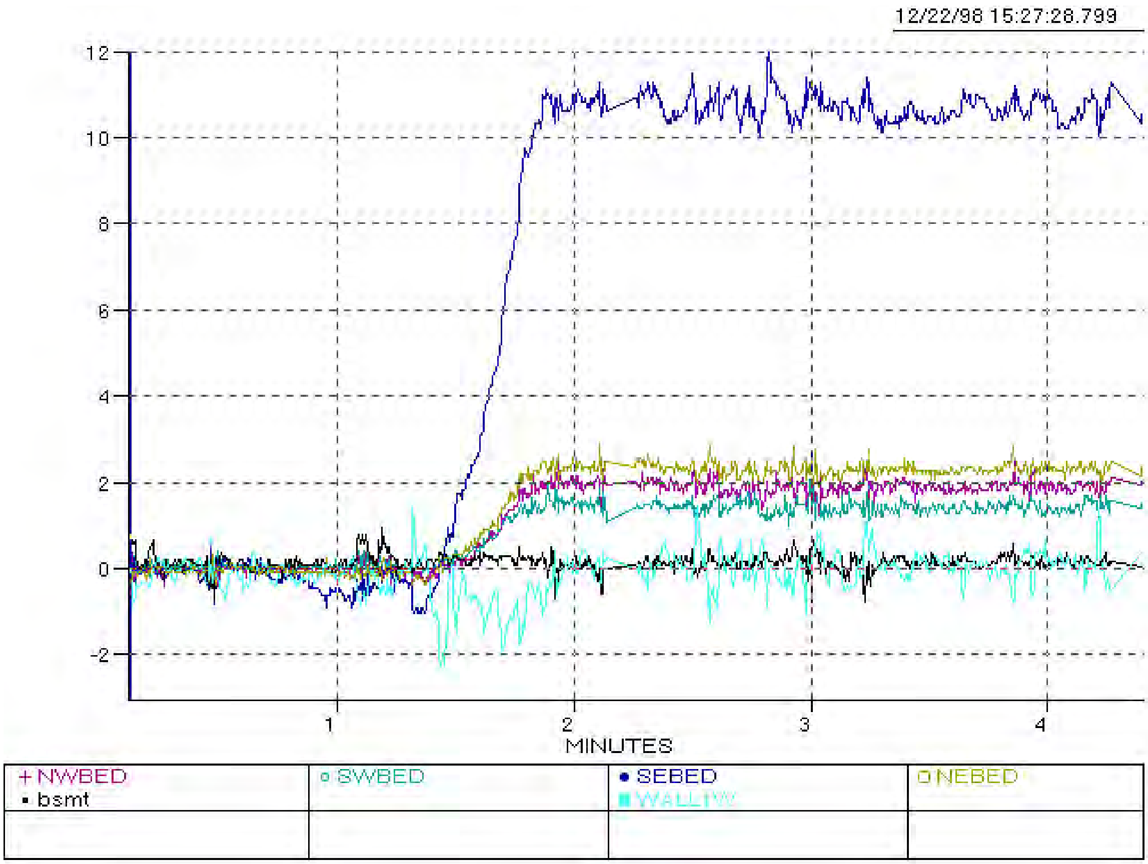


Figure 4.14

Minneapolis House

Measured Differential Pressures Due to Perturbation by Adding a Flow of Known Magnitude (Pa)

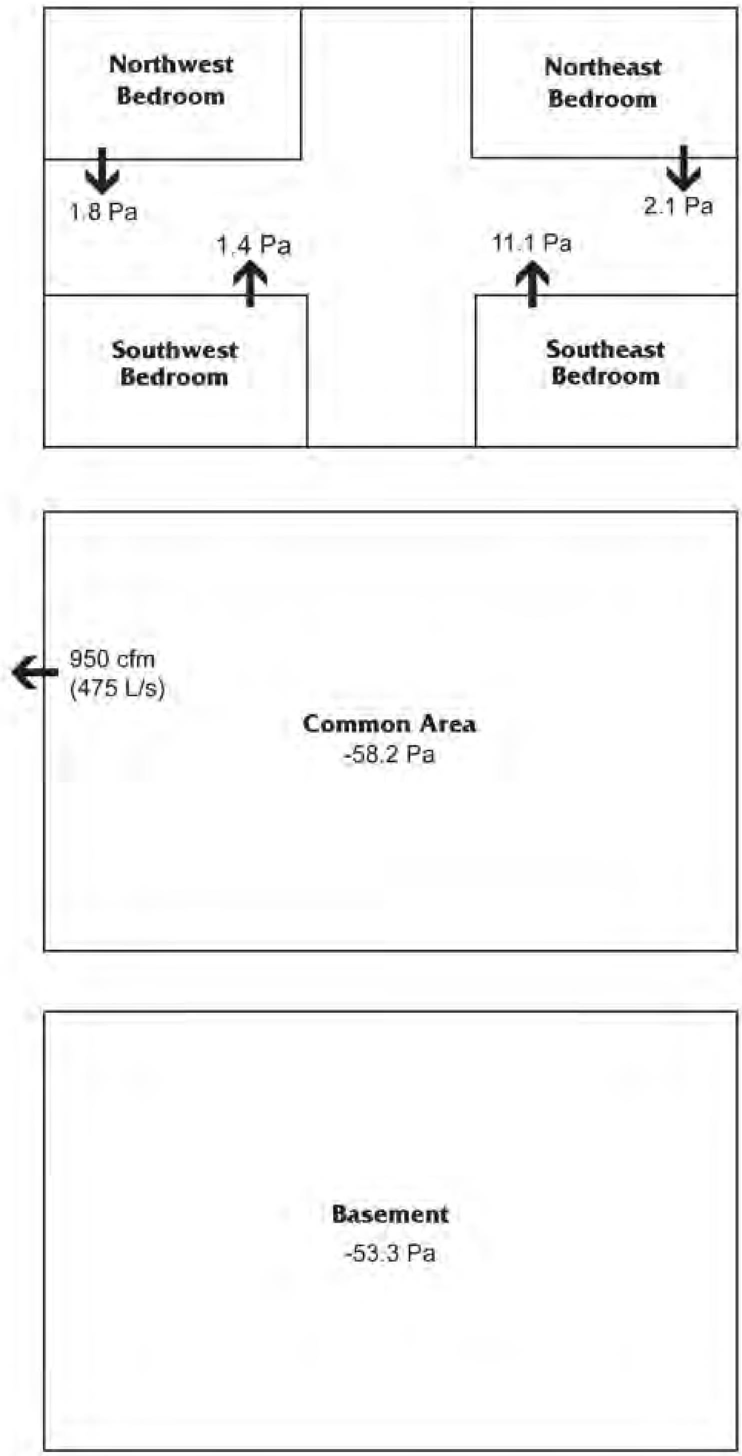


Figure 4.15
Minneapolis House
Measured Differential Pressures

- Pressures as measured with interior door and windows closed, supply and return ducts sealed
- Pressures in common area and basement relative to ambient

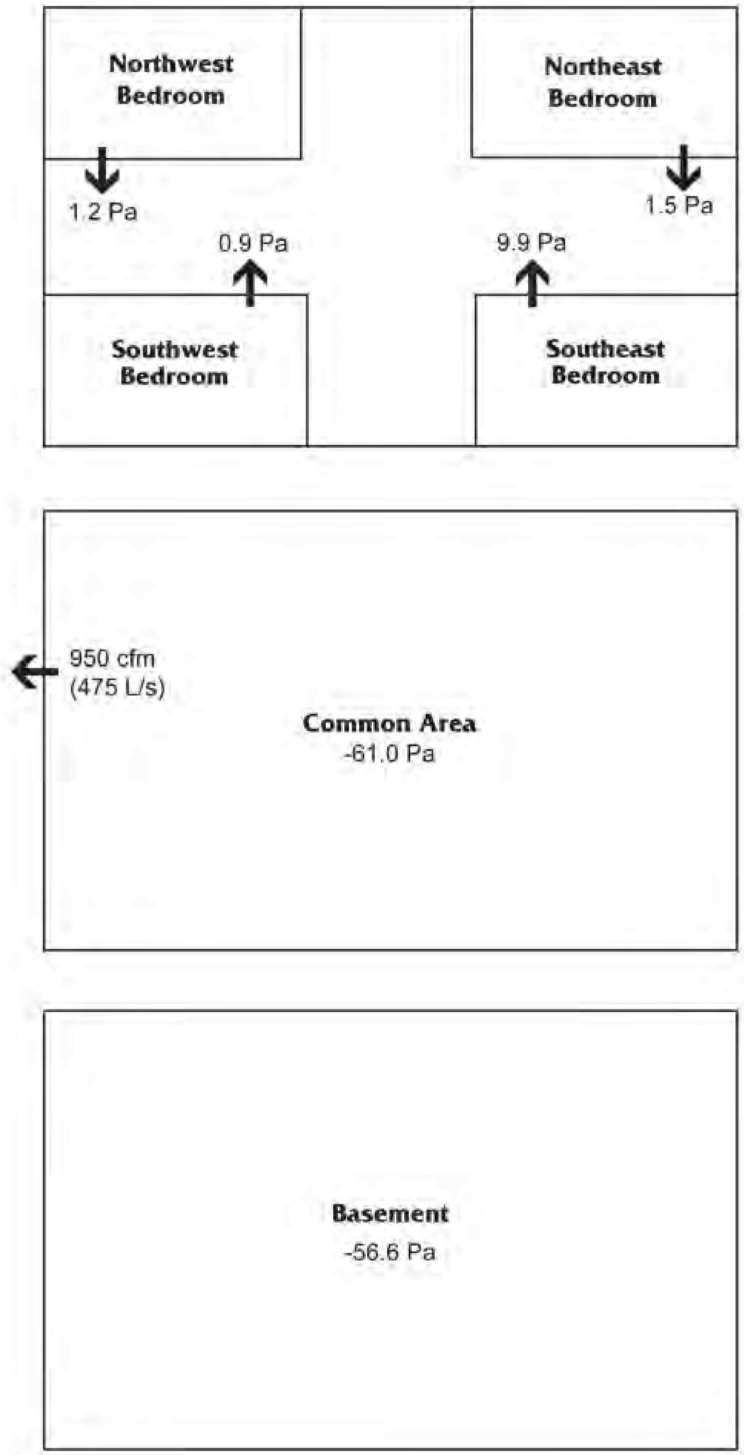


Figure 4.16
Minneapolis House
Calculated Differential Pressures

- Pressures as calculated using CONTAM96 with single exhaust fan from common area (950 cfm = 475 L/s)
- Leakage areas apportioned as described in Appendix A

Table 4-1

Minneapolis House
Measured Differential Pressures vs.
Calculated Differential Pressures (Pa)

	Northwest Bedroom	Southwest Bedroom	Southeast Bedroom	Northeast Bedroom	Common Area	Basement
Measured Pressure Response	1.8	1.4	11.1	2.1	-58.2	-53.3
Calculated Pressure Response	1.2	0.9	9.9	1.5	-61.0	-56.6

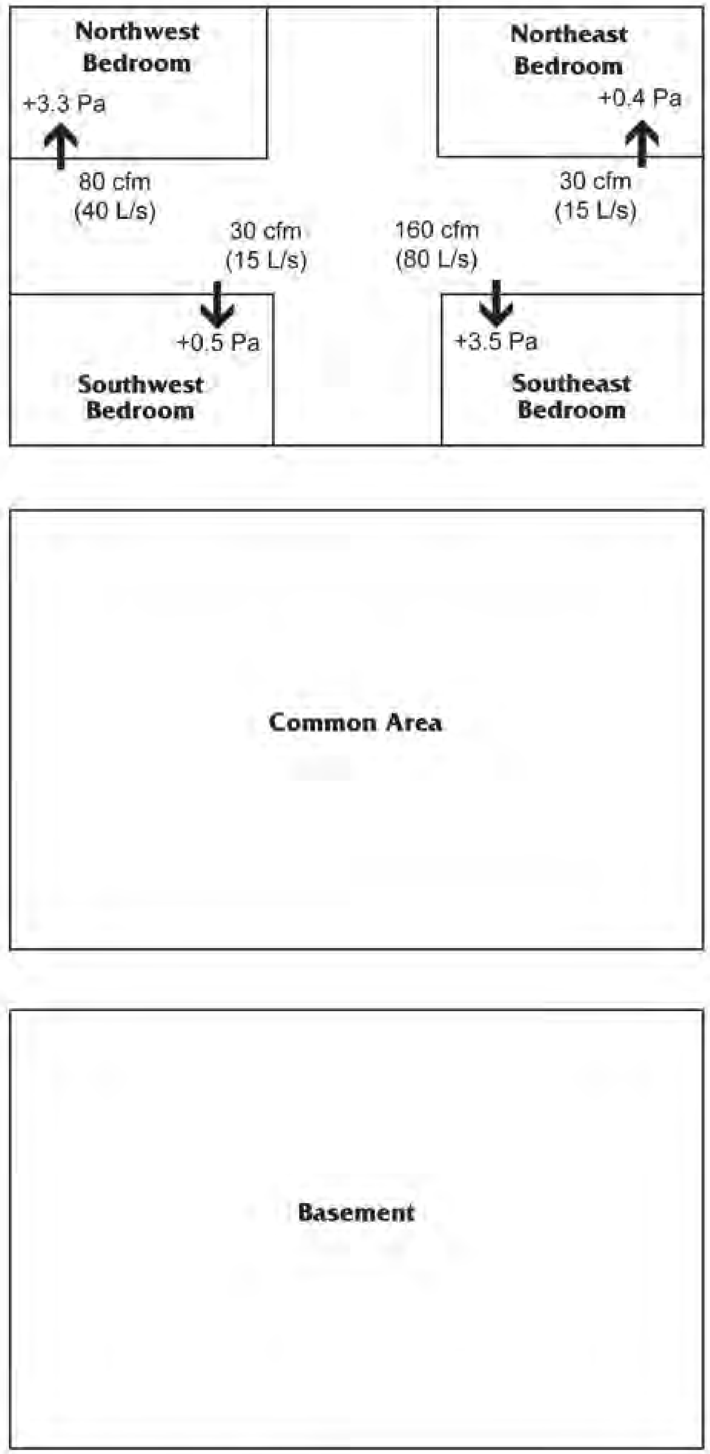


Figure 4.17

Minneapolis House

Measured Pressures Resulting from Imposed Flows

- Bedroom doors closed, basement door open, return ducts in bedrooms sealed
- Pressure field created by furnace air handler supplying air to bedrooms from common area and basement as shown

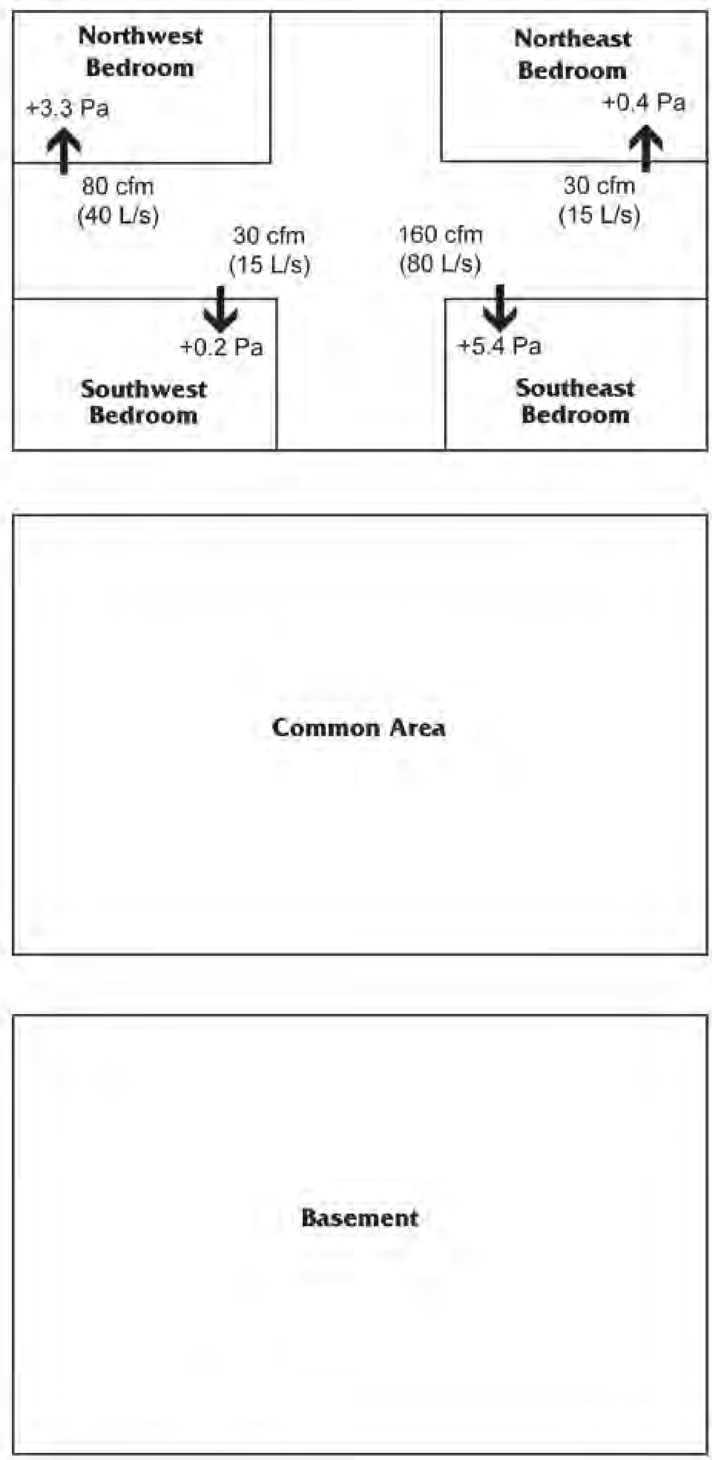


Figure 4.18
Minneapolis House
Calculated Pressures Resulting from Imposed Flows

- Pressures calculated using CONTAM96 with supply flows as shown and leakage areas apportioned as described in Appendix A

Table 4-2

Minneapolis House
Measured Pressures vs.
Calculated Pressures Resulting from Imposed Flows (Pa)

	Northwest Bedroom	Southwest Bedroom	Southeast Bedroom	Northeast Bedroom
Measured Pressure Response	3.3	0.5	3.5	0.4
Calculated Pressure Response	3.3	0.2	5.4	0.4

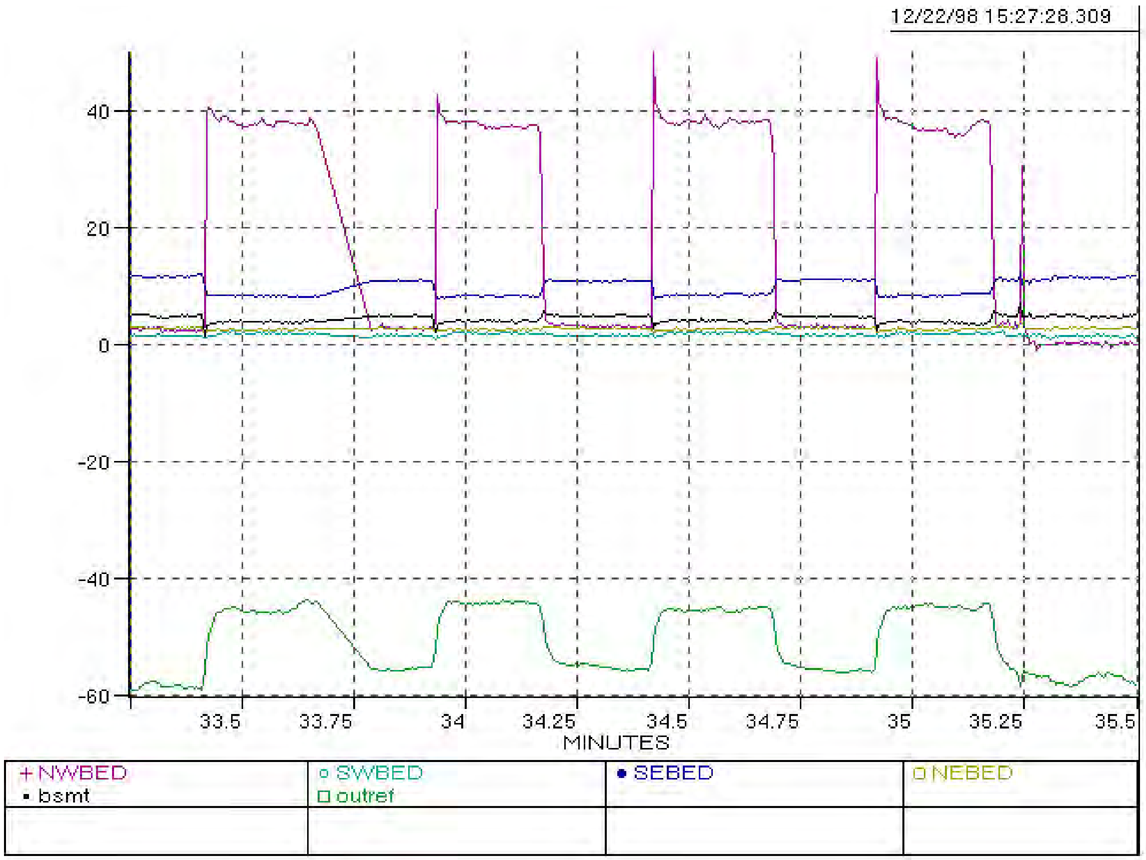


Figure 4.19

Northwest Bedroom Window Pressure Response I (Pa)

- Opening and closing NW bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

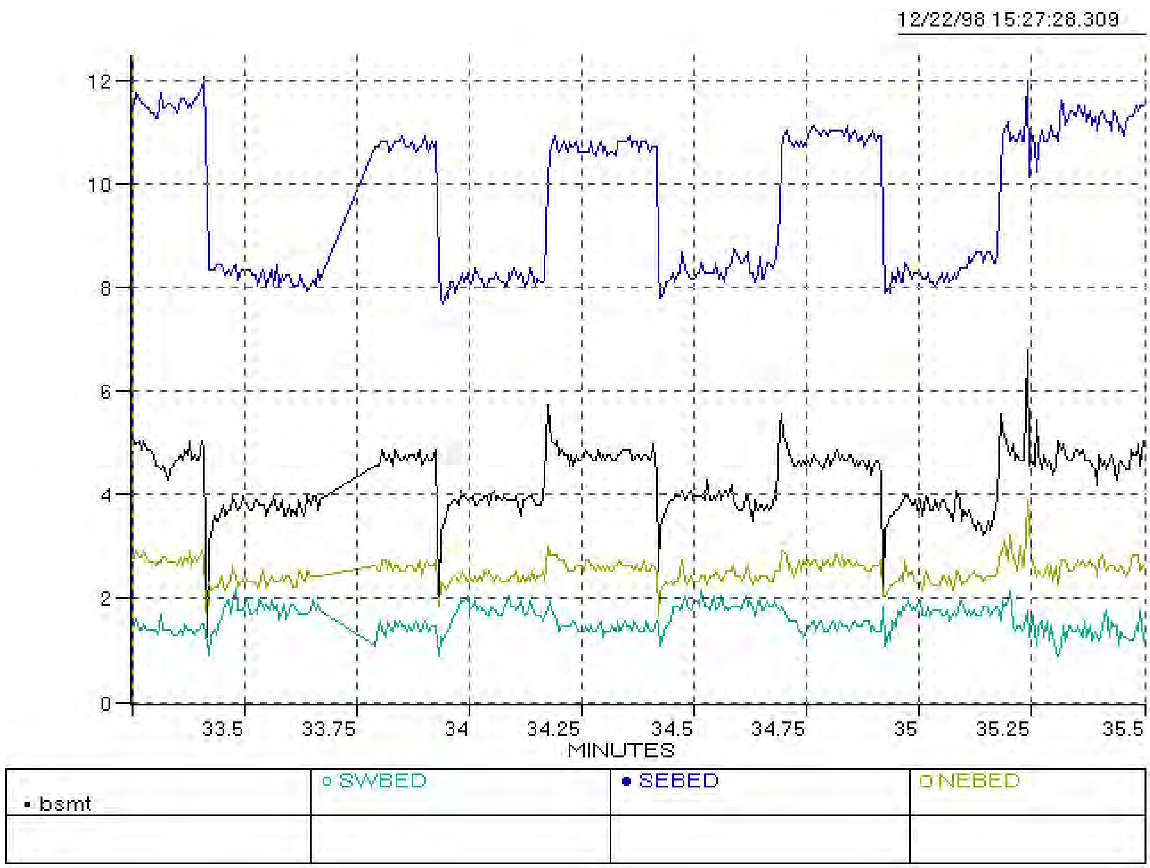


Figure 4.20

Northwest Bedroom Window Pressure Response II (Pa)

- Opening and closing NW bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

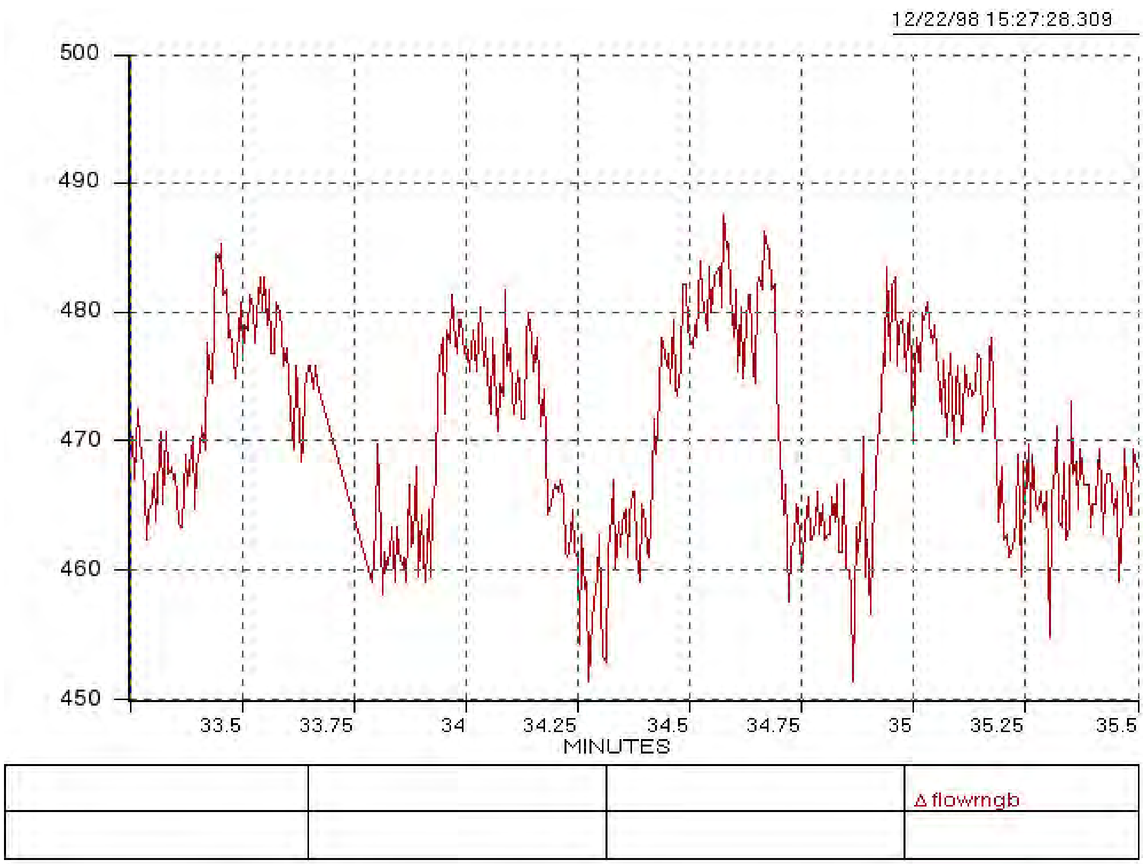


Figure 4.21

Northwest Bedroom Window Flow Response (L/s)

- Opening and closing NW bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

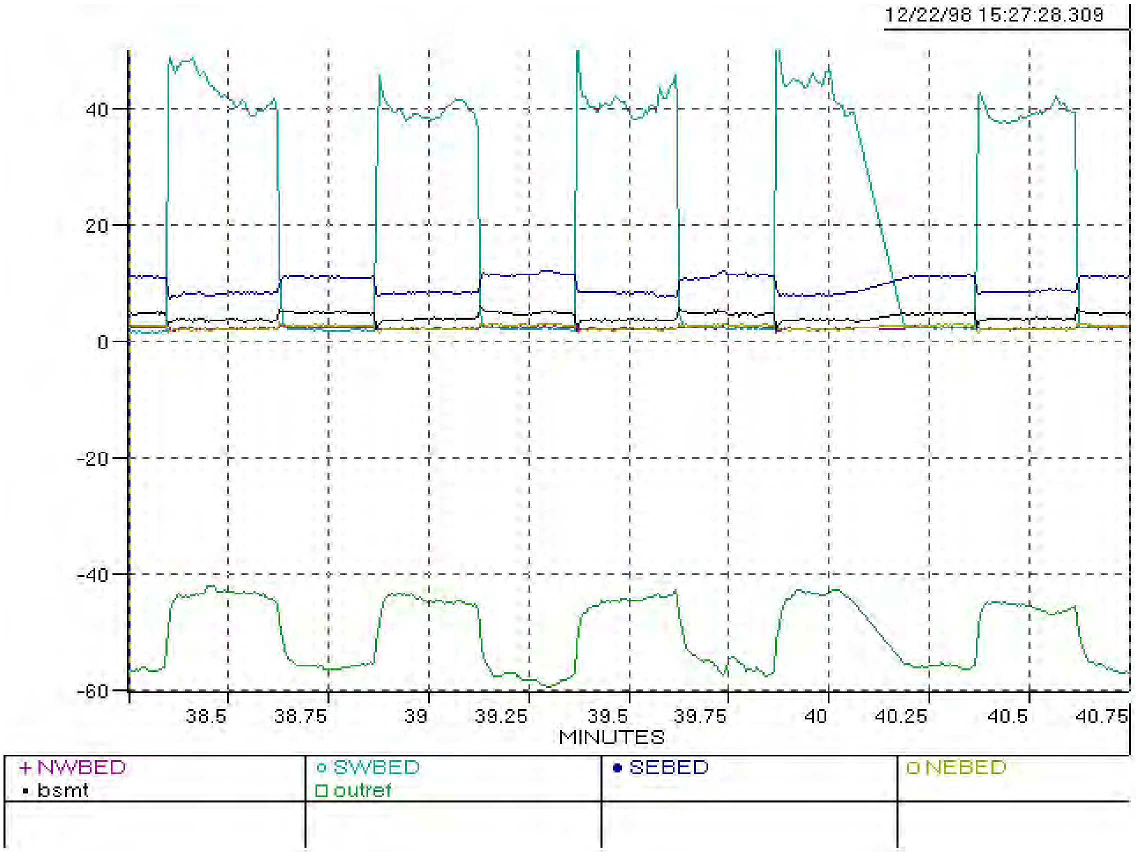


Figure 4.22

Southwest Bedroom Window Pressure Response I (Pa)

- Opening and closing SW bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

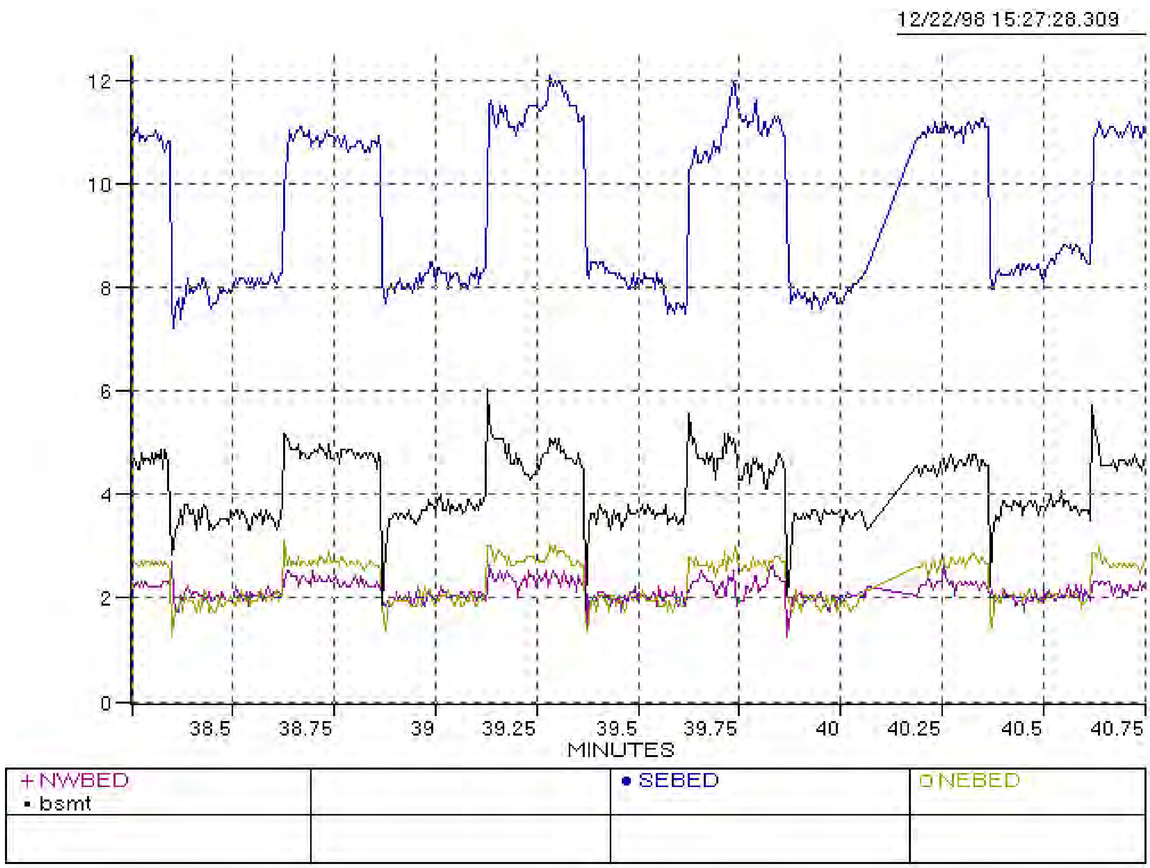


Figure 4.23

Southwest Bedroom Window Pressure Response II (Pa)

- Opening and closing SW bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

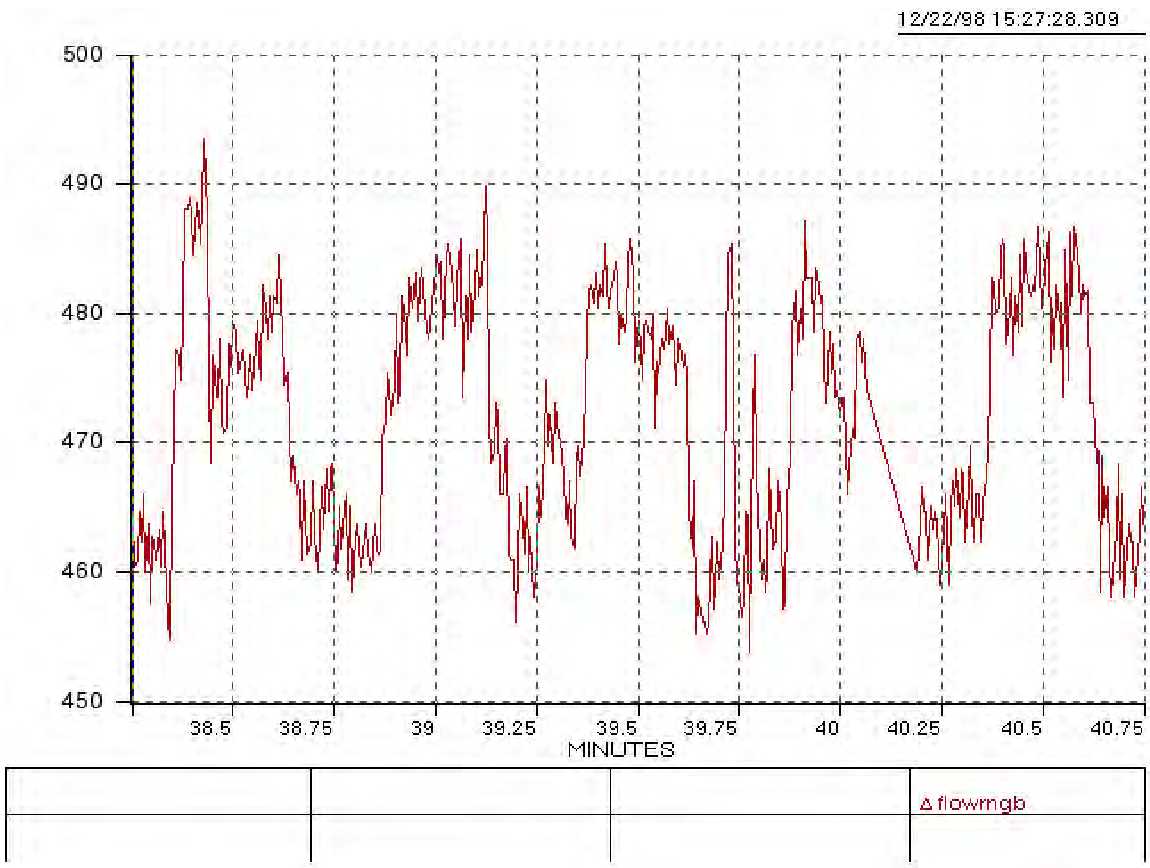


Figure 4.24

Southwest Bedroom Window Flow Response (L/s)

- Opening and closing SW bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

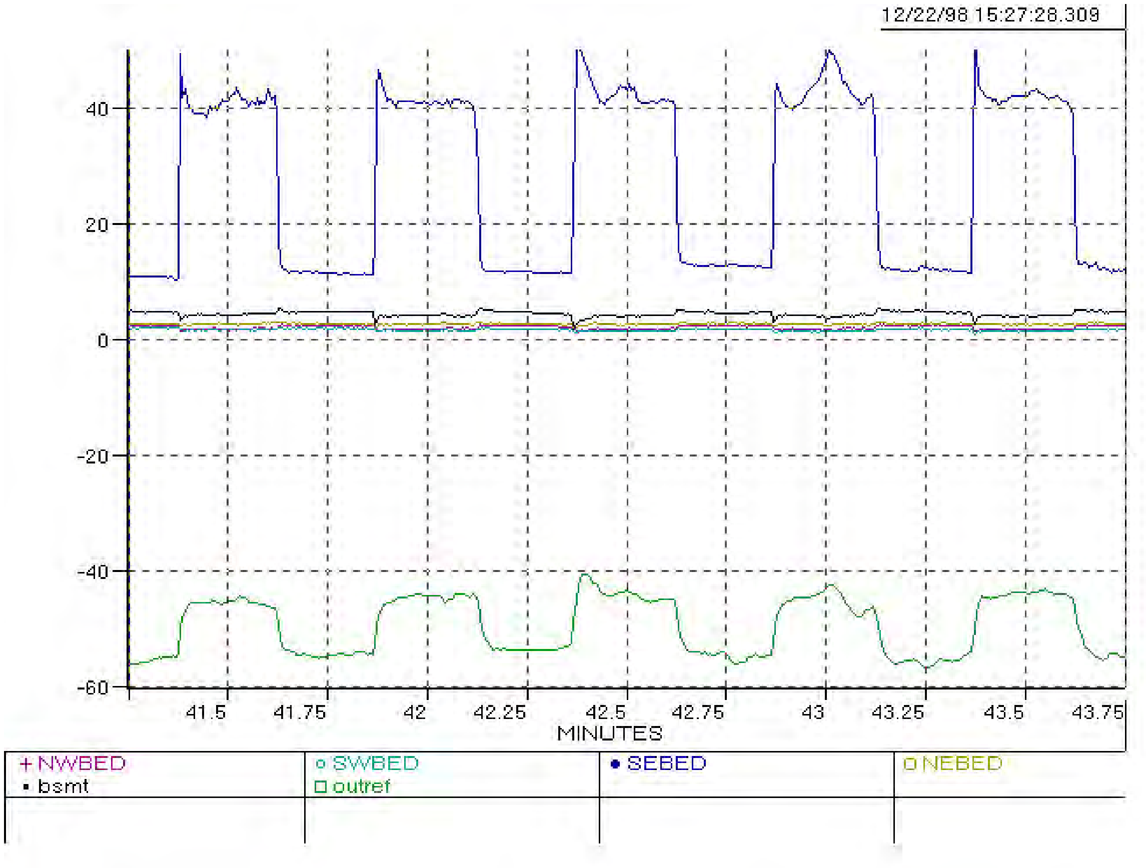


Figure 4.25

Southeast Bedroom Window Pressure Response I (Pa)

- Opening and closing SE bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

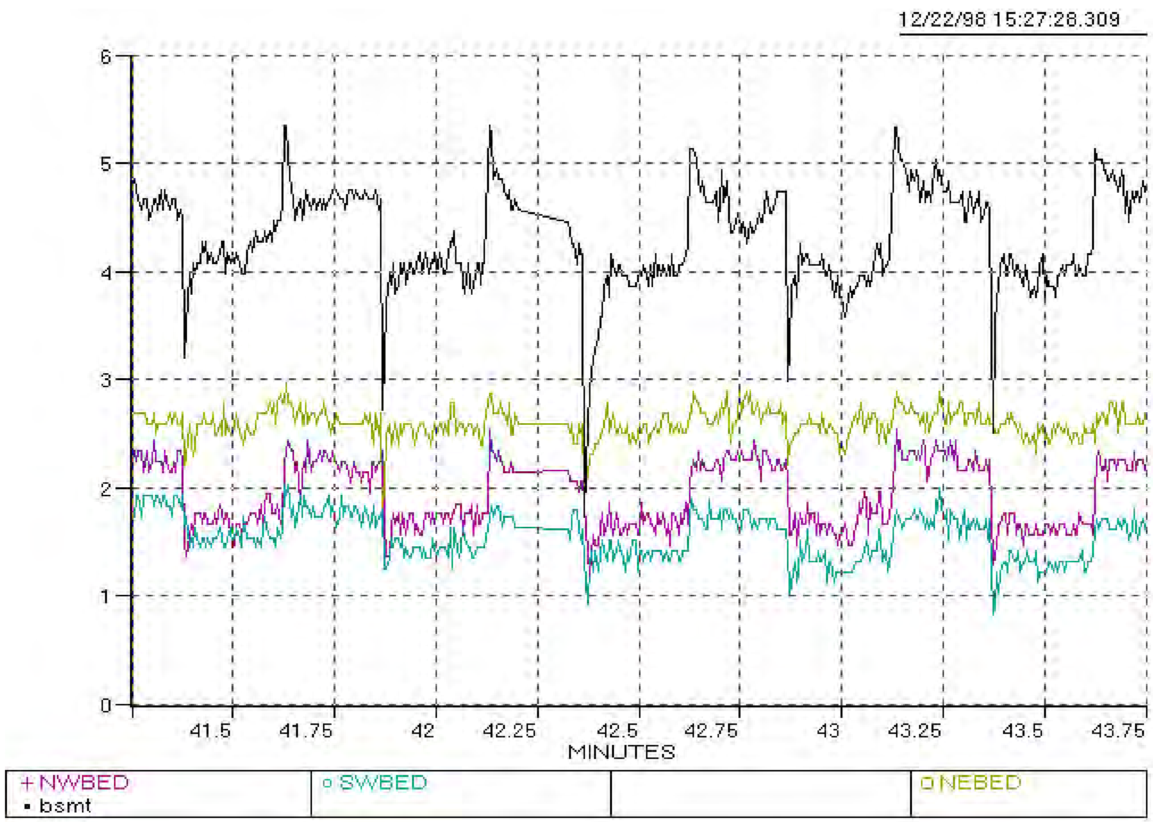


Figure 4.26

Southeast Bedroom Window Pressure Response II (Pa)

- Opening and closing SE bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

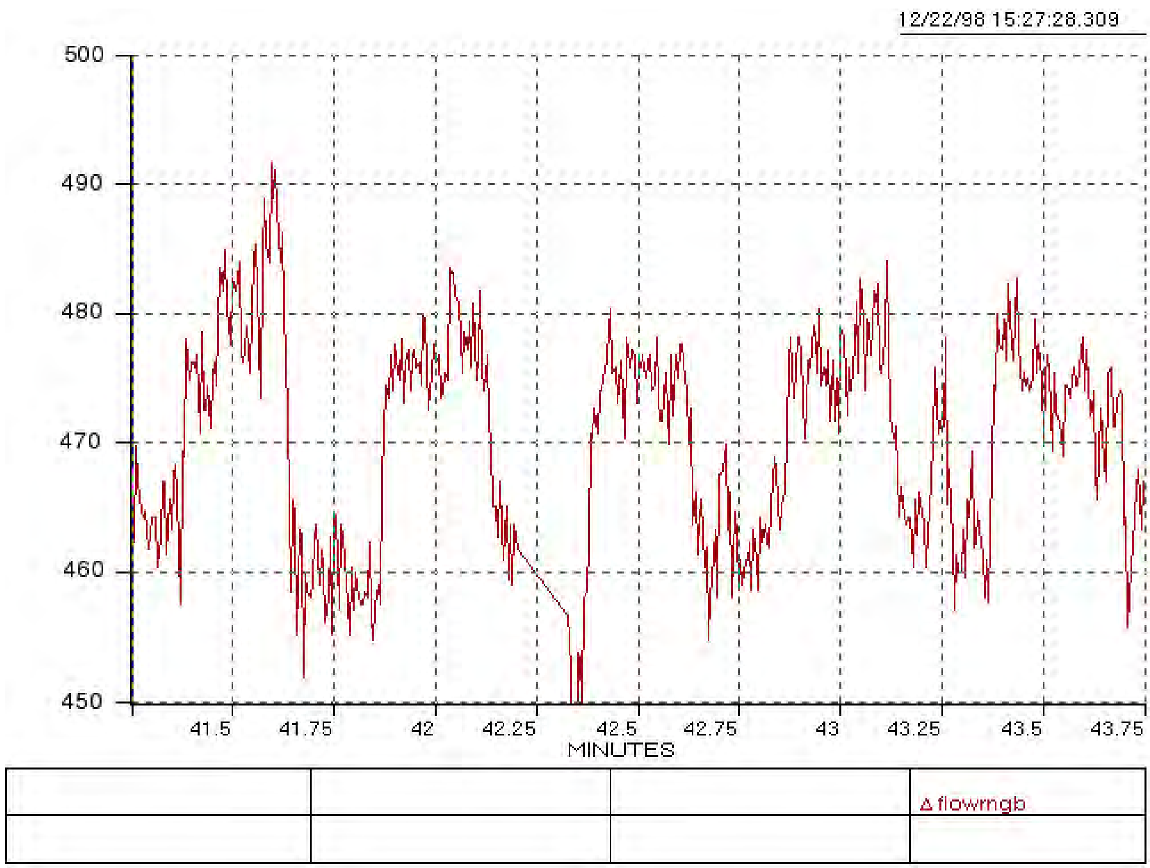


Figure 4.27

Southeast Bedroom Window Flow Response (L/s)

- Opening and closing SE bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

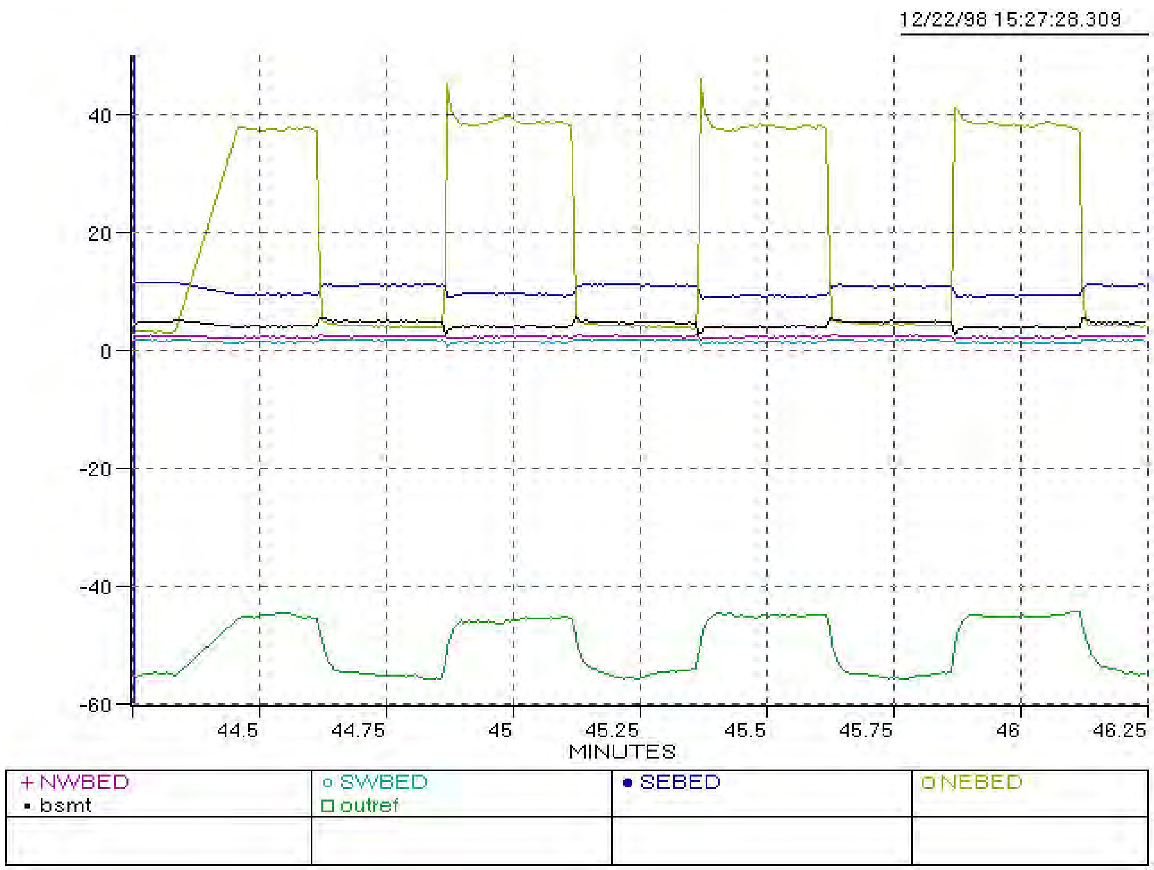


Figure 4.28

Northeast Bedroom Window Pressure Response I (Pa)

- Opening and closing NE bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

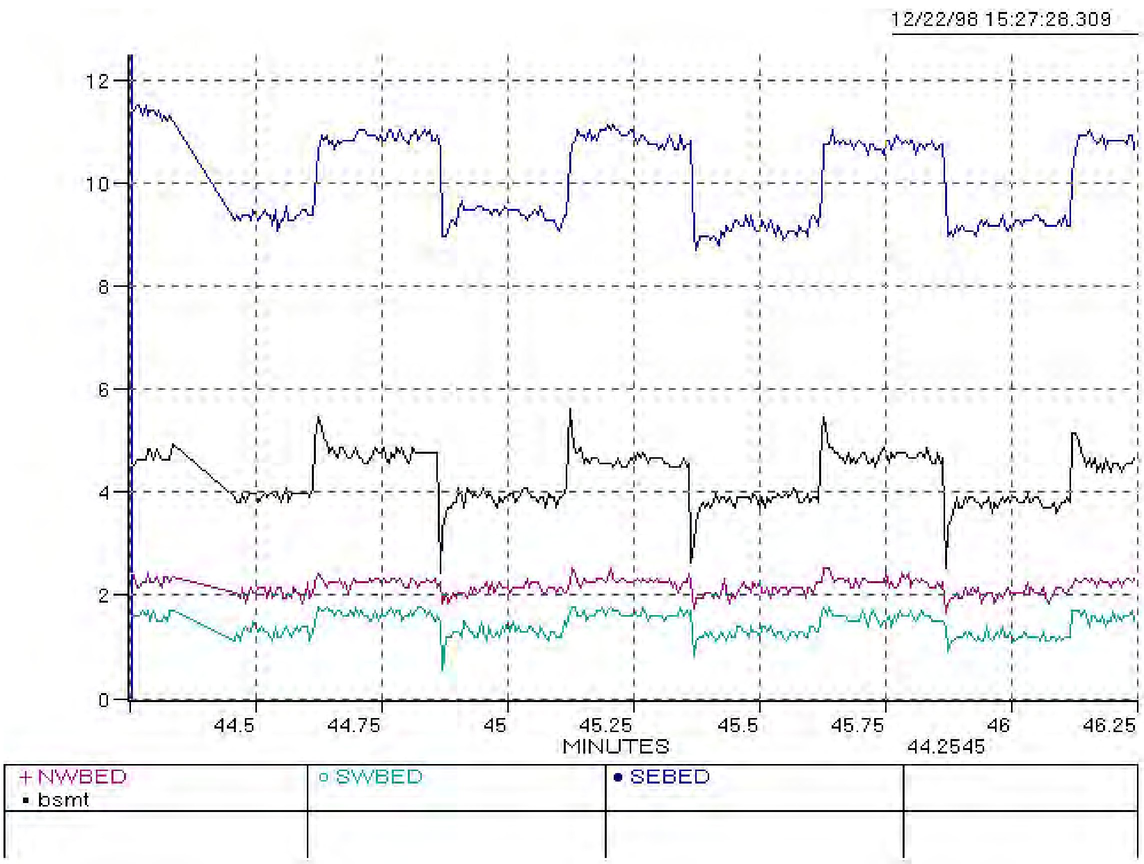


Figure 4.29

Northeast Bedroom Window Pressure Response II (Pa)

- Opening and closing NE bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

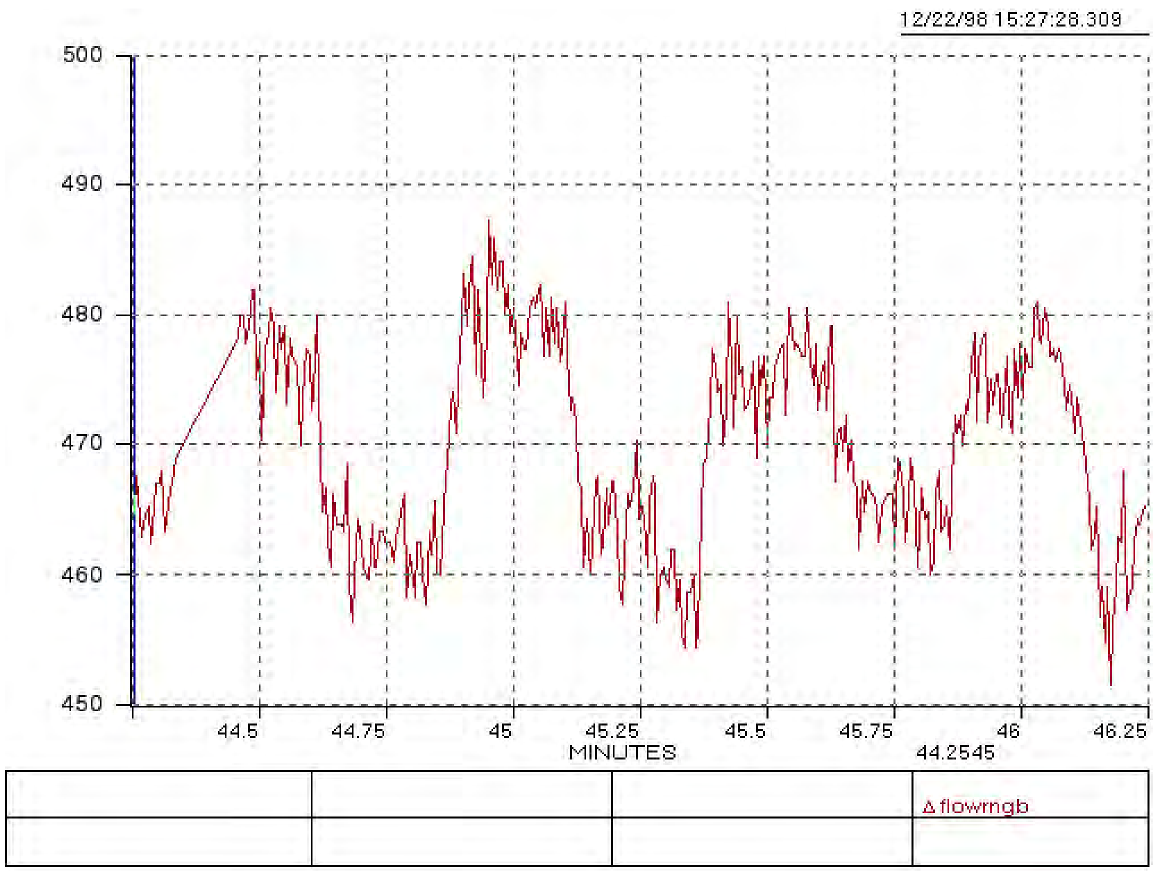


Figure 4.30

Northeast Bedroom Window Flow Response (L/s)

- Opening and closing NE bedroom window
- Bedroom and basement doors closed
- Supply and returns sealed
- Exhaust fan in common area (Blower Door operating)

Table 4-3

Minneapolis House
Dynamic Pressure Response from Imposed Leakage Areas (Pa)

	Windows Closed	Northwest Bedroom Window Open	Southwest Bedroom Window Open	Southeast Bedroom Window Open	Northeast Bedroom Window Open
Flow (L/s)	465	475	475	475	475
House	-56	-44	-44	-44	-44
NW Bedroom	2.2	38	1.9	1.8	2.1
SW Bedroom	1.4	1.9	38	1.0	1.3
SE Bedroom	11.8	8.2	7.8	41	9.0
NE Bedroom	2.6	2.2	1.8	2.6	38
Basement	4.8	3.8	3.4	4.0	3.8

Table 4-4

Minneapolis House
Dynamic Pressure Response of Tuned CONTAM96 Analytical Model (Pa)

	Windows Closed	Northwest Bedroom Window Open	Southwest Bedroom Window Open	Southeast Bedroom Window Open	Northeast Bedroom Window Open
Flow (L/s)	465	475	475	475	475
House	-59	-42	-34	-44	-41
NW Bedroom	1.2	34	0.5	0.8	0.7
SW Bedroom	0.8	0.5	23	0.6	0.5
SE Bedroom	9.5	6.0	4.4	34	5.8
NE Bedroom	1.5	0.9	0.7	0.9	32
Basement	4.2	2.8	2.1	2.9	2.7

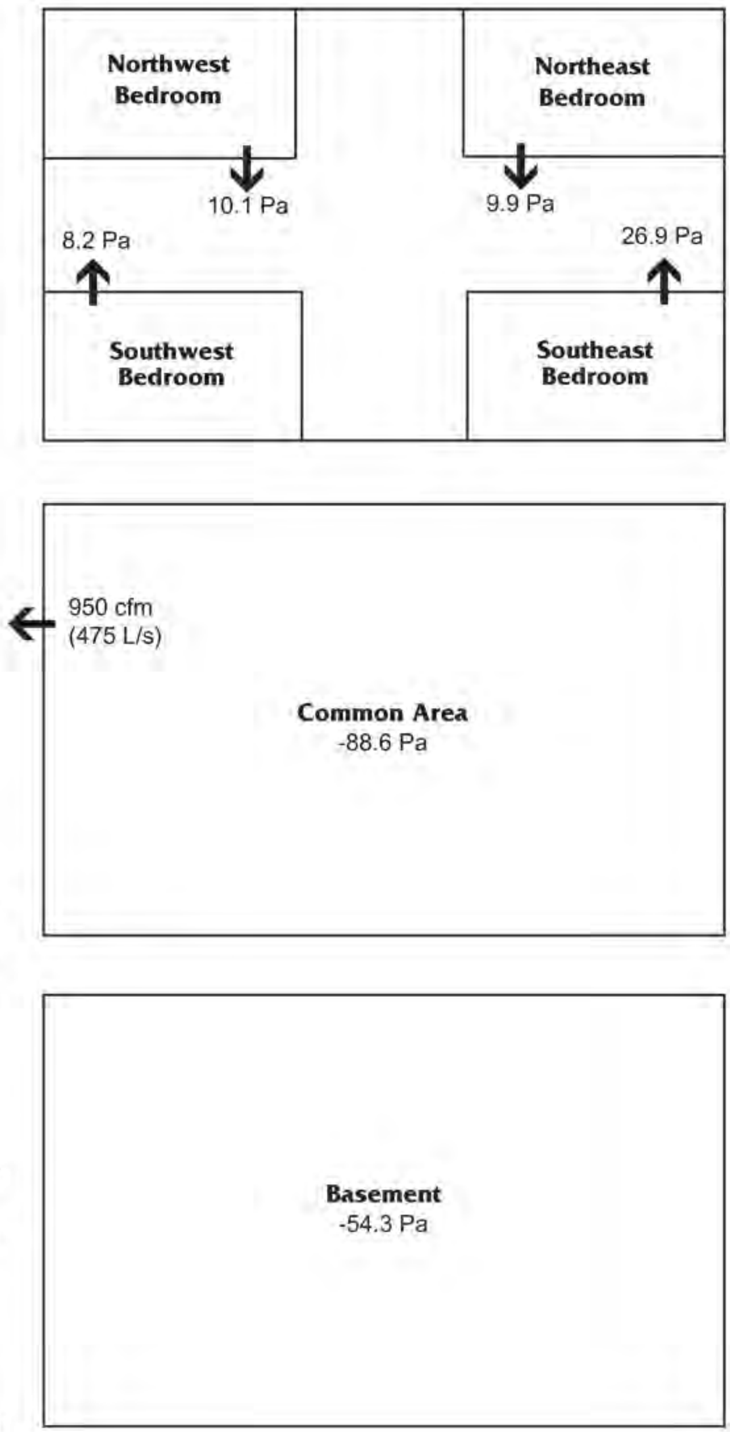


Figure 4.31
Minneapolis House Standard CONTAM96 Analytical Model

- Envelope leakage area from direct measurements (CFM50=730; exhaust flow of 365 L/s depressurized envelope 50 Pa)
- Zonal leakage apportioned from tabulated component leakage in the literature
- Envelope leakage area apportioned 1/3 ceiling, 1/3 exterior walls, 1/3 basement
- Interior leakage areas for interior partitions and floors taken from ASHRAE Fundamentals - 1999

  $A_L/A_W = 0.11 \times 10\text{-}3$

  where A_L = air leakage area

  A_W = wall or floor area

  $C_D = 0.65$ @ 75 Pa
- 25 mm undercut assumed for all interior doors
- Model details contained in Appendix B

Table 4-5

Differences in Pressure Response Between Minneapolis House and Tuned CONTAM96 Analytical Model (Pa)

	Windows Closed	Northwest Bedroom Window Open	Southwest Bedroom Window Open	Southeast Bedroom Window Open	Northeast Bedroom Window Open
NW Bedroom	1.0	—	1.4	1.0	1.4
SW Bedroom	0.6	1.4	—	0.4	0.8
SE Bedroom	2.3	2.2	3.4	—	3.2
NE Bedroom	1.1	1.3	1.1	1.7	—
Basement	0.5	1.0	1.3	1.1	1.1

Table 4-6

Minneapolis House
Comparisons of Measured Differential Pressures with Calculated Differential Pressures for a Tuned Model and a Standard Model (Pa)

	Northwest Bedroom	Southwest Bedroom	Southeast Bedroom	Northeast Bedroom	Common Area	Basement
Actual	1.8	1.4	11.1	2.2	-58.2	-53.3
Tuned Model	1.2	0.9	9.9	1.5	-61.0	-56.6
Standard Model	10.1	8.2	26.9	9.9	-88.6	-54.3

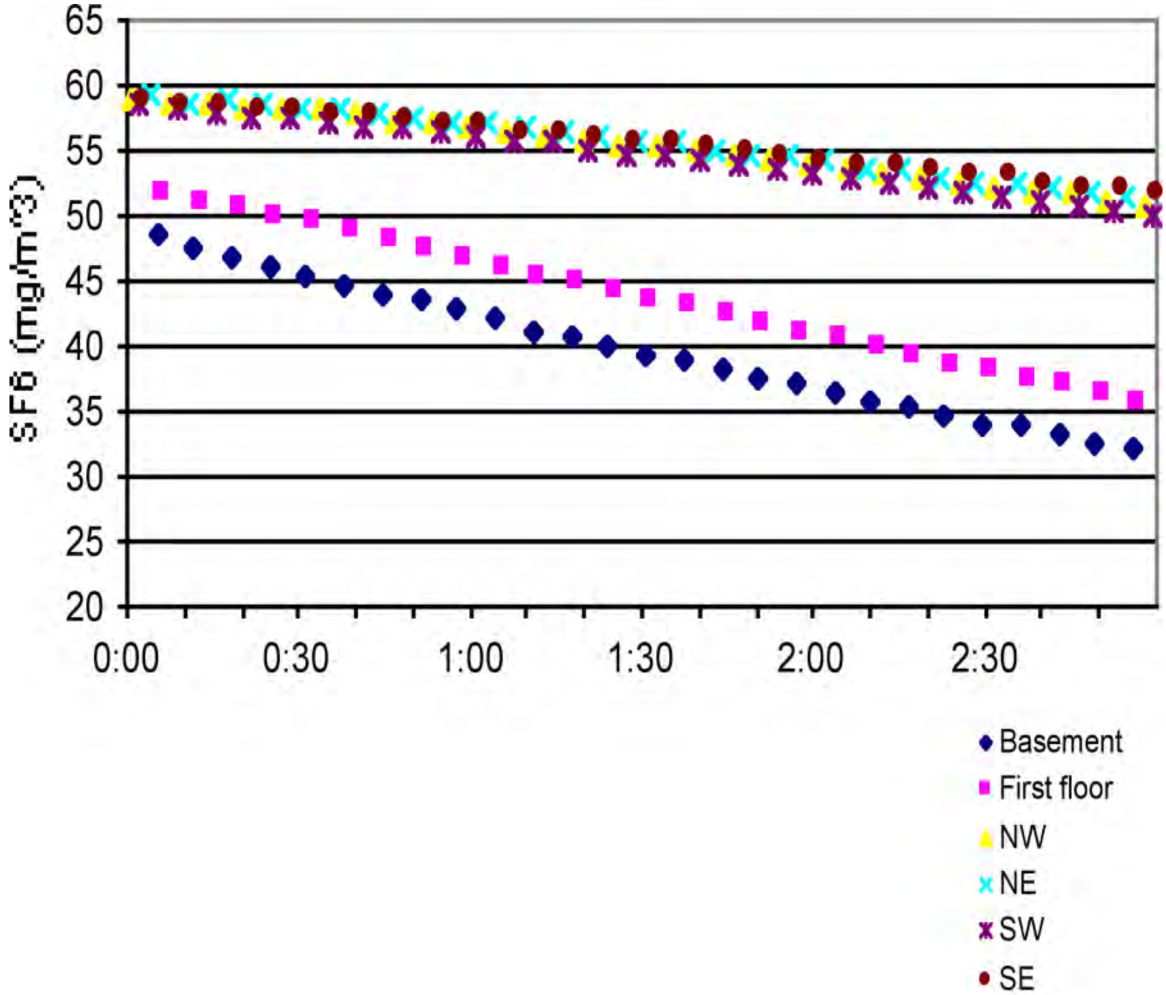


Figure 4.32

Minneapolis House
Tracer Gas Results with HVAC System Off/Doors Closed

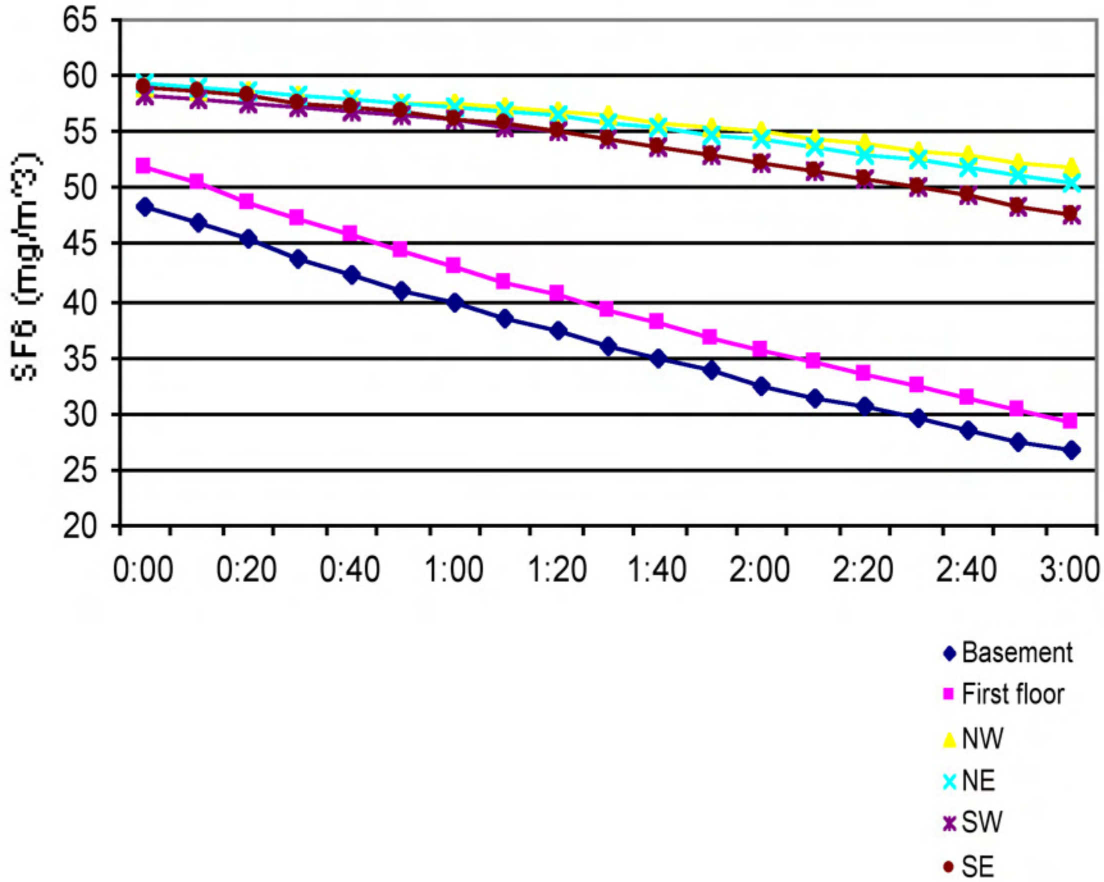


Figure 4.33

Minneapolis House
Tuned CONTAM96 Analytical Model
Tracer Gas Results with HVAC System Off/Doors Closed

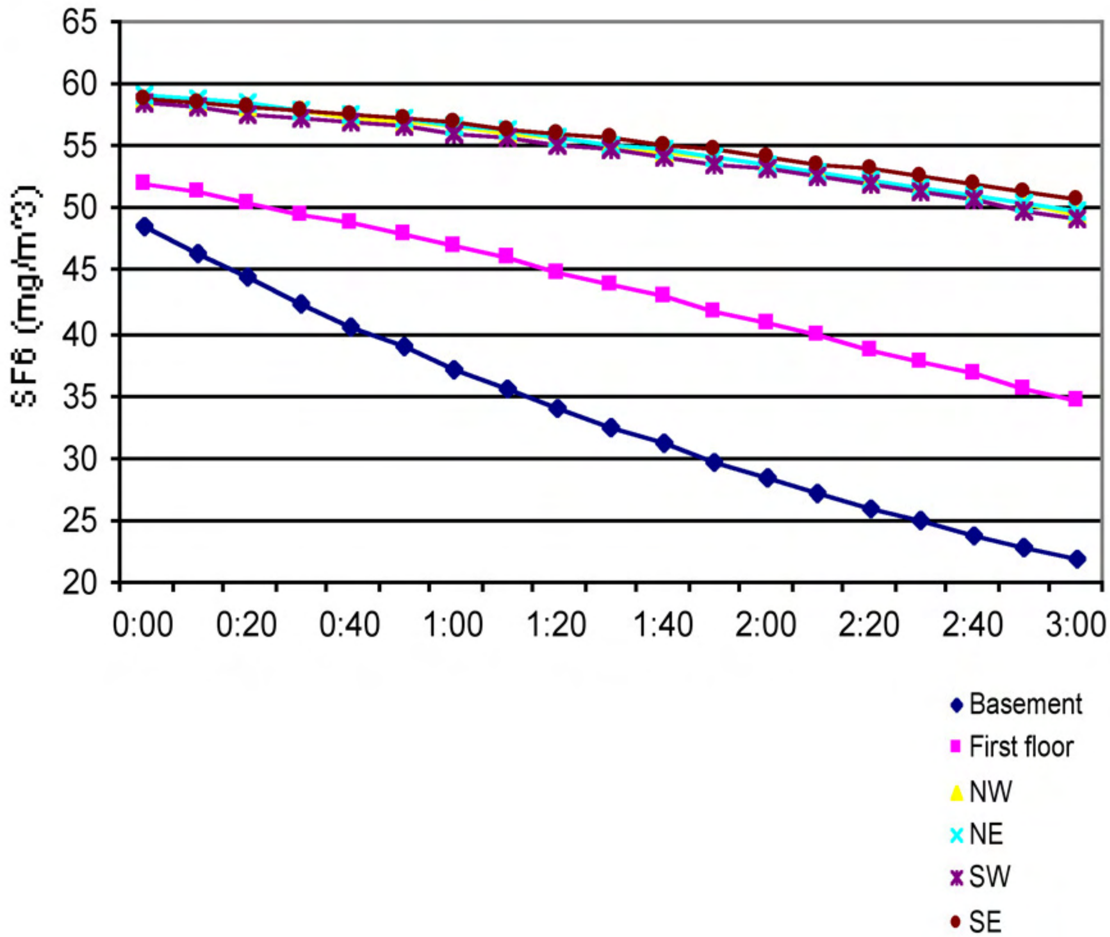


Figure 4.34

Minneapolis House
Standard CONTAM96 Analytical Model
Tracer Gas Results with HVAC System Off/Doors Closed

Table 4-7

Minneapolis House Tracer Gas Comparisons
Actual vs. Analytical Models
HVAC System Off/Doors Closed

	Northwest Bedroom	Southwest Bedroom	Southeast Bedroom	Northeast Bedroom	Basement	First Floor
Initial Condition	58	58	58	58	48	52
Actual	51	50	53	52	32	35
Tuned Model	52	48	48	51	27	29
Standard Model	50	49	51	50	22	35

- SF_6 concentrations given in mg/m^3
- Decay concentration after 3-hour period

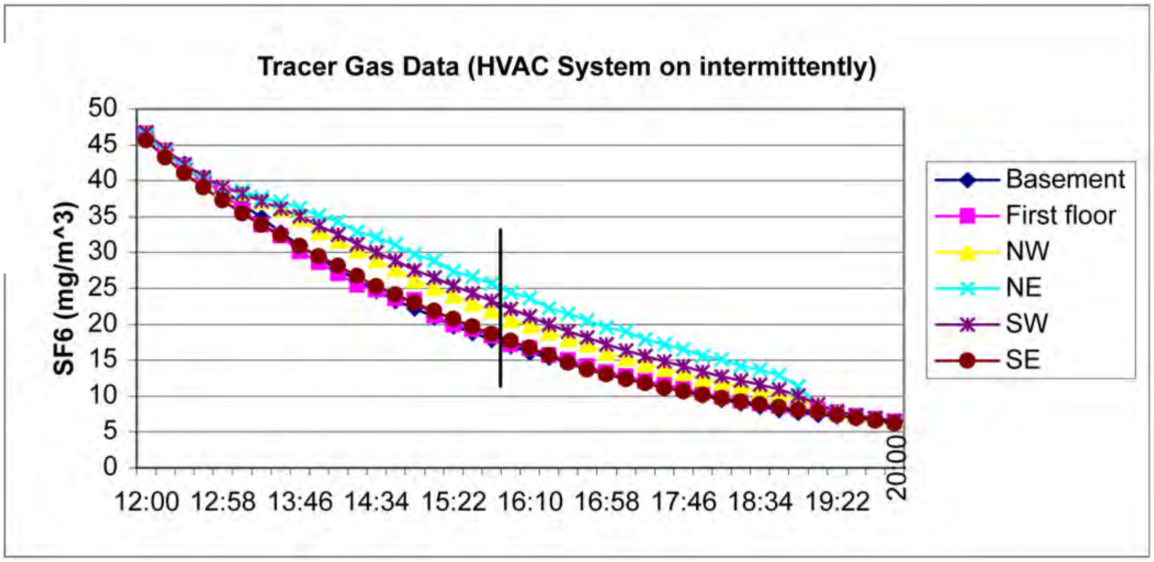


Figure 4.35

Minneapolis House
Tracer Gas Results with HVAC System On/Doors Closed

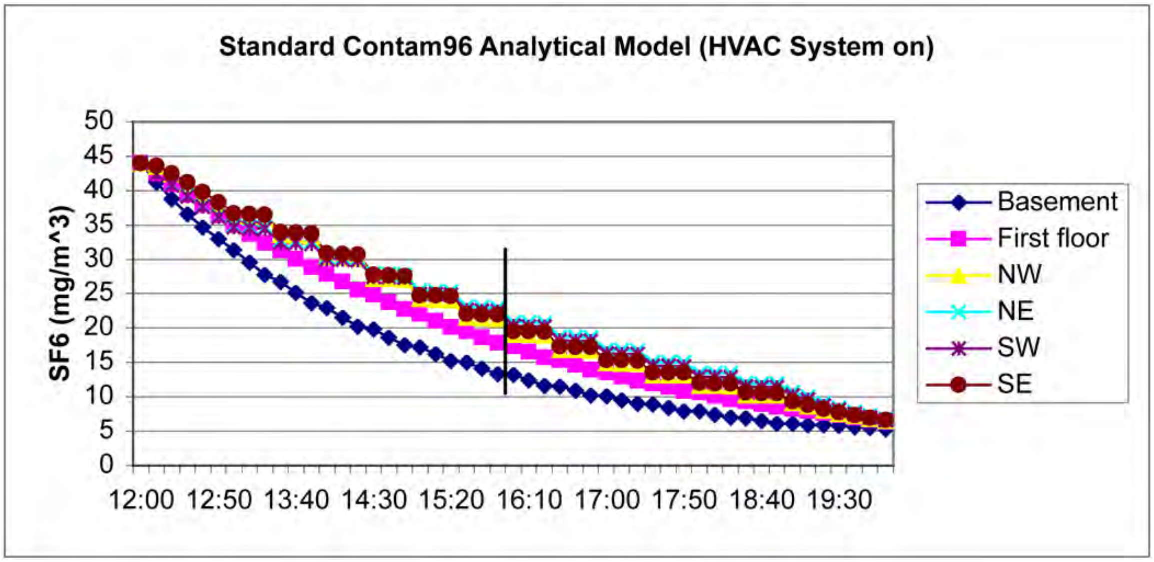


Figure 4.36

Minneapolis House
Tuned CONTAM96 Analytical Model
Tracer Gas Results with HVAC System On/Doors Closed

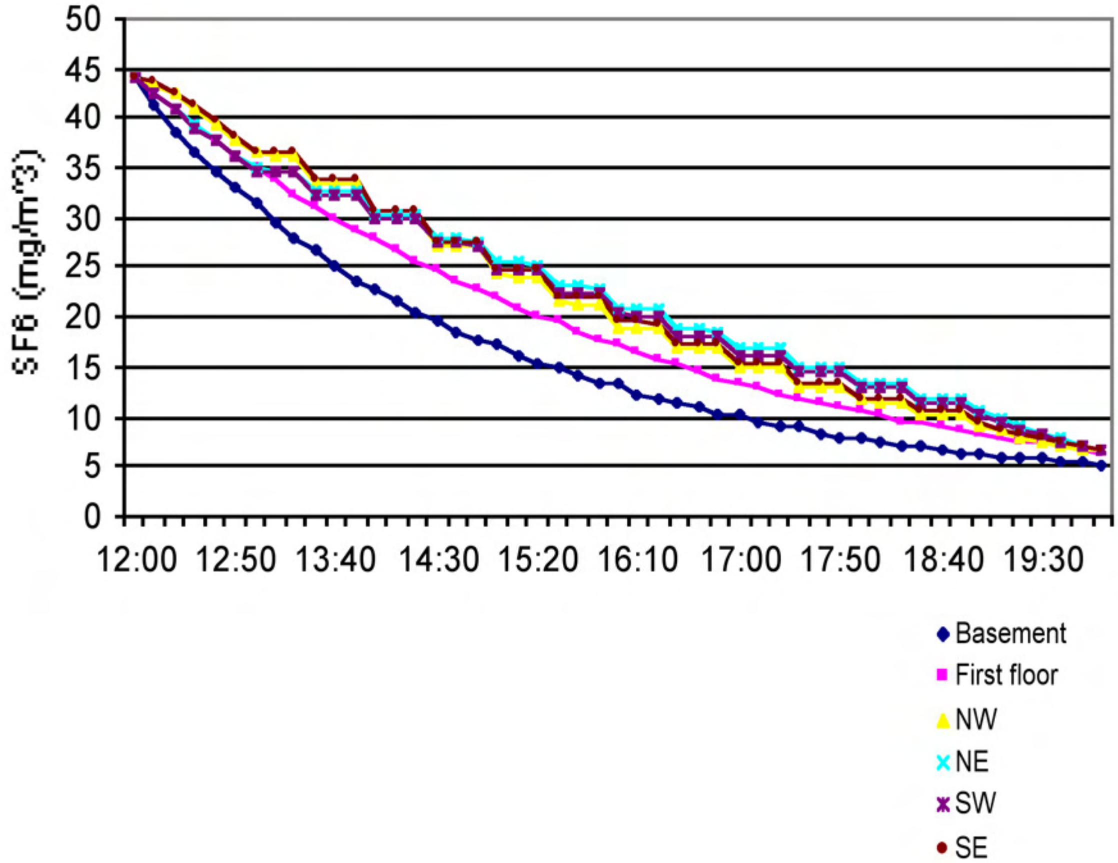


Figure 4.37

Minneapolis House

Standard CONTAM96 Analytical Model

Tracer Gas Results with HVAC System On/Doors Closed

Table 4-8

Minneapolis House Tracer Gas Comparisons
Actual vs. Analytical Models
HVAC System On/Doors Closed

	Northwest Bedroom	Southwest Bedroom	Southeast Bedroom	Northeast Bedroom	Basement	First Floor
Actual	23	24	18	26	17	17
Tuned Model	22	24	22	25	16	17
Standard Model	21	22	22	23	14	18

- SF_6 concentrations given in mg/m^3
- Decay concentration after 4-hour period

School Facility – Westford Academy

A similar experimental and analysis approach to the approach used with the Minneapolis House was employed with a much larger facility. The Westford Academy in Westford, MA was constructed during the early 1970's (Photograph 5). The floor plan is presented in Figure 4.38. The exterior walls are constructed of solid masonry. The floor slabs are concrete and the demising walls are constructed of clay tile masonry. This type of construction results in few connected interstitial cavities and as a result air flow analysis in the facility is considerably simplified.

Experimental Work – Westford Academy

The studied portion of the school selected for analysis is represented by the shaded portion of Figure 4.38. The remainder of the school was isolated from the area of study by opening windows and exterior doors and corridors to the exterior thereby providing "ambient" or outdoor air pressures throughout the second floor and in the non-shaded areas of the first floor.

Conditions during the time of testing were "dead calm". Interior temperatures and exterior temperatures were almost identical, varying between 19 and 21 degrees C. Therefore, wind effects and stack effects can be neglected.

The studied portion of the school is represented by the five zone relational model presented in Figure 4.39.

Depressurization tests of the five individual zones as well as the combined zones (the shaded portion of Figure 4.39) were conducted. During each individual test, adjacent zones were opened/connected to the exterior thereby creating ambient pressure conditions in the adjacent zones. Also during the period of testing, the building exhaust ventilation system was shut down, all exhaust grills sealed, and all unit ventilator openings closed. The results of the depressurization tests are recorded in Figure 4.39 and Figure 4.40.

The building was perturbed by adding a single flow of known magnitude to the corridor zone creating differential pressures across the five zones. The perturbation was accomplished by conducting a modified depressurization test. During this test, the doors connecting the individual zones were closed while air was extracted from the corridor zone. An exhaust flow of 16,750 L/s was imposed on the corridor zone. The resulting pressure field as recorded is presented in Figure 4.41.

Information from the depressurization tests, specifically the zonal leakage areas, was processed with the CONTAM96 network model, to create a five zone analytical model configured to the relational model presented in Figure 4.39. CONTAM96, via a manual iterative (trial and error) process, was used to apportion the leakage areas until reasonable agreement (within 0.5 Pa) occurred between the pressure field recorded in Figure 4.41 and the pressure field output from the "tuned" CONTAM96 analytical model (Figure 4.42). A similar method to the approach used with the Minneapolis House, discussed previously, was used. The details describing this "tuned" CONTAM96 analytical model are contained in Appendix C.

The results are compared in Table 4.9. The match between the actual differential pressures and the calculated pressures are closer than in the Minneapolis House described previously (see Table 4.1). This is believed to be due to simpler construction, more available information about zonal leakage (zonal leakage tests were conducted for the Westford Academy, but not for the Minneapolis House) and calmer weather (the absence of wind and stack effects).

The pressure response of the building was then used to test the pressure response of the "tuned" analytical model. The pressure field in the building was perturbed two different ways to create a pressure response (as with the Minneapolis House discussed previously):

- air flows of known magnitude were imposed on individual zones and the resulting air pressure field recorded; and
- leakage areas of known magnitude were introduced to individual zones and the resulting air pressure field recorded.

The "tuned" CONTAM96 analytical model (as configured in Figure 4.42) was similarly perturbed and the pressure response of the model compared with the actual building pressure response.

Imposed Air Flows – Westford Academy

Air flows of known magnitude were imposed on three individual zones using variable speed calibrated fans ("blower doors'). The corridor zone was further perturbed (depressurized) with an exhaust flow of 16,250 L/s. Doors between individual zones were closed. Flows were added to individual zones as follows:

- 340 L/s from room 117/119 to the corridor zone;
- 125 L/s from room 105/107/109 to the corridor zone; and
- 70 L/s from room 101/103 to the corridor zone.

This approach where multiple blower doors are used to create an air pressure field is similar to using a facilities supply HVAC system (with the return portion of the HVAC system shut down) to create an air pressure field. A ducted supply and return HVAC system was not present in this particular facility. As such, this approach was used to impose air flows and create an air pressure response rather than using an actual HVAC supply system. The building pressure response is recorded in Figure 4.43.

Similar air flows were imposed on the tuned CONTAM96 analytical model (as previously configured in Figure 4.42). The model pressure response is recorded in Figure 4.44. The results are compared in Table 4.10. Pressure differences between zones for both the actual building response and model response agree extremely well.

Imposed Leakage Areas – Westford Academy

Exterior windows and interior doors were opened and closed under conditions where the corridor zone was depressurized with an exhaust flow of 16,250 L/s. Exterior windows in individual zones were opened and closed on a 15 second cycle (closed 15 seconds, open 15 seconds) for four cycles each. The varying pressure field within the facility was continuously recorded (10 readings per second) using a multi-channel digital micromanometer (Energy Conservatory Multi-Channel Mircromanometer) and plotted (Figure 4.45).

Interior doors connecting individual zones to the corridor zone were similarly cycled and the resulting pressure field was recorded and plotted (Figure 4.46).

Examination of the plots indicate that the building pressure field – when window and door openings were closed – remained stable throughout the window and door opening and closing test sequence.

Figure 4.45 shows the pressure in the corridor responding to the opening and closing of the windows in both rooms 101/103 and rooms 105/107/109 with pressure drops in the corridor of approximately 1 Pa and 2 Pa respectively.

Figure 4.47 shows the CONTAM96 analytical model (as configured in Figure 4.42) responding in a similar manner when windows of the same size are opened and closed. The model shows pressure drops of 0.8 Pa and 1.5 Pa respectively.

The effect of opening windows in one zone on the pressure in an adjacent zone is also recorded in Figure 4.45. Opening the windows in room 117 drops the pressure in room 119 approximately 5 Pa when the door between 117 and 119 is closed. Similarly, opening the windows in room 119 drops the pressure in room 117 approximately 5 Pa.

Figure 4.48 shows the CONTAM96 analytical model reacting in a similar manner.

Similar effects are observed when doors are opened and closed (Figure 4.46) leading to a similar response in the CONTAM96 analytical model (Figure 4.49).

A "standard" CONTAM96 analytical model was constructed using the field measured building envelope leakage area. The analytical model was configured to the relational model presented in Figure 4.39. Internal leakage areas were obtained from the literature (ASHRAE, 1997). The envelope leakage area was apportioned as per common convention (ceiling 1/3, exterior walls 1/3, foundation 1/3). A 25 mm undercut was assumed for all interior doors. The details describing this “standard” model are contained in Appendix D.

This standard CONTAM96 analytical model (Figure 4.50) was run with similar flows to the Westford Academy as described in Figure 4.41 and the tuned CONTAM96 analytical model described in Figure 4.42.

Table 4.11 contains a comparison of the actual measured data from the Westford Academy and the data derived from both the standard model and the tuned model. The standard model shows variations from actual measured data and the tuned model with respect to two of the zones – room 117 and room 119.

Tracer Gas Testing – Westford Academy

Tracer gas testing using sulfur hexafluoride (SF6) was subsequently conducted on the building and compared with the predicted flow rates from the tuned CONTAM96 analytical model and the standard CONTAM96 analytical model.

A tracer gas test was conducted on room 117 and room 119. An exhaust fan flow of 50 L/s was imposed on room 117. The door between room 117 and room 119 was closed. All other doors were closed. Concentrations were measured in both rooms. The results are recorded in Figure 4.51.

The exhaust flow was imposed on room 117 to create a driving force for air change due to the absence of wind and the lack of an interior to exterior temperature difference.

The tuned CONTAM96 analytical model (as configured in Figure 4.42) was run under similar conditions. The results are presented in Figure 4.52. The actual air change measurements and the model predictions show good agreement.

A “standard” CONTAM96 analytical model (as described in Appendix D) was run under similar conditions as the tracer gas test. The results are presented in Figure 4.53. The standard model predictions also show a good match.

Unlike the experience with the Minneapolis house, no significant differences in predictive capabilities between the tuned network model and the standard network model were observed with respect to air change (tracer gas concentrations) under the conditions of the actual field test. This was not surprising given the absence of the wind and stack driving forces. However, the tuned network model provided an excellent match with respect to pressure response. This was not the case with the standard network model.

Photograph 5

Westford Academy

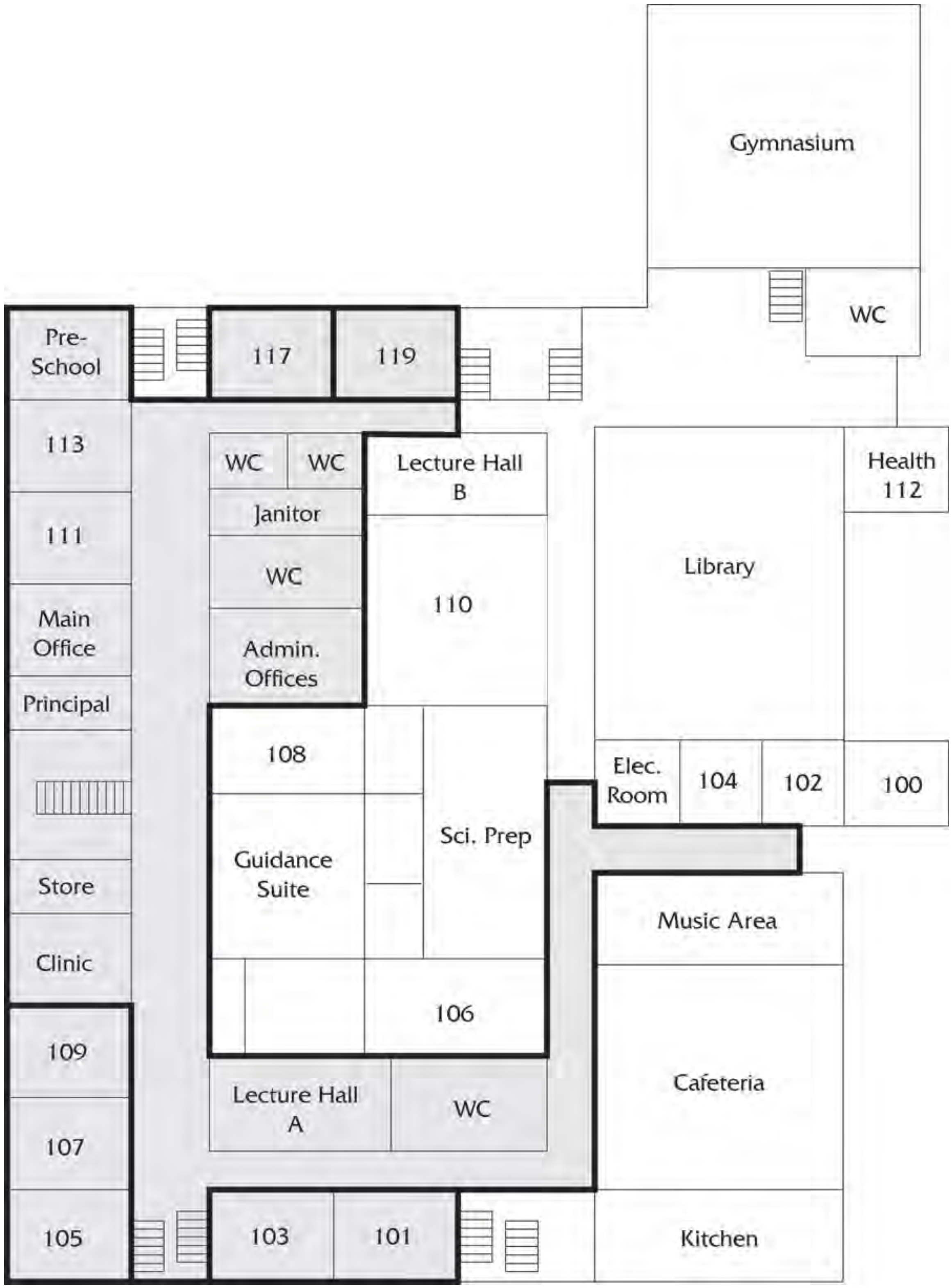


Figure 4.38

Westford Academy Floor Plan

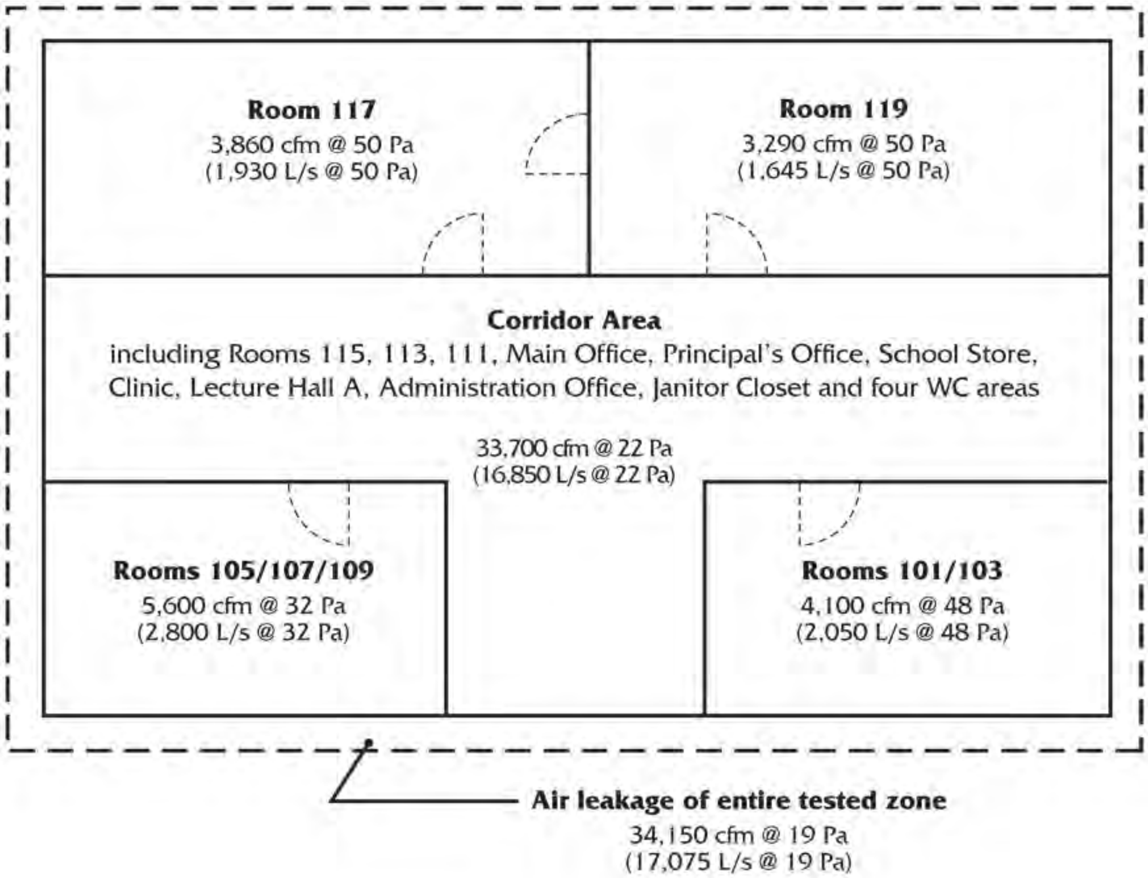


Figure 4.39
Westford Academy
Five Zone Relational Model

- Rooms 101 and 103 have a door between them that is maintained in the open position creating a single zone
- Rooms 105, 107 and 109 are also interconnected as above
- Rooms 117 and 119 have a door between them that can be opened and closed

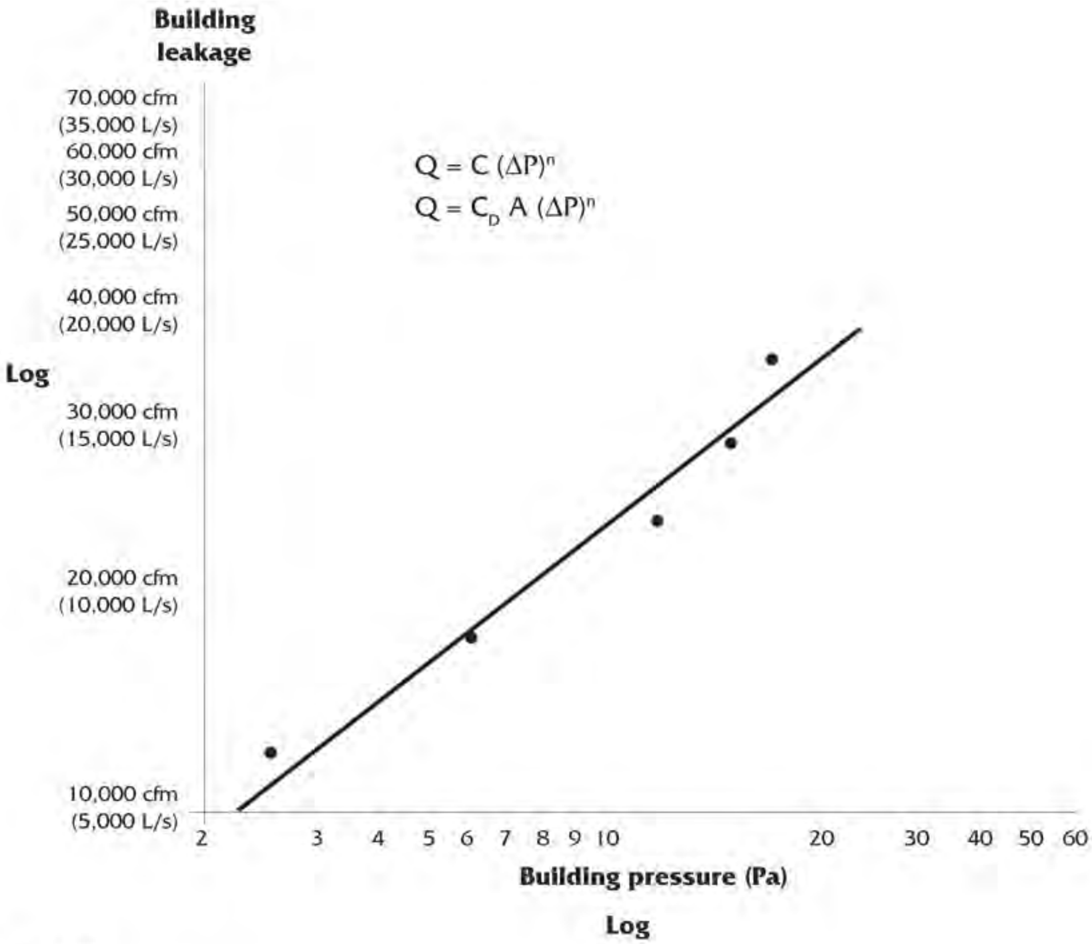


Figure 4.40
Westford Academy
Building Leakage Curve*

A = leakage area (2.5 m², determined @ ΔP=4 Pa

C = leakage coefficient (6300)

C_D = discharge coefficient

n = flow exponent (.55)

ΔP = pressure difference (Pa)

Q = volum flow rate (building leakage)

* For shaded area in Figure 4.38

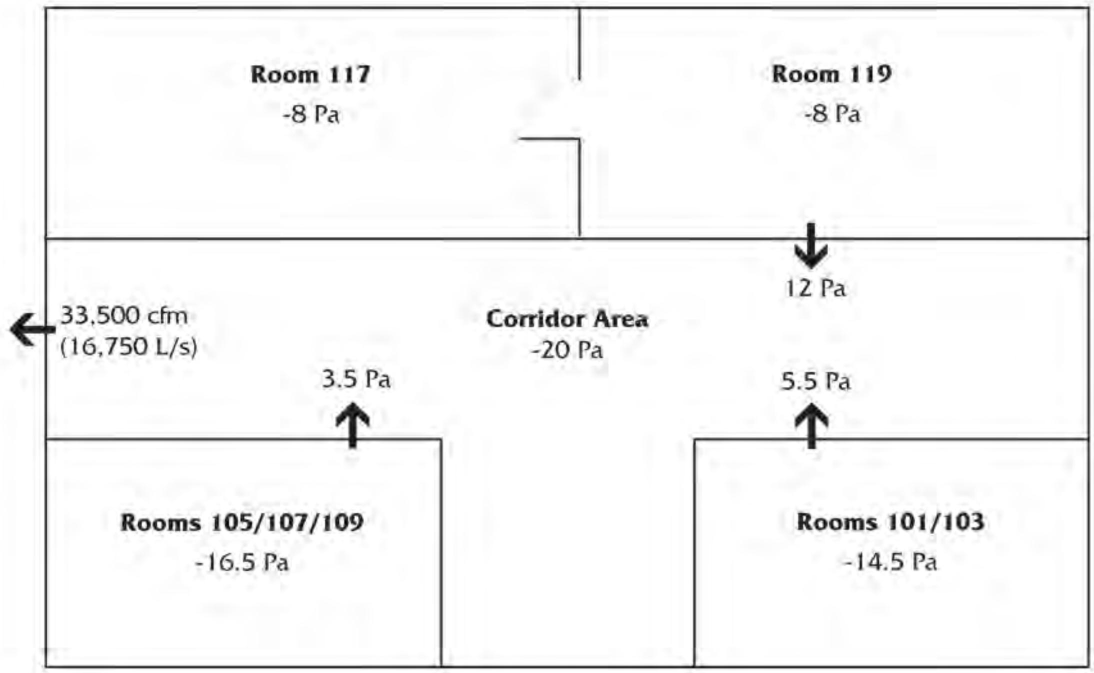


Figure 4.41
Westford Academy
Measured Differential Pressures

- Pressures as measured with all classroom doors and windows closed except the door between Rooms 117 and 119
- Pressures in rooms and corridor relative to ambient

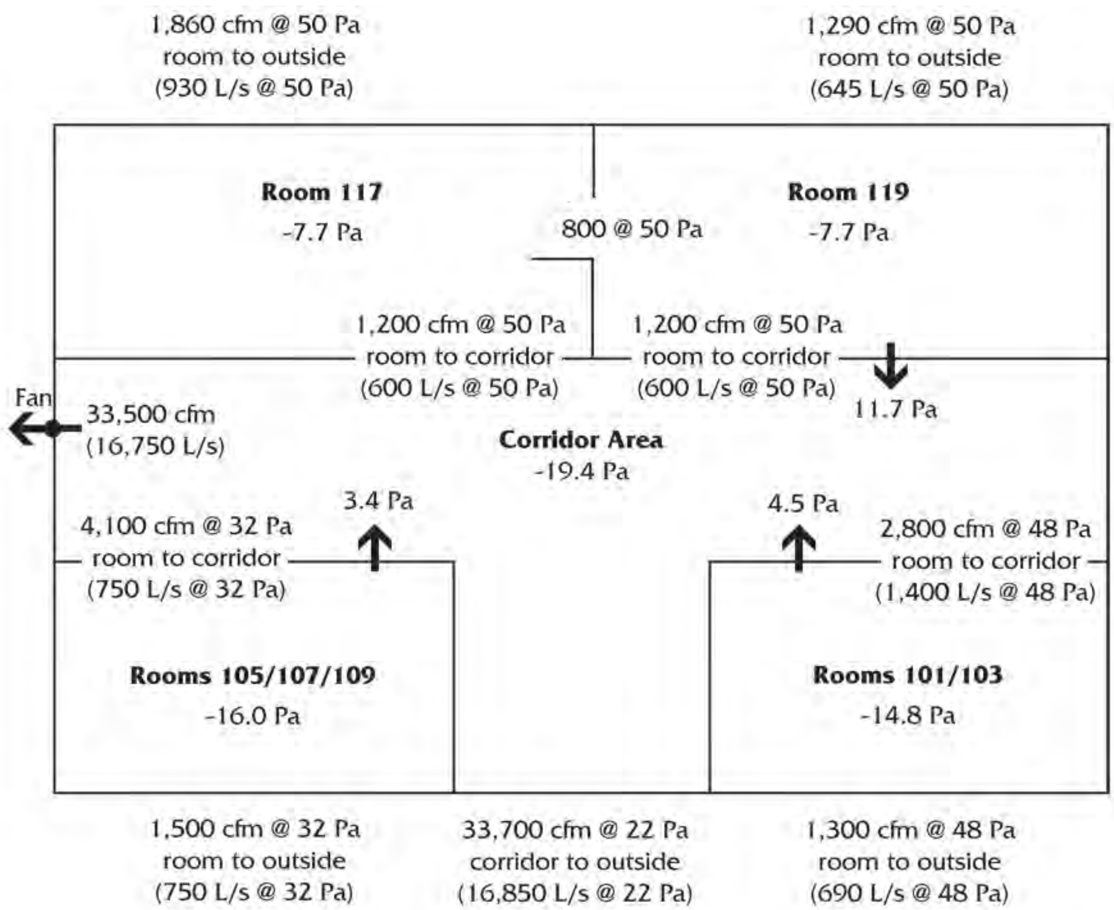


Figure 4.42
Westford Academy
Calculated Differential Pressures

- Pressures as calculated using CONTAM96 with single exhaust fan from corridor (33,500 cfm = 16,750 L/s)
- Leakage areas apportioned as shown
- Door between Rooms 117 and 119 is open

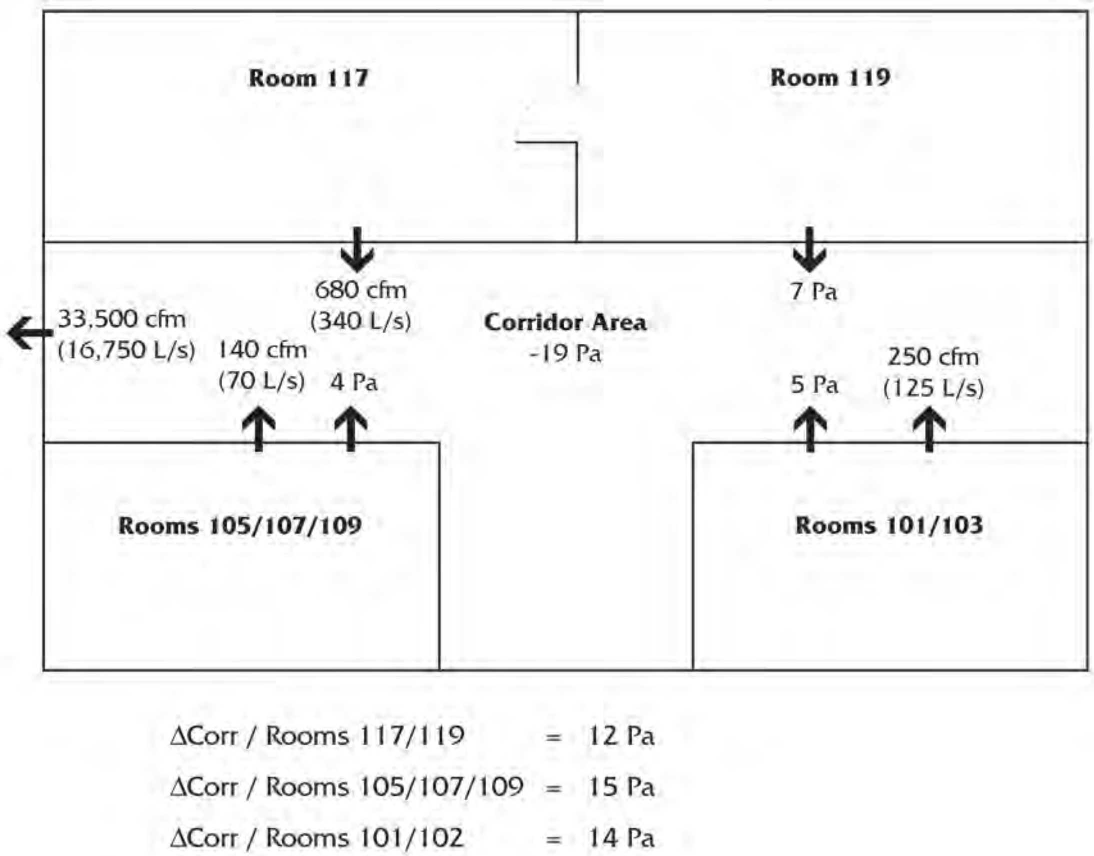
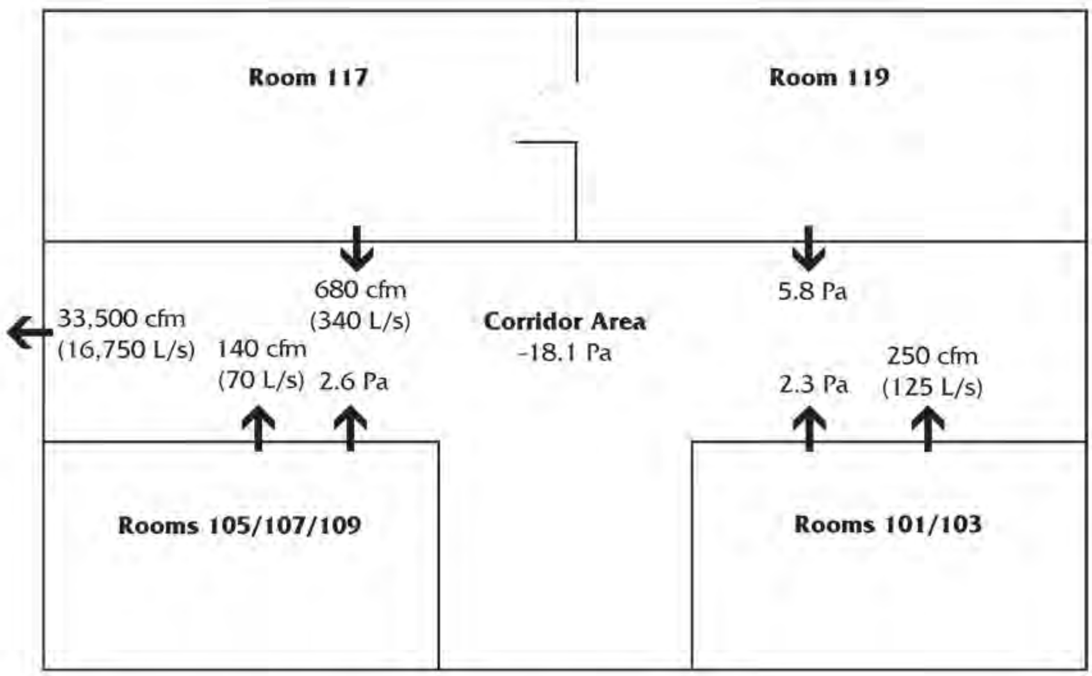


Figure 4.43
Westford Academy
Measured Pressures Resulting from Imposed Flows

- Door open between Rooms 117 and 119
- Corridor exhaust fans operate continuously, but, fans installed in room doorways cycled one at a time, i.e., when fan in Room 117 is exhausting 680 cfm (340 L/s) into corridor the fans in Rooms 101/103 and Rooms 105/107/109 are off



ΔCorr / Rooms 117/119	=	12.3 Pa
ΔCorr / Rooms 105/107/109	=	15.5 Pa
ΔCorr / Rooms 101/102	=	15.8 Pa

Figure 4.44
Westford Academy
Calculated Pressures Resulting from Imposed Flows

- Pressures calculated using CONTAM96 with exhaust flows as shown and leakage areas apportioned as before
- Corridor exhaust fans operate continuously, but, fans installed in room doorways cycled one at a time, i.e., when fan in Room 117 is exhausting 680 cfm (340 L/s) into corridor the fans in Rooms 101/103 and Rooms 105/107/109 are off

Table 4-9

Westford Academy
Measured Differential Pressures (Pa) vs.
Calculated Differential Pressures (Pa)

	Room 117	Room 119	Rooms 105/107/109	Rooms 101/103	Common Area
Measured Pressure Response	12	12	3.5	5.5	-20
Calculated Pressure Response	11.7	11.7	3.4	4.5	-19.4

Table 4-10

Westford Academy
Measured Pressures (Pa) vs. Calculated Pressures (Pa)
Resulting from Imposed Flows

	Room 117	Room 119	Rooms 105/107/109	Rooms 101/103	Common Area
Measured Pressure Response	7	7	4	5	-19
Calculated Pressure Response	5.8	5.8	2.6	2.3	-18.1

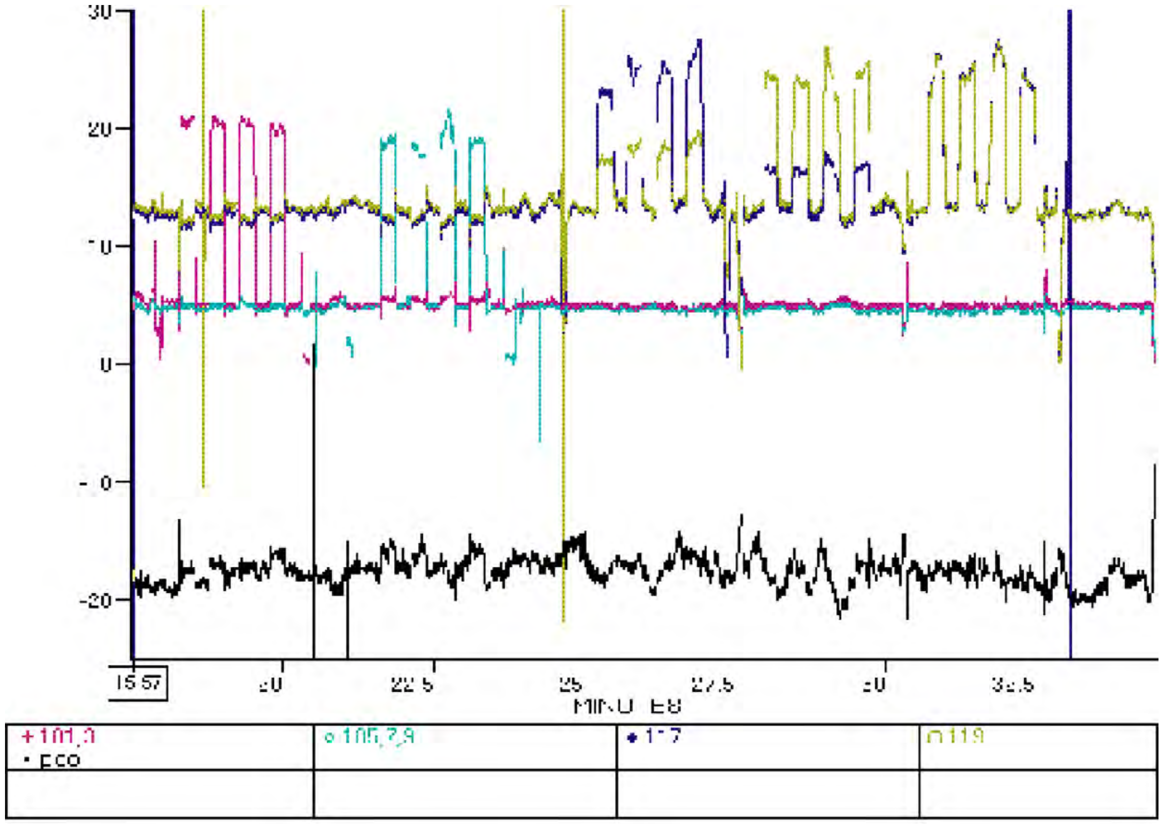


Figure 4.45
Westford Academy
Measured Pressure Response of Opening/Closing Windows (Pa)

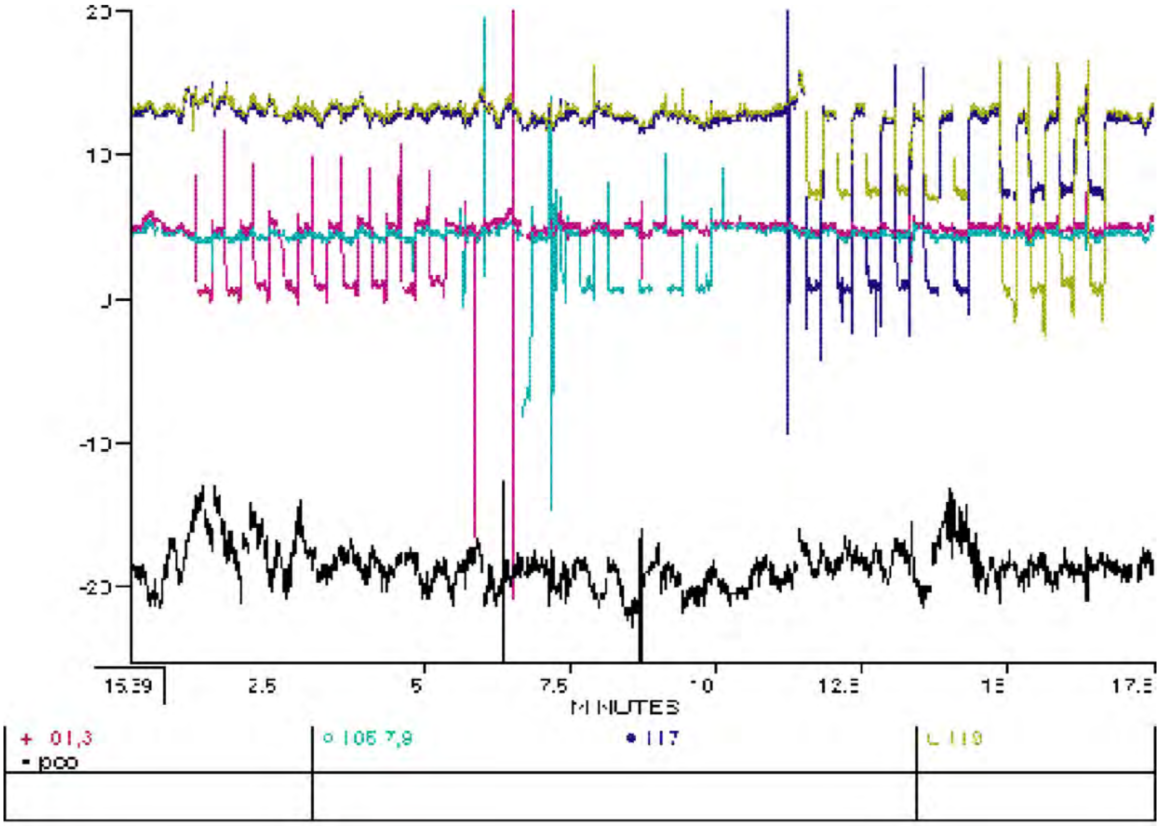


Figure 4.46
Westford Academy
Measured Pressure Response of Opening/Closing Doors (Pa)

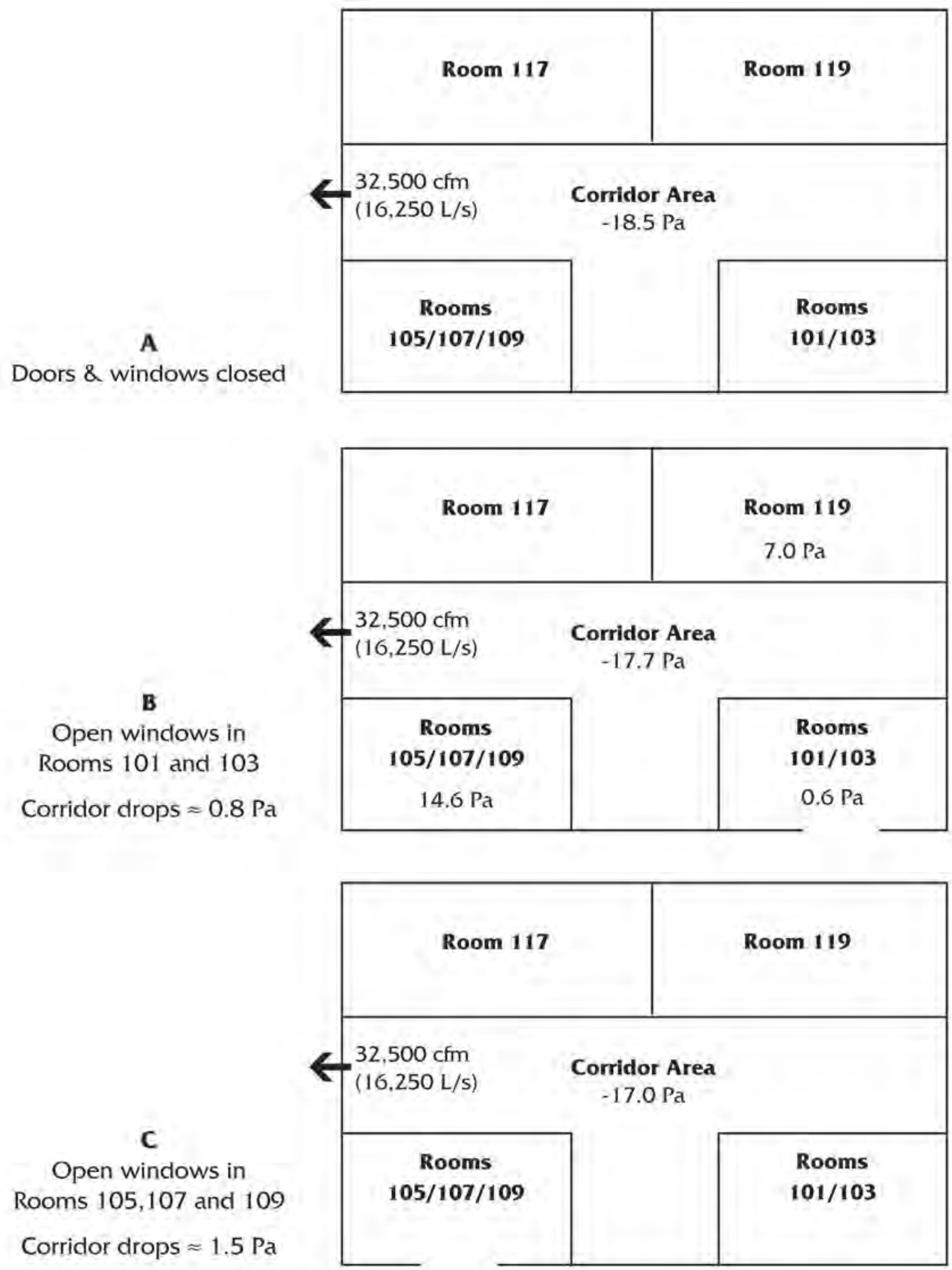
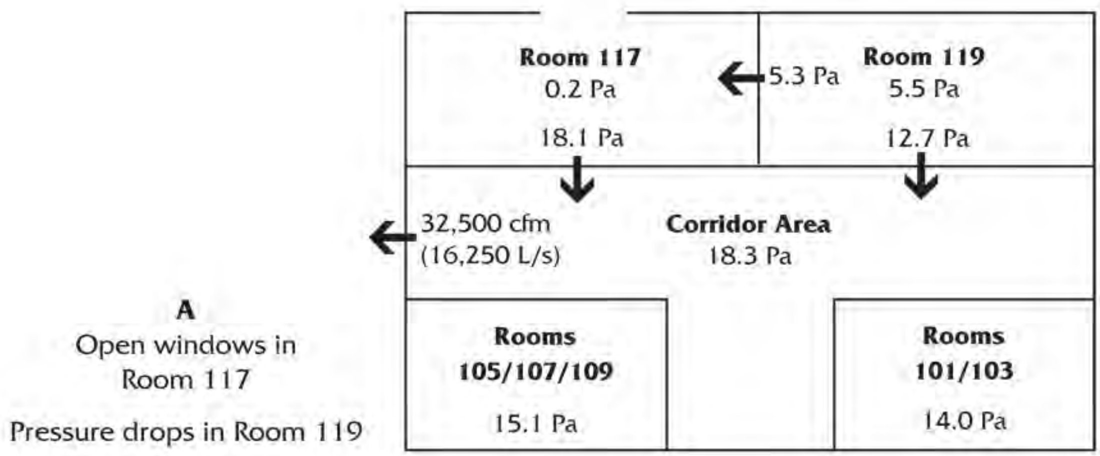


Figure 4.47
Westford Academy
Calculated Pressure Response of Opening/Closing Windows

- Pressures calculated using CONTAM96 with exhaust flows as shown and leakage areas apportioned as before
- Corridor pressure response with cycling windows



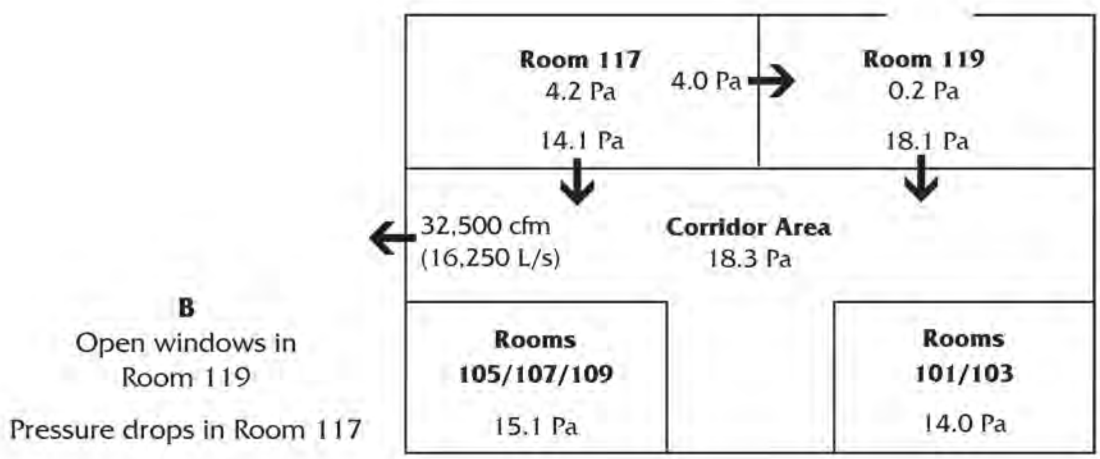
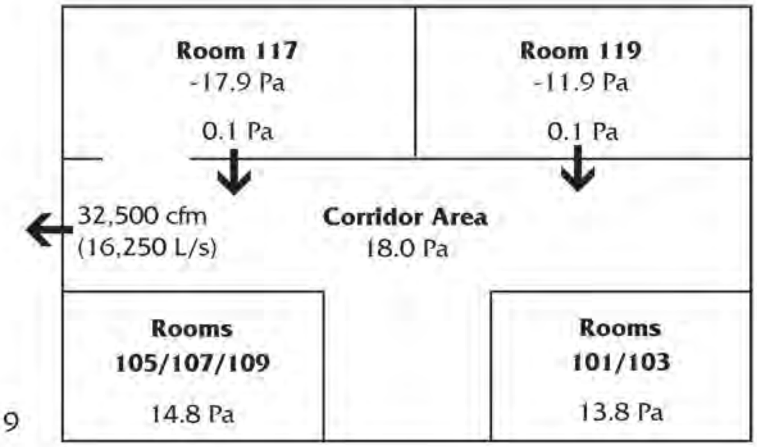


Figure 4.48
Westford Academy
Calculated Pressure Response of Opening/Closing Windows on Adjacent Spaces

A
Open door in
Room 117

Pressure drops in Room 119



B
Open door in
Room 119

Pressure drops in Room 117

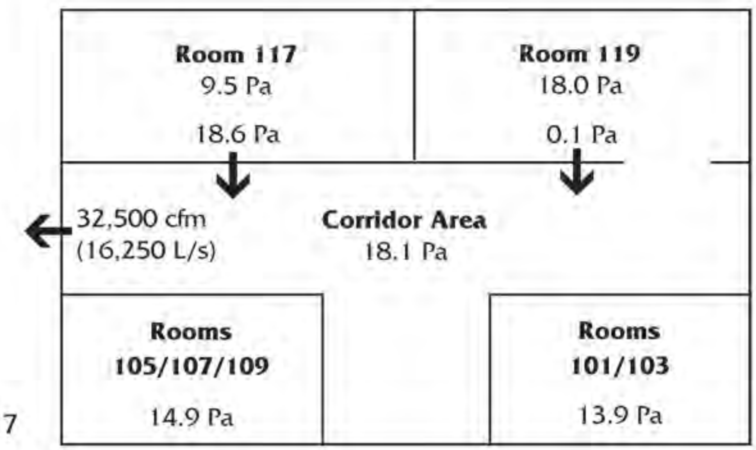
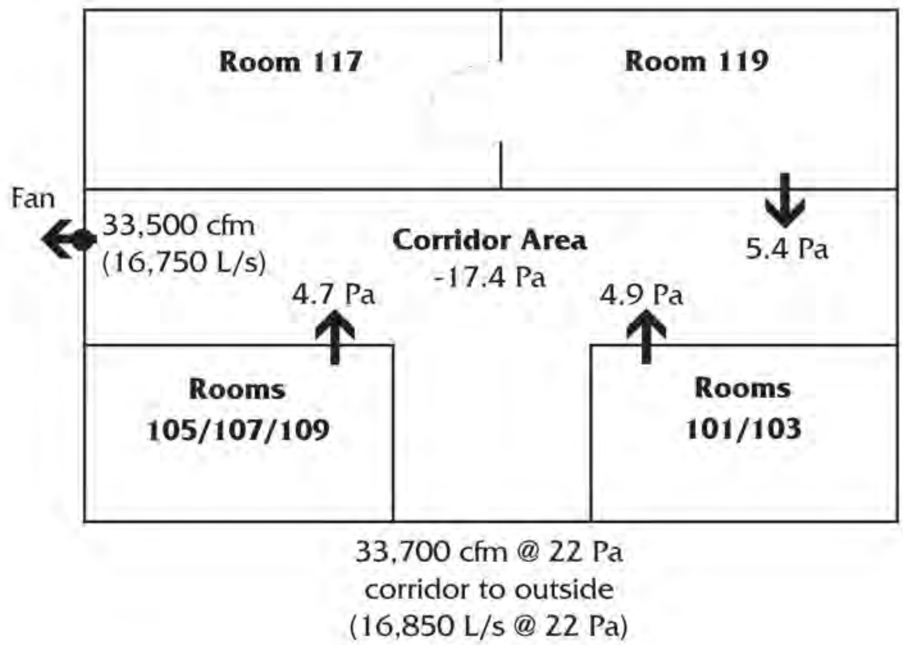


Figure 4.49
Westford Academy
Calculated Pressure Response of Opening/Closing Doors on Adjacent Spaces



- Envelope leakage from direct measurement
- Interior doors undercut 25 mm
- Interior leakage areas taken from ASHRAE Fundamentals - 1999

$$A_L / A_W = 0.11 \times 10^{-3}$$

where A_L = air leakage area

A_W = wall or floor area

C_D = 0.65 @ 75 Pa

- Model details contained in Appendix D

Figure 4.50

Westford Academy
Calculated Differential Pressures
Standard CONTAM96 Analytical Model

Table 4-11

Westford Academy Comparisons of Measured Differential Pressures (Pa) with Calculated Differential Pressures (Pa) for a Tuned Model and a Standard Model

	Room 117	Room 119	Rooms 105/107/109	Rooms 101/103	Common Area
Actual	12	12	3.5	5.5	-20
Tuned Model	11.7	11.7	3.4	4.5	-19.4
Standard Model	5.4	5.4	4.7	4.9	-17.4

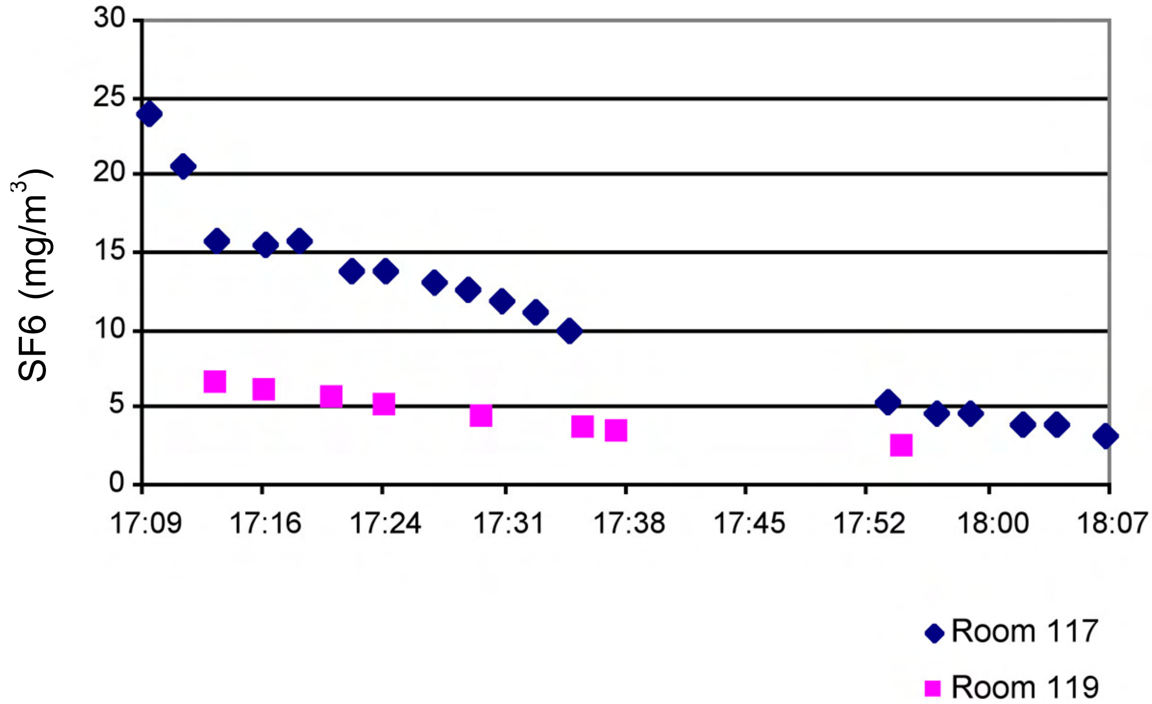


Figure 4.51

Westford Academy Tracer Gas Results

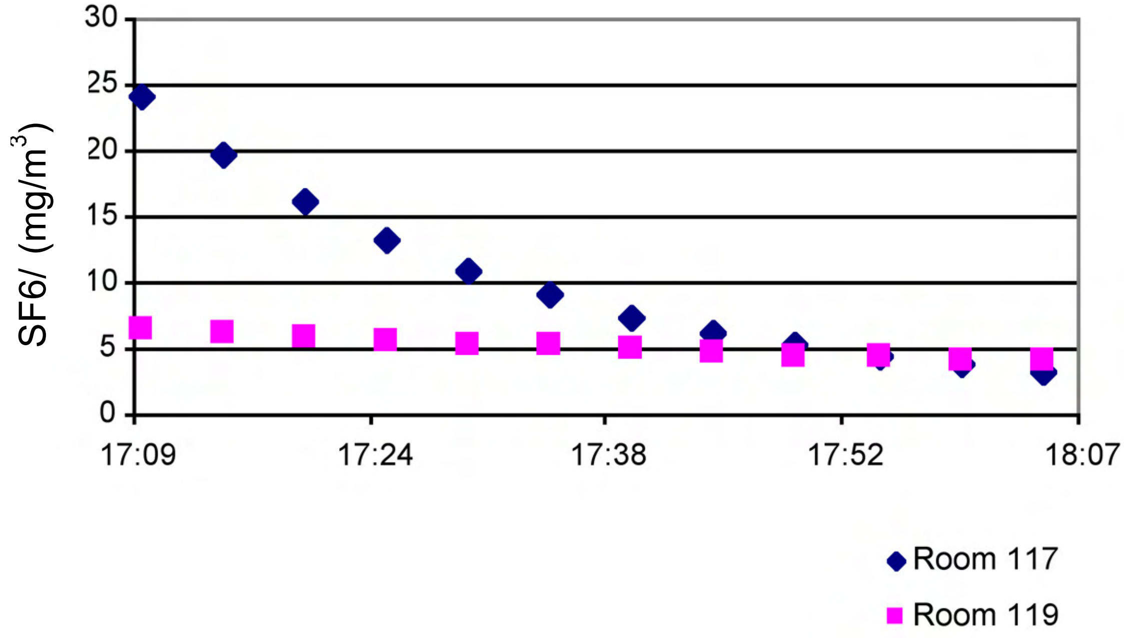


Figure 4.52

Westford Academy
Tuned CONTAM96 Analytical Model Prediction of Tracer Gas Results

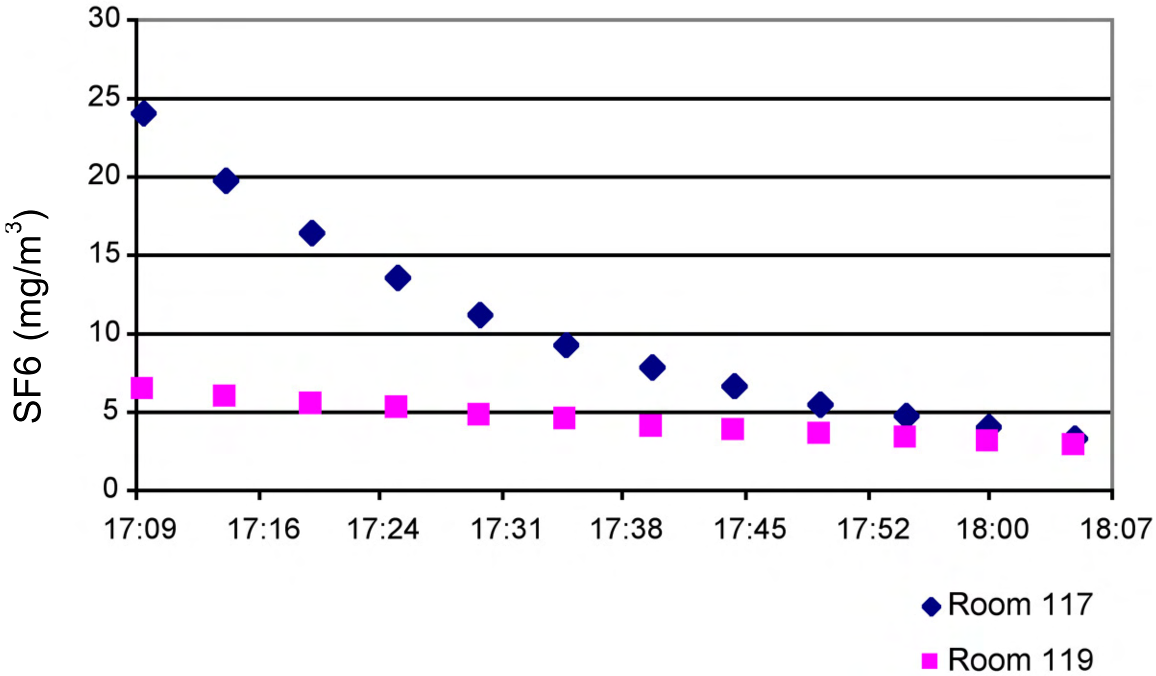


Figure 4.53

Westford Academy
Standard CONTAM96 Analytical Model Prediction of Tracer Gas Results

Boundary Conditions for Analytical Macro and Micro Models

The type and amount of information available determines the approach used in establishing the boundary conditions. Based on the tracer gas measurements, zonal leakage measurements and pressure responses obtained from the Minneapolis House and the Westford Academy, two distinct approaches to initialize model boundary conditions can be used interchangeably or in combination to yield similar results:

- air flows of known magnitude (an imposed flow field) can be used to perturb the building pressure field; or
- leakage areas of known magnitude can be introduced in a controlled manner to perturb the building pressure field.

The measured air pressure response to these perturbations can be used to apportion leakage areas in the network analytical model. The propagation of the pressure response in the building can be compared to the propagation of the predicted pressure response of the model and the model leakage areas adjusted as necessary to bring convergence. This approach provides a previously missing logic to apportioning leakage areas while constructing an analytical model.

It is important to note that this pressure response approach to determine boundary conditions for analytic macro models for the general building flow and leakage regime cannot be used to predict, solve or analyze the interstitial flow, pressure and leakage regime. This approach may suggest that such flows exist, but as noted in the analysis of the Minneapolis house, confirmation requires direct measurement. This approach can provide the general conditions surrounding the interstitial regime, but the pressures and flows within the interstitial spaces cannot be predicted with certainty using analytical means.

Boundary Conditions for Analytical Micro Models

If an interstitial flow regime has been identified by direct measurement of pressures, flows, leakage paths or by indirect means such as the presence of mold or condensation, an analytic micro model can be developed. The accuracy of the micro model can be enhanced using similar means to those used with analytical macro models. For example, the interstitial regime described in the hotel room example of Figure 3.10 or of Figure 3.11 can be modeled by obtaining the response of the interstitial air pressure fields to perturbations created by adding an air flow of known magnitude to the interstitial cavity or by adding a leakage area of known magnitude (a variation of "the add a hole approach" – see Blasnik and Fitzerald, 1992).

V Practical Applications of the Work

Diagnostics and Design

Understanding the significance of the complex flow and pressure distribution problems created by the interaction of the building envelope with the mechanical system and climate can lead to changes in building design, commissioning, operations, maintenance, diagnostics and rehabilitation.

Diagnostic protocols can be based on the enhanced understanding of pressures and air flows in buildings and the measurement techniques presented in this thesis. These diagnostic protocols can be used to aid in identifying problems in buildings related to indoor air quality, smoke and fire spread, durability of the building envelope relating to air transport of moisture, operating costs relating to energy use, and comfort issues related to humidity, temperature and odors.

Additionally, rehabilitation approaches can also be developed that allow an assessment of the existing interactions in buildings to be rehabilitated, provide the designer with choices as to desired interactions given the constraints of the existing building, give the commissioning agent performance guidelines to compare against after rehabilitation is complete and provide the building operators with building operating instructions and required operating air pressure relationships.

The designer can now have a choice to either prevent accidental coupling of the mechanical system to the building envelope by design changes to the building envelope and the mechanical system or to deliberately couple the mechanical system to the building envelope to provide enhanced control of air transported moisture control, odor control, smoke control or heat transfer control.

The commissioning agent can now have the ability to determine the interactions of the building envelope and the mechanical system in a systematic, repeatable manner and compare the interactions to design intent.

Finally, the building operators can now have the ability to determine the interactions of the building envelope and the mechanical system on an ongoing basis in a systematic, repeatable manner and compare the interactions to design intent, the initial commissioned state and building operating instructions.

The following five examples are applicable to:

- Indoor Air Quality
- Smoke and Fire Spread
- Durability (moisture)
- Comfort
- Operating Cost (energy)

Indoor Air Quality

A school located in Trenton, NJ provides a good example of using the relational model of air pressure relationships in buildings and the air pressure measurement techniques developed in this thesis to diagnose and remediate indoor air quality complaints associated with the facility.

Description of Facility and History of Problems

The facility in question is a single story masonry school building constructed over a crawl space foundation. The facility consists of several wings constructed at different periods over the past 60 years. Each wing has a separate foundation system, although communication between the various crawl space foundations was present. The crawl space in the affected area of the facility consists of a perimeter cast concrete foundation wall on concrete strip footings. The floor deck consists of cast concrete supported on precast concrete beams supported on the perimeter foundation walls and interior cast concrete bearing walls. The crawl space floor surfaces were uncovered earth. Crawl space ventilation consisted of numerous 20 cm x 30 cm vents, distributed in an approximate ratio of 1/1500 between vent area and floor area.

A teacher in one of the classrooms of the affected area of the facility was complaining of mold odors, headaches, fatigue, and flue like symptoms. Discussions with the teacher indicated that similar complaints were also common among the students. Further discussions indicated that complaints had been registered for several months with no action resulting. It appeared that no record of complaints had been kept.

Investigation and Testing

Upon entering the classroom which the affected teacher and students occupied, visible deterioration of plaster and baseboard surfaces were observed along interior and exterior walls. The deterioration was most intense at the baseboard level, and decreased in intensity with height. Paint had peeled from the plaster at many locations. Water markings were observed on the plaster surfaces. The plaster was soft to the touch and disintegrated when probed. When the plastic covering over the wood baseboard trim was removed, noticeable musty odors were encountered. The wood was soft and "punky". Significant decay of the wood was observed. When the wood baseboard was pulled away from the wall, the intensity of the musty odors increased significantly.

Visual observations revealed a joint between the concrete floor slab and the masonry perimeter wall. Other joints were observed in the concrete floor slab at the interior concrete foundation walls. Smoke pencil testing indicated substantial air flow between the crawl space and the classroom through these exposed joints. Readings taken with a digital micromanometer indicated that the classroom was operating at 4 Pa negative with respect to the crawl space (Figure 5.1). Furthermore, interior wall cavities were found to operate at 1 Pa negative with respect to the classroom.

Removal of deteriorated plaster revealed the wall construction. Interior plaster was installed over wood furring strips creating an air space (or channels) between the plaster and the masonry wall. Removal of ceiling tiles indicated that the plaster finish extended just above the dropped ceiling level and that the air space (or channels) between the plaster and the masonry wall was open at the top and connected to the air space above the dropped ceiling. This wall geometry created "chimneys" which extended from the crawl space to the air space above the dropped ceiling.

The air space above the dropped ceiling was used as a return air plenum that operated under a negative air pressure relative to the classroom due to the operation of air handling units within the dropped ceiling (Figure 5.2). Additionally, each classroom was equipped with a roof top exhaust fan that extracted air from the dropped ceiling depressurizing both the dropped ceiling and the classroom relative to the exterior. When the roof top exhaust fan was shut down, the negative air pressure difference between the classroom and the crawl space was reduced to less than 1 Pa.

Discussion with school district staff, and photographs indicated that no ground cover was present in the crawl space. According to staff, the top surface of the soil appeared dry. In addition, many of the steam lines in the crawl space were reported to be uninsulated due to ongoing asbestos mitigation work. Crawl space temperatures in excess of 30 degrees C were typical according to staff.

Crawl space vents were sealed and an exhaust fan was installed in the crawl space exhausting air to the exterior. The access opening connecting the affected crawl space and the adjacent crawl space was also sealed. Air pressure differentials between the affected classroom and the crawl space were monitored. Extracting approximately 325 L/s of air from the crawl space by means of an exhaust fan depressurized the crawl space 4 Pa with respect to the classroom area. This was shown to result in a flow reversal of air between the crawl space and the classroom area. Using a smoke pencil air could be shown to flow from the classroom area into the crawl space when the exhaust fan was operating rather than from the crawl space into the classroom.

Conclusions

The complaints from the teacher and students were due to musty odors resulting from the deterioration of wood trim and other building materials. These odors and deterioration were due to excessive moisture migrating from the crawl space under the classrooms into the interstitial spaces of interior and exterior walls as a result of the air pressure relationship between these spaces and the crawl space.

The rationale for these conclusions follows.

For an odor or indoor air quality problem to occur, four factors are necessary:

- Pollutants are necessary;
- People (receptors) are necessary;
- Pathways are necessary (connecting the pollutants to the people); and
- Pressure differences are necessary (to push or pull the pollutants down the pathways to the people).

It is obvious that people are necessary to be present in order for a problem to be detected, or for a problem to exist. It is clear that although removing occupants is an effective short term solution, this strategy is not an appropriate long term solution. The receptors in this case are the teacher and students.

A pollutant is also necessary. In this case the primary pollutant is moisture, and this moisture pollutant leads to the creation of the secondary pollutants which are mold and other biological agents. Eliminating (removing) the pollutant (source control) is a very effective approach to controlling indoor air quality problems.

A pathway connecting the pollutant and people (receptors) is also necessary. If pollutants and receptors are isolated from each other by "perfect" barriers, then problems can also be eliminated. In this case the pathway connecting the moisture pollutant and the receptor are the openings connecting the crawl space and the channels between the plaster surfaces and the masonry walls.

Finally, a driving force is required to "push" or “pull” the pollutant down the pathway to the occupants (receptors). In this case the driving force is an air pressure difference between the crawl space and the classrooms. This air pressure difference is created by a combination of the operation of the roof top exhaust fans and the operation of the air handling units within the dropped ceiling areas.

Moisture (the primary pollutant) in the soil in the crawl space is evaporated due to the elevated temperatures in the crawl space. Warm moisture saturated air migrates through openings in the floor slab into the air space created by the plaster and wood furring (the pathway). The air is pulled into the air space between the plaster and wood furring as a result of the operation of the roof top exhaust fans and the operation of the air handling units (the pressure “drivers”). The moisture saturated air cools once it is in the furring space leading to condensation and saturation of the building materials at this location. The saturation of the building materials leads to their deterioration and the creation of odors and other biological agents (the secondary pollutants). These secondary pollutants enter the classroom and come in contact with the teacher and students (the receptors).

The dry crawl space soil surface observed is dry due to the rapid rate of evaporation of moisture (vapor diffusion) from the upper surface of the crawl space soil surface into the crawl space enclosure due to the heat from the uninsulated steam lines, resulting in the upper surfaces appearing dry. Where it was possible to probe several inches beneath the crawl space floor surface, the ground material was damp to the touch.

Ventilation as a moisture removal mechanism was present in the crawl space by virtue of the fact that crawl space vents were present and that the ambient (exterior) vapor pressure was lower than the crawl space enclosure vapor pressures. However, the rate of moisture removal by ventilation was extremely low due to the small number of vents, their location and small cross sectional areas.

Moisture levels within enclosures are determined by a combination of moisture source strength (rate of moisture generation or entry) and air change or ventilation (rate of moisture removal). If the rate of moisture generation or entry is higher than the rate of moisture removal then high enclosure moisture levels can occur. The crawl space airborne moisture levels were high. These crawl space airborne moisture levels were high because the rate of moisture generation or entry in the crawl spaces is high compared to the rate of moisture removal by ventilation.

Rehabilitation Measures

The rehabilitation measures involved the four factors active in air quality and odor problems (people, pollutants, pathways and pressures).

In the short term, the receptors were removed. Students and teachers were not allowed access to the affected classrooms until the rehabilitation measures were implemented.

Source control for the primary and secondary pollutants was undertaken. The secondary pollutants were removed by stripping the damaged portions of the interior plaster surfaces and removing all wood baseboard trim. The carpets were discarded.

The primary pollutant, airborne moisture from the crawl space, was controlled at the source. Crawl space enclosure moisture levels can be reduced only two ways, by limiting moisture source strength (moisture entry) or by dilution (moisture removal by ventilation or dehumidification). A desired result is where the rate of moisture entry is lower than the rate of moisture removal, or where moisture accumulation in building materials does lead to deterioration. In order to achieve this desired result, the control the source strength (moisture entry by evaporation from the ground) was selected rather than dilution (moisture removal by ventilation).

A temporary polyethylene ground cover was installed immediately. A permanent stabilized, reinforced polyethylene ground cover was subsequently installed after mechanical system work was completed in the crawl space (Figure 5.3). As part of this work, all steam lines were re-insulated.

The pathway for the primary pollutant (moisture) was sealed by installation of foam sealants after damaged and deteriorated materials were removed at baseboard locations.

Finally, the driving force for pollutant transfer, specifically the air pressure relationship between the crawl space and the classrooms, was altered by the installation and operation of an exhaust fan (Figure 5.4). This exhaust fan runs continuously. In order to facilitate air pressure control the crawl space vent openings were permanently closed. Crawl space perimeter walls were insulated creating a conditioned crawl space that is permanently maintained at a slight negative pressure with respect to the classrooms via the operation of the crawl space exhaust fan.

Discussion

Traditional analysis would be unable to explain the extent of the damage to interior surface finishes on interior partition walls. The relational model developed previously to reflect the complex three dimensional flow paths existing in multi-layer buildings provides a basis for investigation and an explanation of the observed damage. Direct measurement of interstitial air pressures identifies the link of the interstitial cavities to the operation of the mechanical system.

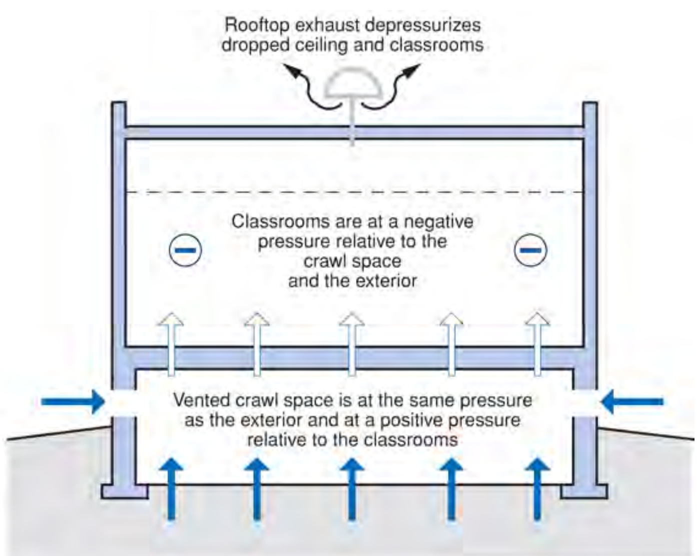


Figure 5.1
Problem Pressure Relationship
- The classrooms in this school operate at a negative pressure with respect to the crawl space

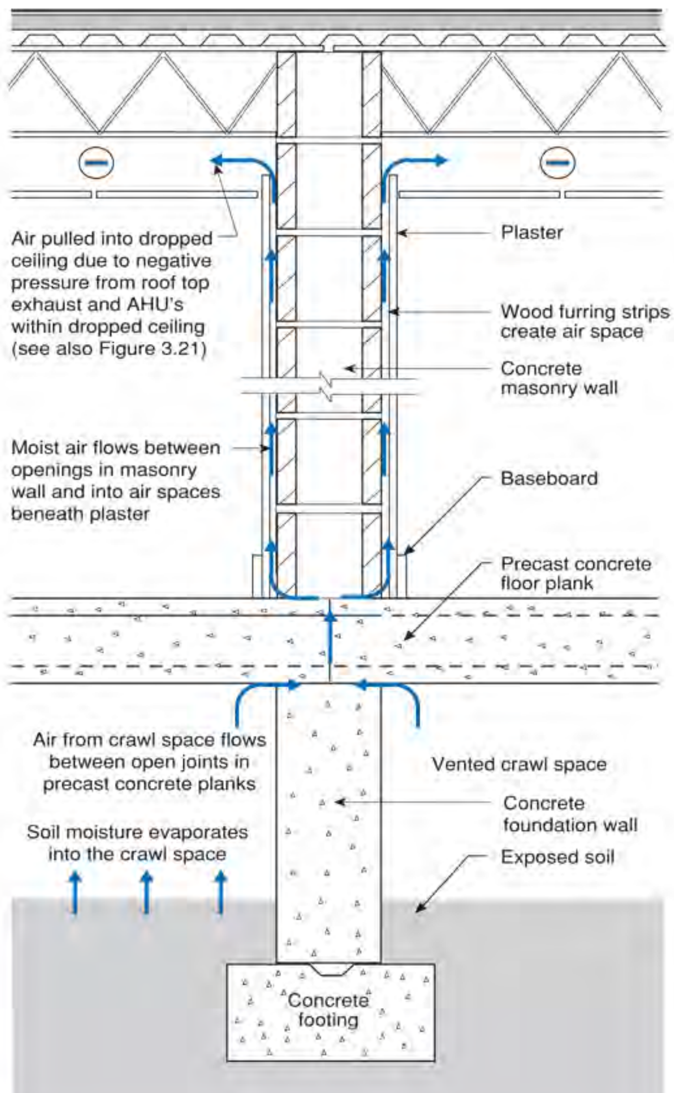


Figure 5.2
Moisture Movement
- This wall section illustrates moisture movement from the crawl space into the wall cavities and dropped ceiling

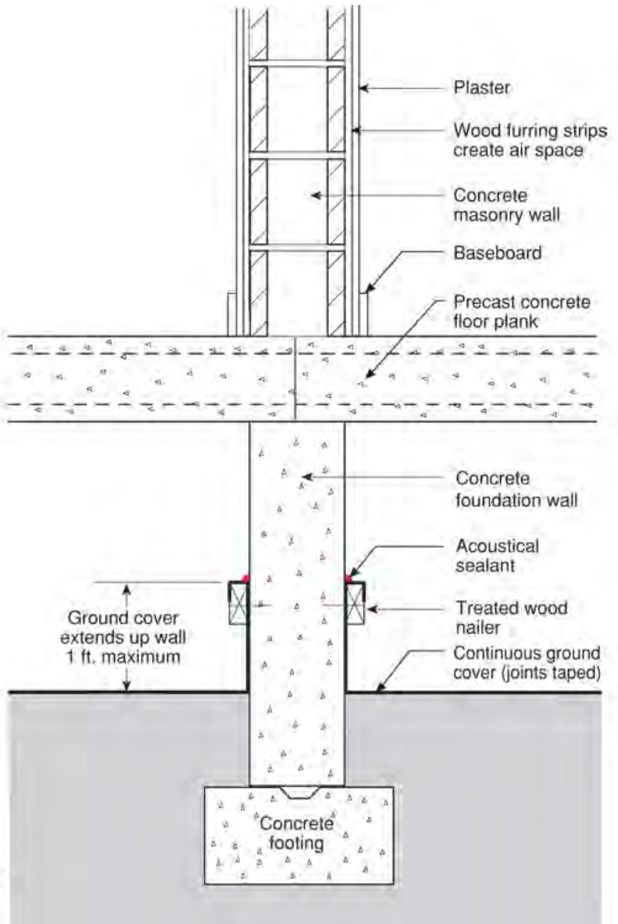


Figure 5.3
Ground Cover Installation
- This wall section illustrates proper installation of the polyethylene ground cover

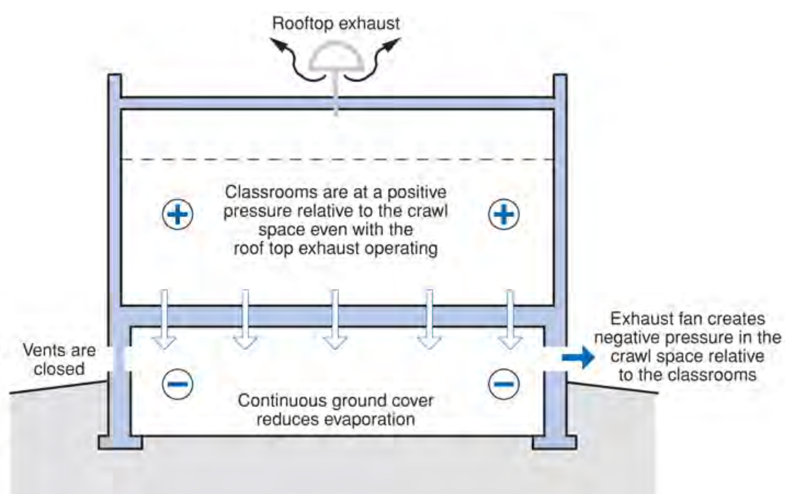


Figure 5.4
New Air Pressure Relationship
- Closing the crawl space vents and using an exhaust fan in the crawl space depressurizes the crawl space relative to the classrooms

Smoke and Fire Spread

A hotel located in Tallahasee, FL provides a good example of addressing smoke and fire spread concerns in an existing facility scheduled for renovation by using pressurization testing and pressure field measurements, developing a smoke and fire spread analytical model based on the pressure field measurements and altering air pressure relationships based on the analytical modeling and pressurization testing.

Description of Facility and History of Problems

The facility is a seven story concrete frame building constructed on a concrete grade beam/slab foundation. The ground level contains the hotel registration area, restaurant, meeting rooms, and service areas. The remaining upper six floors contain hotel suites. There are 15 suites per floor or 90 suites in total. Each suite contains a hotel room and a bathroom containing a bathtub/shower, vanity and toilet.

The exterior infill walls are steel stud with interior and exterior gypsum sheathing. The exterior cladding is a traditional hardcoat stucco system over building paper. The stud cavities are insulated with kraft faced fiberglass batt insulation. The interior surfaces are finished with a vinyl wall covering.

According to design drawings roof top exhaust fans extract 25 L/s from each suite at bathrooms (Figure 5.5). Additionally, 100 L/s is extracted from each corridor. In other words, 475 L/s is extracted from each floor. Total exhaust for the six floors containing suites is 2,850 L/s. The roof top exhaust fans operate continuously.

Each suite contains a through-wall packaged terminal heat pump (PTHP) for space conditioning. Each PTHP supplies 30 L/s of outside air when it is operating. An additional PTHP also serves each corridor suppling an additional 100 L/s to the corridors. Approximately 550 L/s of outside air is supplied to each floor when all the PTHP's on a floor are operating.

The facility has been experiencing persistent high humidity problems since it was constructed 5 years earlier. Additionally, it has been scheduled for a major renovation where interior rooms are to be refurbished. As part of the renovation, a smoke pressurization and smoke extraction system are to be installed.

Investigation and Testing

Digital manometers were used to establish the air pressure relationships throughout the facility. Air pressure measurements were taken during calm weather in April. Exterior temperatures were approximately 27 degrees C. Interior temperatures were approximately 24 degrees C. The facility in general was found to be operating at between 3 and 5 Pa negative with respect to the exterior. The facility was most negative at the upper floors.

Flow hood measurements of flow through exhaust grills in suites in upper floors indicated greater exhaust flow than similar measurements in lower floors. The air pressure driver was the roof top exhaust fans. When roof top fans were shut down, the hotel suite floors became slightly positive with respect to the exterior - approximately 1 to 2 Pa. Most, but not all PTHP's, were shut down during the time that roof top exhaust fans were shut down.

The typical duty cycle of individual PTHP units was found to be about 20 percent. It was estimated that only three suite PTHP's plus the corridor PTHP operate at any one time per floor supplying only approximately 190 L/s of outside air per floor. This yields a deficit of supply to exhaust of approximately 285 L/s per floor.

Leakage testing of individual floors was conducted using variable speed pressurization fans. Two types of measurements were taken. The first involved pressurizing an individual floor by extracting air from a stairwell whose exterior doors were opened to the exterior. The floors above and below the floor being tested were maintained at exterior pressure by opening all windows and corridor doors. The second type of measurement involved pressurizing the floors above and below the test floor as well as the elevator shafts to identical pressures to the test floor thereby providing isolation of test floor leakage to floors above and below. The experimental set-up is presented in Figure 5.6.

During both types of testing the individual bathroom exhaust grills and supply air PTHP registers were taped shut. Additionally, hallway supply air grills were also sealed. Under the first approach, approximately 500 L/s of outside air was required to pressurize individual floors 5 Pa to the exterior. Under the second approach, approximately 275 L/s of outside air was required to pressurize individual floors 5 Pa to the exterior.

Air pressure measurements within interior partition walls were also taken with portable digital micromanometers. Walls connected to the service shafts containing the exhaust ducts were found to operate 1 to 2 Pa negative with respect to interior rooms. Walls not connected to service shafts appeared to operate at the same pressure as interior rooms. When individual roof top exhaust fans servicing a particular service shaft were shut down, wall cavity pressure differences relative to interior rooms disappeared.

Wall coverings were removed at select locations from interior partition walls. Additionally, access openings were cut through gypsum board to allow inspection of wall cavities. Vinyl wall coverings were found to be discolored with pink spots on room side surfaces and discolored with black spots on gypsum side surfaces. Both types of discoloration were more severe on interior partition walls connected to service shafts. Mold growth was found within wall cavities. Again, as with the case of the wall coverings, more growth was found within wall cavities connected to service shafts than wall cavities not connected to service shafts.

Conclusions

The deficit of exhaust to supply air flow is responsible for the negative air pressure within the facility. The negative air pressure causes the infiltration of exterior unconditioned air. This unconditioned air is responsible for the high interior humidity except during the winter months when the exterior air has a low moisture content. Additionally, the negative pressure field developed in interior partition walls connected to service shafts is due to leakage of exhaust ductwork contained within the service shafts. This negative pressure field causes the infiltration of exterior unconditioned air into the interior wall cavities leading to mold growth and discoloration of the interior vinyl wall coverings.

Rehabilitation Measures

A supply air system was designed to pressurize the hotel suite floors. The key features of this system follow:

- In order to achieve pressurization, the existing supply air vents in each PTHP unit are permanently closed.
- Two roof top units supplying 2,100 L/s of neutral temperature air at approximately 50 percent relative humidity are used to supply 700 L/s of air to each floor (Figure 5.7).
- The existing exhaust system is balanced to extract 475 L/s from each floor.
- The supply excess of approximately 225 L/s per floor pressurizes each floor approximately 2 Pa relative to the exterior.
- A grill is installed between the corridors and each service shaft at each floor to allow the extension of the corridor air pressure field into the service shafts at each floor thereby eliminating the previous negative pressure field that extended from the service shafts within interior partition walls to the exterior (Figure 5.8).

The existing vinyl wall coverings were removed and decontamination of the mold occurred. Vapor permeable interior finishes were specified to replace the impermeable vinyl wall coverings.

A smoke pressurization and smoke extraction system was also designed using the pressurization test results (Figure 5.9). A minimum 25 Pa pressure difference between fire floors and non fire floors was specified as a design criteria. Approximately 1000 L/s was found to pressurize each floor approximately 25 Pa relative to the exterior when the roof top exhaust fans are not operating. Conversely, an approximate exhaust flow of 1,000 L/s was found to depressurize each floor 25 Pa relative to the exterior when the corridor supply system is not operating. By supplying 1,000 L/s to non fire floors and extracting 1,000 L/s from fire floors when the supply and exhaust systems are de-energized a greater than 25 Pa pressure difference can be maintained.

Discussion

An analytical model for smoke propagation was constructed using the CONTAM96 network model. The network model was configured to the relational model presented in Figure 5.9 and "tuned" using the zonal pressure measurements to apportion leakage areas thereby establishing boundary conditions.

Modeling confirmed the expected design performance of the smoke extraction system and smoke pressurization system described in Figure 5.9. The actual measurement of boundary conditions through pressurization testing significantly reduced the installation cost of the smoke extraction and pressurization systems. Required air flows were reduced approximately 35 percent over those of standard analysis.

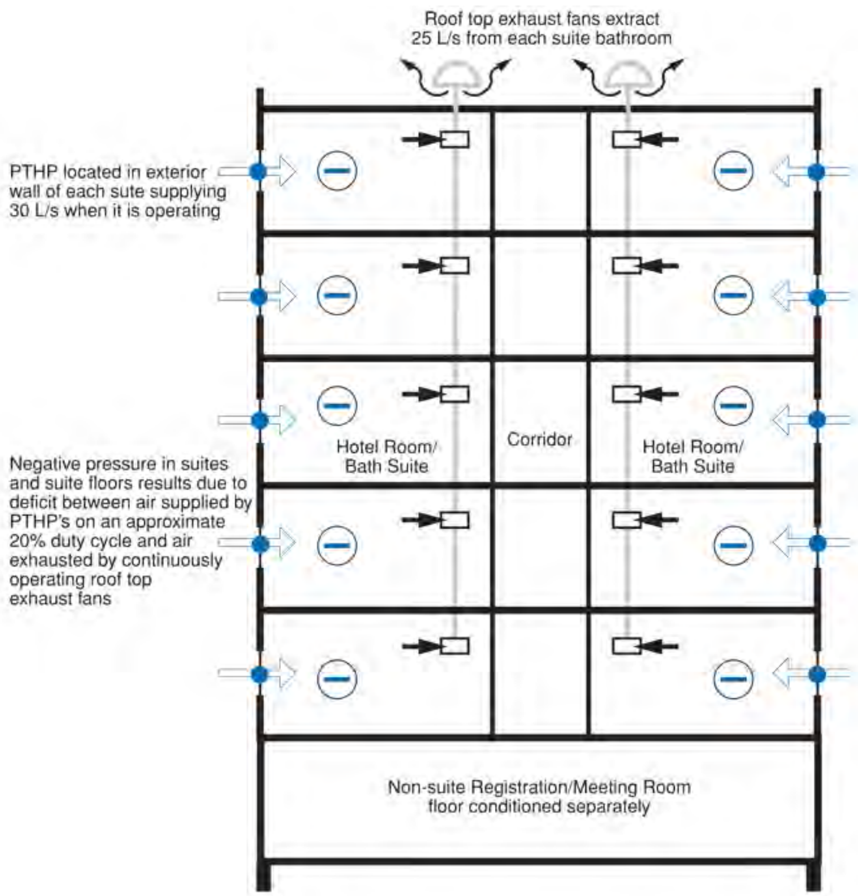


Figure 5.5
HVAC System for Hotel

- 25 L/s is extracted from each suite
- 15 suites per floor plus 100 L/s extracted from each corridor
- 475 L/s extracted per floor
- 2,850 L/s extracted from 6 floors with suites
- Each suite's PTHP supplies 30 L/s when it is operating. One additional PTHP serves each corridor supplying 100 L/s of outside air. A total of 550 L/s is supplied per floor when all the PTHP's on a floor are operating.
- However, the typical duty cycle of a PTHP is approximately 20%, i.e. 80% of the units are off at any one time.
- When 3 suite PTHP's and the corridor PTHP are operating only 190 L/s supplied to a floor. If 475 L/s is extracted per floor, a deficit of 285 L/s exists per floor or 1,710 L/s for all the suite floors combined.

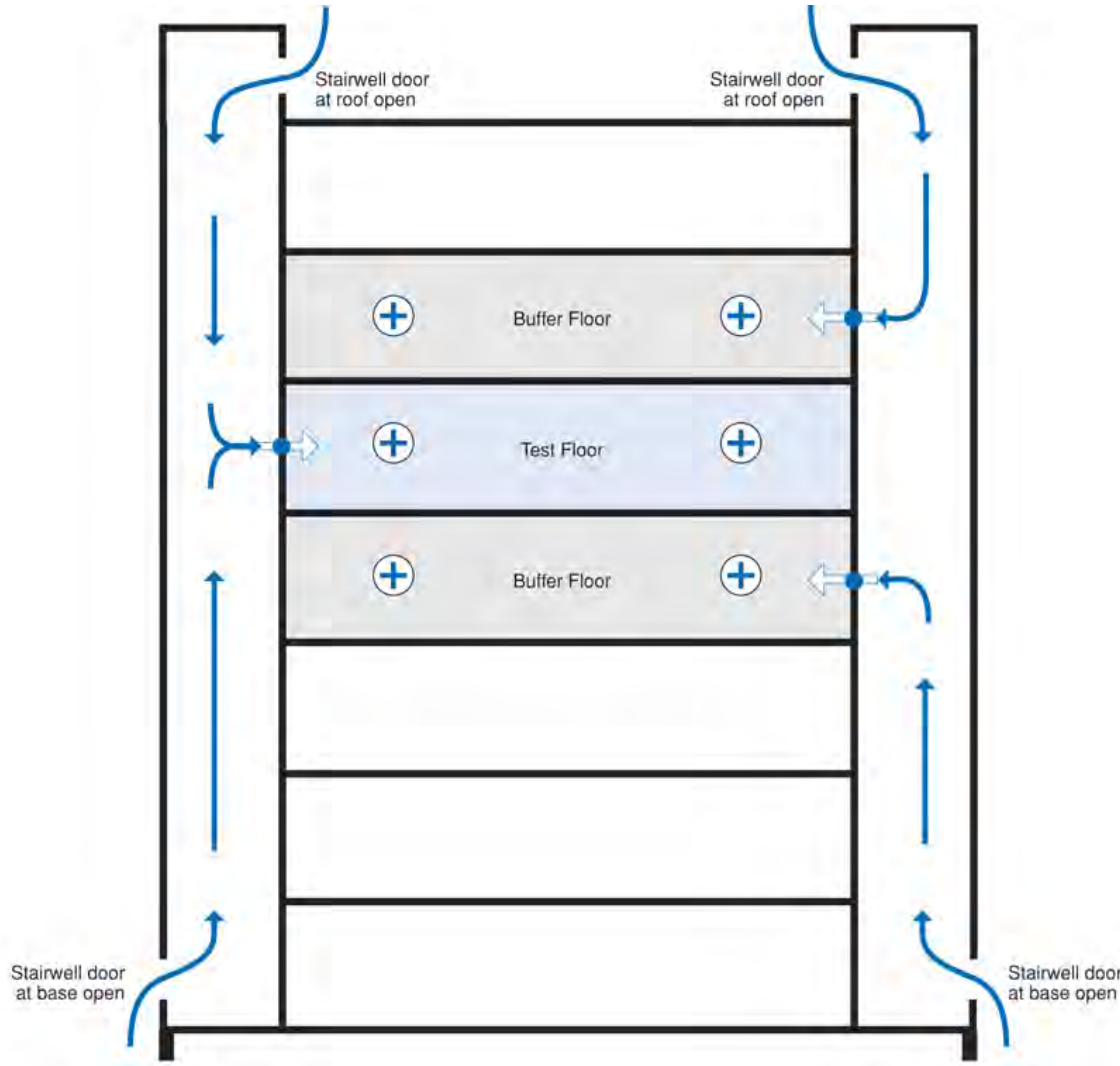


Figure 5.6
Air Leakage Test Zones

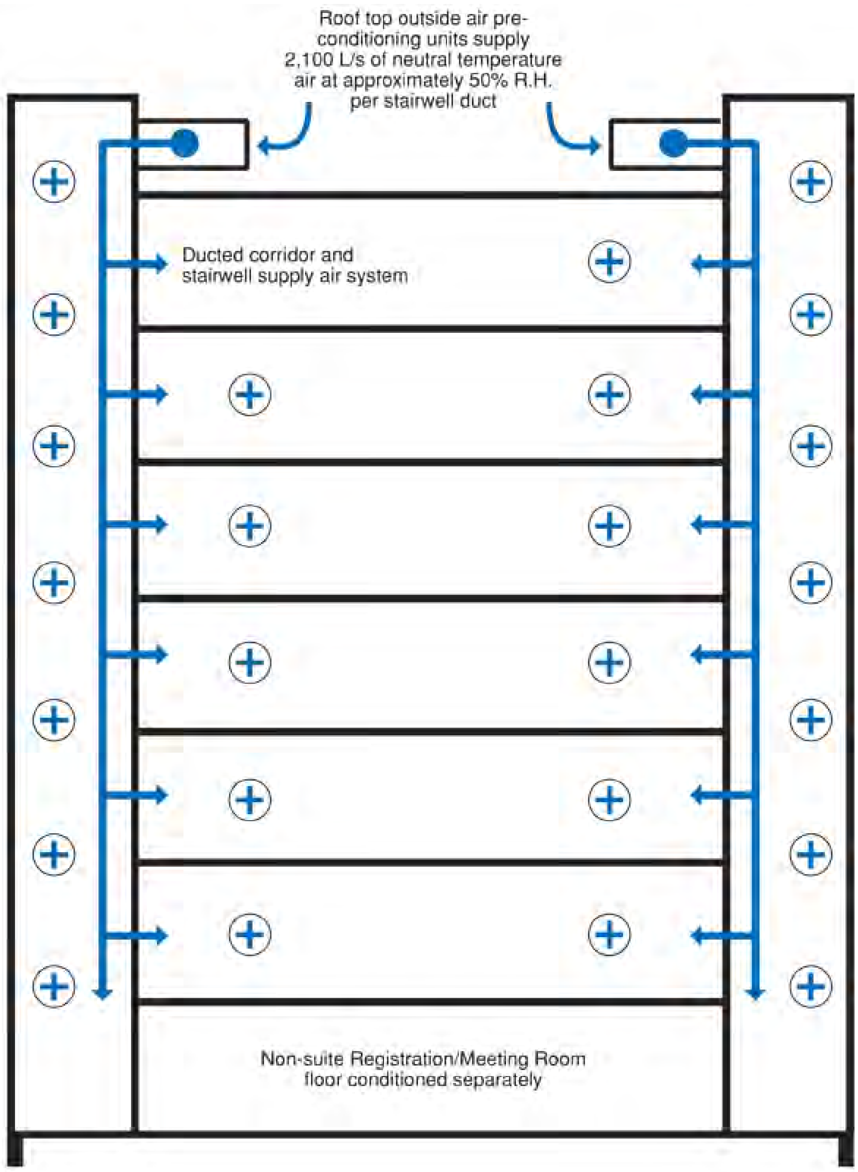


Figure 5.7

New Air Pressure Relationships

- Hotel suite floors supplied with 4,200 L/s of preconditioned air
- Hotel suite floors are exhausted to a total of 2,850 L/s
- Surplus of 1350 L/s pressurizes suite floors
- Stairwell held open with magnetic latches

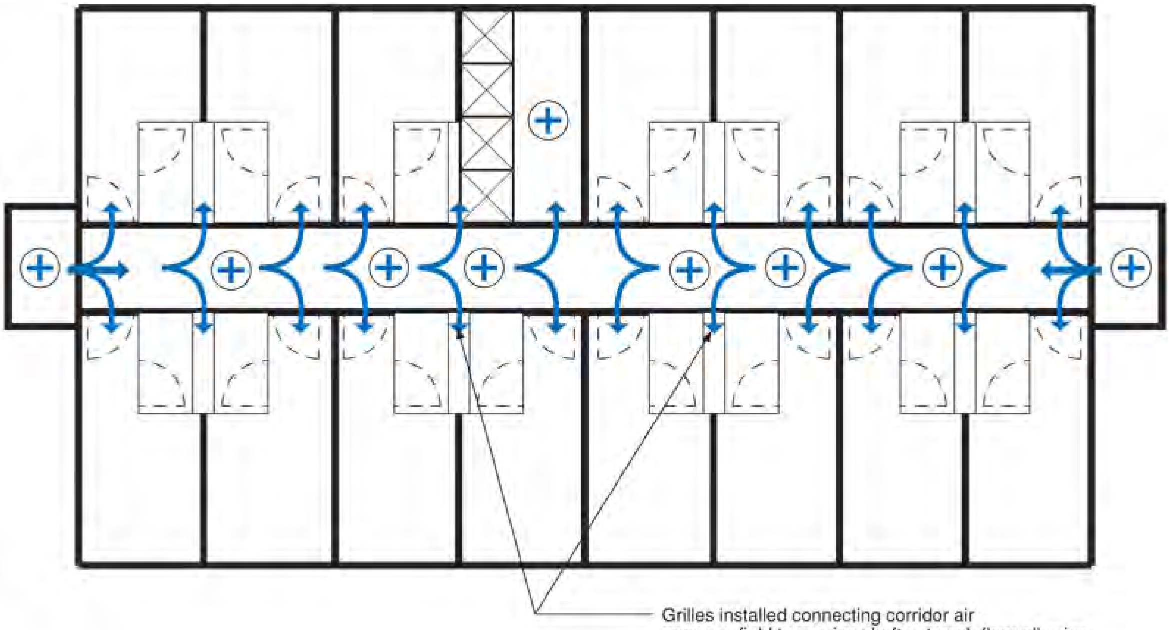


Figure 5.8
Supply Air Approach
Plan View

- 700 L/s supplied to each corridor from ducted system in each stairwell
- A total of 4,200 L/s is supplied for all suite floors combined via two stairwells (or 2,100 L/s per stairwell)

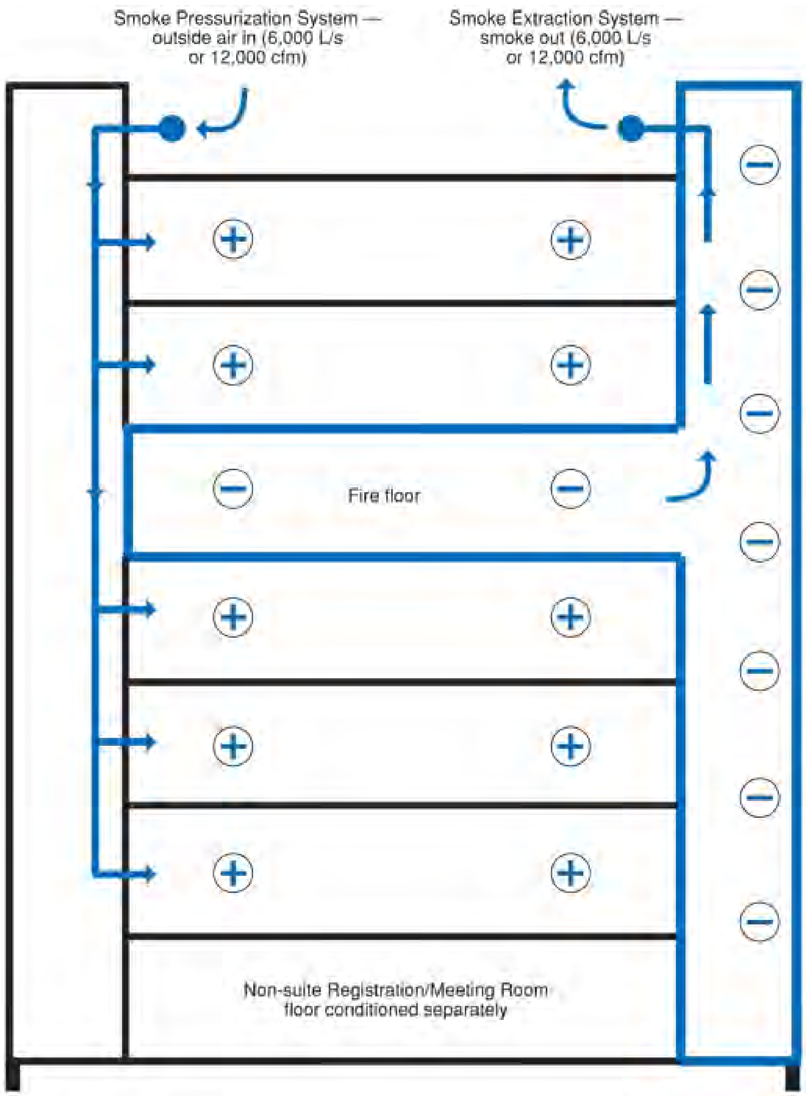


Figure 5.9

Smoke Extraction System

- If hotel is pressurized 25 Pa and smoke floor/floors are depressurized 25 Pa, net minimum smoke control pressure difference is greater than the design specified 25 Pa
- Approximately 1,000 L/s per floor is required to pressurized each floor 25 Pa relative to the exterior or approximately 6,000 L/s to pressurize the 6 hotel floors with suites when the roof top exhaust systems are not operating

Durability (moisture)

A data processing center located in Hartford, CT provides a good example of addressing durability (moisture) concerns in an existing facility by using “pressure mapping” to diagnose the problems (identify the linkage among the constituent building pressure fields) and by using temperature controlled pressurization of interstitial cavities to remediate the facility.

Description of Facility and History of Problems

The facility is a 10,000 m2 two story steel framed structure on a concrete slab supported by a grade beam foundation. The exterior cladding consists of face sealed precast panels. Insulated steel stud walls are constructed to the interior of the precast panels. A cavity varying between 50 mm and 500 mm exists between the interior surfaces of the precast panels and the exterior face of the insulated steel stud walls. Gypsum board is installed on the interior of the steel stud walls over a polyethylene air-vapor barrier.

The roof assembly is a built up roof over 100 mm of rigid insulation installed over a concrete roof deck.

The facility contains raised floor plenums that provide conditioned air throughout. The conditioned air is heated, cooled, humdified, dehumidified as necessary by floor mounted conditioning units that supply air to the under floor plenums. Outdoor air is preconditioned and introduced to each floor by roof mounted air handlers.

The space conditioning and outdoor air systems (Figure 5.10) create a pressurized enclosure that is maintained at 24 degrees C., 50 percent relative humidity year round.

Condensation during winter months occurs on the inside face of the precast panels and drains out at floor slabs and window penetrations leading to deterioration of interior finishes, mold odors and microbial contamination of interstitial cavities.

Investigation and Testing

Air pressure differential measurements of the facility and interstitial cavities (“pressure mapping” of the facility) were taken when exterior temperatures were approximately 15 degrees C. Wind conditions were dead calm. The air pressure differential relationships as measured are presented in Figure 5.11.

Four portable variable speed calibrated flow fans (“blower doors”) were used to introduce outside air to the interstitial space between the precast panels and the insulated steel stud walls. The fans were positioned at the four exterior corners of the building and introduced air into the interstitial spaces via access holes that were cut in soffits over exterior doors. Approximately 4,000 L/s of outside air was necessary to pressurize the interstitial spaces 5 Pa relative to the interior space above the raised floors (the occupied space).

Conclusions

The pressurization of both the occupied space and the area under the raised floors leads to the exfiltration of interior moisture laden air into the interstitial cavities between the precast panels and the interior insulated steel stud walls.

Condensation on the cavity side of the precast panels occurs whenever the exterior temperature drops approximately 5 degrees C below the dew point temperature of the interior air/vapor mix. Based on interior conditions, the exterior temperature at which condensation typically occurs is approximately 10 degrees C.

The precast panels are significantly tighter than the interior insulated steel stud wall assembly as can be seen by examining the ratio of air pressures across the assemblies (approximately 80 percent of the air pressure drop across the exterior wall assembly occurs across the precast panels). The rate of moisture entry into the wall cavities via air flow is greater than the rate of moisture removal by air flow.

The original design of the wall assembly should have provided for back venting of the precast panels coupled with drainage of the interstitial cavities to the exterior. A drainage plane system for rain control should have been provided on the exterior of the insulated steel stud wall assembly.

It is not practical as a retrofit measure to tighten the interior insulated steel stud wall such that it becomes significantly tighter than the exterior precast panels. Conversely, it is not possible to introduce drainage and ventilation to the exterior precast panel system without removing the panel system and incurring an enormous cost.

Rehabilitation Measures

A cavity pressurization system was designed (Figure 5.12) that introduces outside air to pressurize the interstitial space between the precast panels and the interior insulated steel stud wall system. The outside air is introduced at the roof top via 4 variable speed fans that can introduce up to 2,000 L/s of outside air each. The fans are connected to the building automation system. The building automation system monitors the air pressure difference between the interior occupied space and the interstitial cavity as well as the exterior temperature. When the exterior temperature drops below 10 degrees C. the interstitial cavity is pressurized approximately 5 Pa relative to the interior occupied space using exterior air.

A buffer air space is provided at the perimeter of the raised floor plenum system by the installation of a baffle and floor grilles. In this manner the high positive air pressure field existing in the under floor plenum is prevented from extending to the exterior wall.

The variable speed fans allow compensation for stack effect pressures during cold weather. Using the pressure difference between the interior occupied space and the interstitial cavity as a reference pressure difference compensates for the dynamic effects of wind allowing the building itself to act as a "dash pot". Using the exterior air pressure as a reference pressure is impractical due to the high variability of the boundary layer air pressure regime.

Discussion

The relational air pressure field model describing the building (Figure 5.11) developed from identifying the linkage among the constituent building pressure fields allows the implementation of an innovative cavity pressurization system to rehabilitate the facility.

The cavity pressurization system provided a low cost alternative to reconstructing the exterior wall assembly. The cost of the pressurization system was approximately $35,000 (including diagnostics, testing, design, installation and commissioning). The cost to reconstruct the exterior wall assembly was estimated at approximately $2,500,000. The disruption to facility operations during exterior wall assembly reconstruction was not considered.

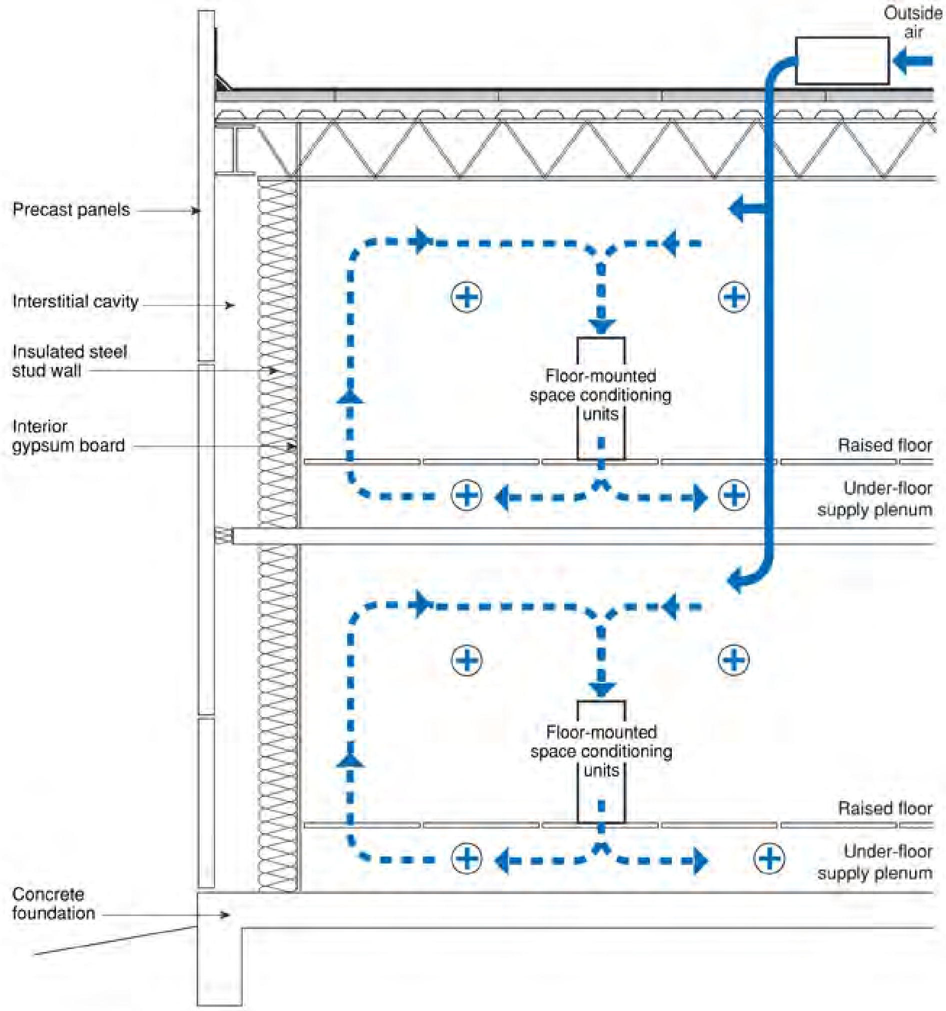


Figure 5.10
HVAC System as Designed

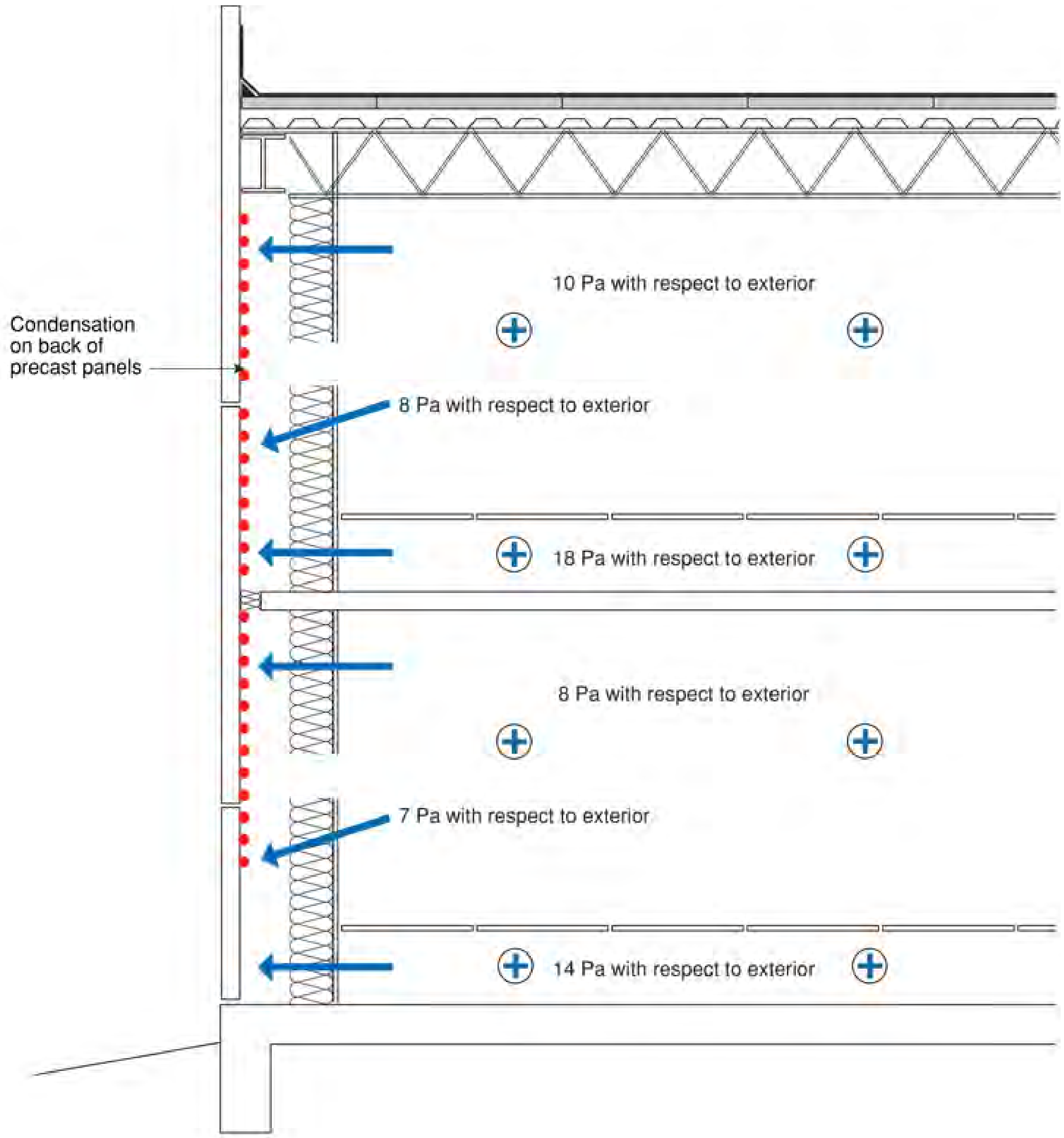


Figure 5.11
Unintended Pressurization of Interstitial Cavity

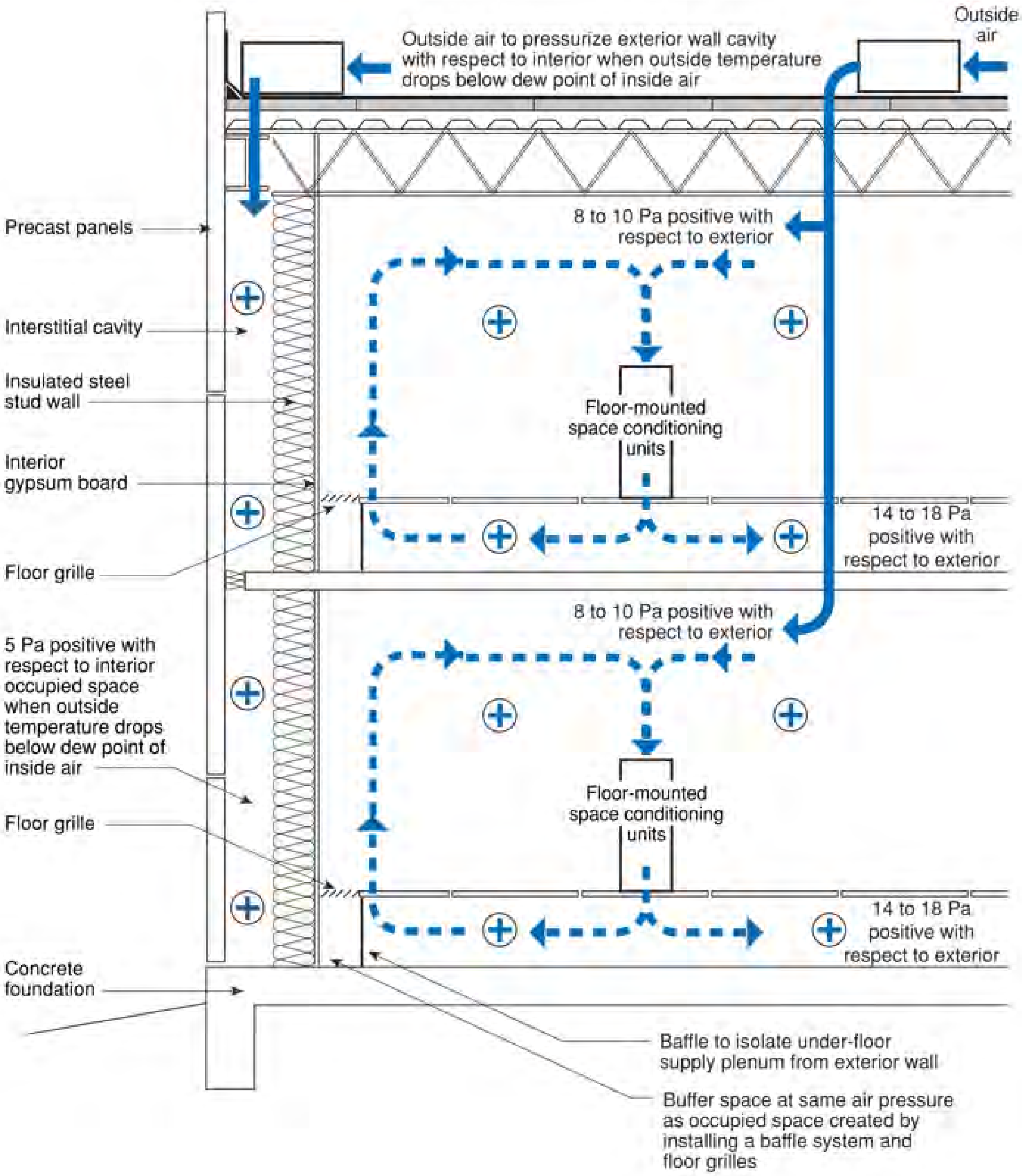


Figure 5.12
Modified Pressure Relationship

Comfort

A condominium development located in Mahwah, NJ provides a good example of addressing comfort concerns using pressurization testing and series air pressure differential measurements to diagnose building related problems.

Description of Facility & History of Problems

The development in question is multi-unit project constructed between 1990 and 1991. The units are multi story wood framed structures. Floor framing consist of open webbed floor trusses. Party walls are double wood frame with fire rated gypsum.

The space conditioning systems consist of forced air natural gas units. These units are located in utility rooms. A natural gas water heater is also located within each utility room. Meter closets are constructed external to the units.

The residents of some of the suites had been complaining of cold interior floor temperatures, high heating bills, an inability to heat the units, large temperature differences between rooms, between upper floors and lower floors, frozen pipes, and water leakage from ice damming.

Investigation and Testing

The interior structure of the buildings was visually examined from within via existing access openings, from within the attic spaces and from access openings (intrusive disassembly) cut in interior gypsum board and through wood subfloor sheathing. Particular attention was focused on utility chaseways, fireplace chaseways and enclosures, party wall construction, floor framing, bulkheads, service penetrations, the intersection of sloped ceilings and partition walls and mechanical system installation.

Visual observations from within attic spaces of roof assembly perimeters indicated insulation substantially filling the majority of the spaces between the underside of roof sheathing and the top plates of exterior walls. Insulation vent baffles were intermittently installed in truss bays. Soffit venting was discontinuous. Soffit venting, where installed, occurred through the use of perforated soffit closures.

In roof regions which experienced the greatest amount of ice damming, specifically the lower reaches of valleys at the intersection of two different roof slopes, no provision for roof ventilation was found. Intersecting roof truss cavities were blocked solid with wood framing and filled with insulation.

Attic temperatures were measured in the range of 5 to 10 degrees C when the exterior temperature was - 18 degrees C indicating a combination of substantial heat loss and a likely lack of effective attic ventilation. Large gaps were observed between openings cut in ceiling gypsum board and boots connected to supply ductwork installed in attics penetrating the ceiling gypsum board openings. Voids and gaps were observed between ceiling gypsum board and the underside of attic ceiling batt insulation.

Visual observations indicated that the building envelopes were "leaky" at utility chaseways, fireplace chaseways and enclosures, party wall locations, perimeter "band" joist/"rim" joist locations, bulkheads, and service penetrations.

Observations, comfort indicators (temperature measurements) and discussions with occupants indicated imbalances in flow between levels within units as well as between rooms. In multi level units, most of the delivered air from supply ductwork appeared to be supplied to the second floor /upper levels. In single level units, large differences in comfort levels between rooms was noted. Occupants claimed that very little supply air got delivered by the heating systems.

Large chaseways and related air flow pathways were identified by cutting access openings over fireplace mantles. Many of these chaseways and flow paths were connected to vented roof/attic areas constituting significant attic "bypasses". Chimney enclosures were subject to particularly strong air flows. The installed mineral wool firestopping appeared to be ineffective in reducing/controlling this air flow.

In units where kitchen sinks shared a common wall with fireplace enclosures and where in turn these fireplaces and common walls were adjacent to and intersected exterior walls which in turn were connected to exterior meter closets, particularly strong air flow/air leakage was observed across access openings cut through interior gypsum board. Investigation also revealed that the exterior meter closets had no floors and were constructed directly over a gravel pad. Investigation revealed these gravel pads were directly connected to the interior basement spaces through openings at the rim joist. These locations also appeared to correspond with numerous incidences of freezing water pipes.

The garage ceiling of a unit which had experienced frozen sprinkler lines was removed. The front portion of the garage ceiling was connected to a vented roof area. Significant flow pathways between the garage ceiling, the insulated floor area and the conditioned spaces were observed. The rim joist area of the heated floor space above the garage was constructed from an open webbed girder truss with substantial air leakage pathways connecting the insulated floor area directly to the vented roof area.

Fiberglass batt insulation completely filled the space between the floor trusses. However, numerous void areas and pathways in the insulation was observed related to the inherent nature of several layers of batt insulation installed in a semi-open cavity. These void areas were directly connected to the vented roof area through the open webbed girder truss allowing the floor insulation to be effectively short circuited.

Access into the attic space of the roofs constructed over deck areas allowed visual observation of the construction of floor framing installed above unit kitchen areas. No rim joist closures were installed allowing the free flow of cold attic air directly into the floor truss space.

In summary, large building envelope air leakage sites were identified during the investigation at the following locations:

- utility chaseways;
- fireplace chaseways;
- party walls;
- penetration of ductwork through gypsum board;
- rim joist assemblies;
- bulkheads and dropped ceiling areas;
- service penetrations;
- combustion air ducts;
- tubs adjacent exterior walls;
- intersection of shed roofs and exterior walls;
- intersection of interior demising walls and sloped cathedral ceilings; and
- joints between exterior sheathing in all buildings due to an absence of building paper.

Building Envelope Air Leakage Testing

Building envelope air leakage testing was conducted to quantify the air leakage of the building envelopes. The testing was conducted using the fan depressurization approach. In this approach, air is extracted from the buildings conditioned (heated) spaces using a portable exhaust fan. This controlled air exhaust results in a negative air pressure within the building with respect to the exterior (depressurization). The quantity of air exhausted from the interior of a unit is increased until a standard reference negative air pressure is achieved.

This standard reference negative air pressure is typically 50 Pa (chosen by popular convention). The amount of air necessary to be exhausted from a unit in order to depressurize the unit 50 Pa relative to the exterior is then measured. The leakier the building envelope, the greater the amount of air required to depressurize the building envelope 50 Pa relative to the exterior. The quantity of air is expressed in liters per second and is referred to as the building envelope's LPS50 value.

A dozen randomly picked units were tested using the fan depressurization approach. Leakage values ranged between 1,250 LPS50 and 2,900 LPS50. These values represent extremely leaky building envelopes given the size (volume) of the units tested. These leakage values are approximately twice as large as what would be considered acceptable practice for similar construction of this type, age and geographic location.

Relative leakage of building envelope assemblies was also determined. The assemblies tested were roof/attic assemblies and floor assemblies. The testing was conducted using the series air pressure approach. In this approach, a reference air pressure differential is established across a building envelope utilizing a portable exhaust fan. Air pressure differences across individual building assemblies and components are then measured and compared to the reference air pressure differential.

The following series of examples are used to illustrate the approach. In Figure 5.13, a simple building envelope is depressurized to 50 Pa relative to the exterior. If an air pressure measurement is made between the interior and exterior across the four exterior walls, the air pressure measurement will be 50 Pa regardless of how leaky or tight the wall construction will be. However, the air pressure measurement across the attic ceiling will be very dependent on the tightness of the ceiling construction. Figure 5.13 illustrates the presence of a well-defined pressure boundary across the attic ceiling.

In Figure 5.14, the building envelope is depressurized 50 Pa relative to the exterior and an air pressure difference of 25 Pa is measured between the interior and the attic. A pressure difference of 25 Pa also exists between the attic and the exterior since the total air pressure difference must equal 50 Pa. This implies that the flow path resistance into the attic cavity from the interior is approximately equal to the flow path resistance out of the attic cavity to the exterior.

A tightly constructed attic ceiling with a well vented attic cavity would be expected to have an air pressure drop approaching 50 Pa, and an extremely leaky attic ceiling would have an air pressure drop much lower than 50 Pa. In residential construction, with code compliant attic ventilation ratios (i.e. 1:300), insulated ceiling air pressure drops greater than 40 Pa are viewed as providing acceptable performance by the author when a building envelope is depressurized 50 Pa. In other words, acceptable performance requires that more than 80 percent of the air pressure drop should occur across a well-defined pressure boundary (the attic ceiling gypsum board in this example). Acceptable performance being defined arbitrarily as buildings with vented attics in cold climates not experiencing ice damming, roof sheathing moisture induced deterioration or upper floor thermal comfort complaints.

In this condominium development, air pressure measurements were taken across insulated ceilings when units were depressurized 50 Pa relative to the exterior. Measurements ranged between 25 and 35 Pa in the dozen units tested. These values signify extremely leaky attic ceiling construction, extremely poor attic ventilation or some combination of both.

A similar approach was used to determine leakage between floor assemblies and the exterior. In Figure 5.15, a more complex building envelope is depressurized 50 Pa relative to the exterior. This building envelope describes a two story building with a floor assembly separating the two stories. An open stair well connects the two stories. The floor assembly is constructed from open webbed floor trusses creating a floor plenum. If the interior of the building is depressurized 50 Pa relative to the exterior, and if the floor assembly is "inside" the building, no air pressure difference should exist between the floor assembly and the interior.

In Figure 5.16, the building envelope is depressurized to 50 Pa relative to the exterior and an air pressure difference of 25 Pa is measured between the interior and the floor assembly. A pressure difference of 25 Pa also exists between the floor assembly and the exterior since the total air pressure difference must equal 50 Pa. This implies that the flow path resistance into the floor assembly from the interior is approximately equal to the flow path resistance out of the floor assembly to the exterior.

Figure 5.17 and Figure 5.18 illustrate the net effect when floor assembly rim closures are not installed with open webbed floor joist construction. The hollow floor cavity created by utilizing open webbed floor joists is effectively moved outside of a well defined pressure boundary. A similar (to the authors vented attic assembly pressure boundary performance requirement) ad hoc definition of acceptable performance requires more than 80 percent of the air pressure drop occurs across a well defined pressure boundary (the rim closure in this example). This would entail limiting the pressure drop across the floor assembly to less than 10 Pa when the building envelope is depressurized 50 Pa relative to the exterior.

At this condominium development, air pressure measurements were taken across floor assemblies when units were depressurized 50 Pa relative to the exterior. Measurements ranged between 20 and 30 Pa in the dozen units tested. This signifies extremely poor rim joist closure construction.

Mechanical System Air Leakage Testing

Large mechanical system air leakage sites were identified during the investigation at the following locations in all unit types in all buildings:

- connections between boots and gypsum board penetrations;
- connections between boots and subfloor penetrations;
- connections between boots and flex ducts;
- connections between flex ducts and sheet metal ducts;
- connections between return grills and return systems;
- return system cavity framing;
- air handler housings;
- connections between supply and return plenums with air handlers;

- connections between supply plenums and supply ducts;
- connections between return plenums and return chaseways and ducts; and
- joints in sheet metal ductwork.

Mechanical system air leakage testing was conducted to quantify the air leakage of the mechanical systems installed. The testing was conducted using the fan pressurization approach. In this approach, supply and return diffusers and grills are temporarily sealed (closed). Air is blown into the duct distribution system (heating system) using a portable fan. This controlled air supply results in a positive air pressure in the duct system with respect to the building (pressurization). The quantity of air supplied to the duct system is increased until a standard reference positive air pressure is achieved. This standard reference positive air pressure is typically 25 Pa (chosen by popular convention as it is the typical average air pressure in most duct systems when they are operating). The amount of air necessary to be added to the duct system in order to pressurize the duct system 25 Pa relative to the interior is then measured. The leakier the duct system, the greater the amount of air required to pressurize the duct system 25 Pa relative to the interior. The quantity of air required for pressurization is expressed in litres per second and is referred to as the duct system's LPS25 value. This approach is analogous to a plumber pressure testing plumbing in order to identify leaks.

A dozen mechanical systems were tested using the fan pressurization approach. These systems were randomly picked and corresponded to the unit types previously tested for building envelope leakage and building envelope air pressure measurements. Leakage values ranged between 300 LPS25 and 500 LPS25. These values represent extremely leaky mechanical systems given the size of the systems tested. These leakage values are approximately three times as large as what would be considered acceptable practice for similar construction of this type, age and geographic location.

The total quantity of air circulated by the mechanical systems (through the furnace blowers) was found to range between 400 and 900 L/s (as per the manufacturers specifications). Therefore, the total leakage of air flow in the mechanical systems tested at 25 Pa represents approximately 30 to 80 percent of the total quantity of air circulated.

The operation of leaky ducted forced air heating systems often leads to air pressure differences which induce air leakage/air change. Figure 5.19 illustrates the effect of leaky supply ducts in an open floor plenum which lead to pressurization of the floor plenum and exfiltration out the rim closure. Figure 5.20 illustrates the similar (opposite) effect of leaky supply ducts leading to depressurization of the floor plenum and infiltration through the rim closure.

The measurement of the air pressures of interstitial spaces (floor cavities and chimney chaseways) supports the effects of air pressure differentials resulting from leakage of the air handling systems.

Air pressure measurements indicated significant changes in air pressure relationships within the floor interstitial/plenum spaces when furnace fans operated. Floor spaces tended to go to both positive and negative up to 3 Pa relative to the exterior and relative to the conditioned space on a random (unit-per-unit) basis when the air handlers operated indicating substantial supply or return duct leakage.

Interaction of Building Envelope Air Leakage and Mechanical System Leakage

The leakage of the duct system when the air handlers are operating induces higher than typical driving forces across the building envelope. Furthermore, the construction and communication of the interstitial cavities, the fireplace chaseways, the party walls, and the attic spaces lead to stack effect air pressure driving forces in addition to the air handler induced air pressures. When stack effect air pressure differentials are combined with duct leakage/air handler induced air pressure differentials as well as wind induced air pressure differences the combined driving forces and identified air leakage sites account for the significant building envelope air leakage which occurred and resultant complaints and problems.

When wind blows over a building, the exterior of the windward side of the building experiences a positive air pressure, and the exterior of the leeward side experiences a negative air pressure. Side walls typically experience negative air pressures. Leakage openings in the building envelope which are exposed to these wind induced air pressure differences leak air. In general the greater the leakage areas the greater the effect of wind on total air leakage/air change.

This condominium development had significant windward, leeward and sidewall leakage areas throughout the project. These leakage areas communicated with each other across the open webbed floor system.

Additionally, large voids and chaseways extended vertically between stories, thereby creating significant stack effect air pressures and large air flows. These flows were exacerbated by the open webbed floor construction creating floor plenums which communicated with these vertical voids and chaseways (Figure 5.21). The most significant of the vertical chaseways were the fireplace chaseways. However, all units in all buildings were affected by vertical communication.

Conclusions

The units leaked substantial quantities of air both across the building envelope as well as from the mechanical system ductwork. The building envelope and mechanical system air leakage was the cause of the comfort complaints, high utility bills and frozen pipes at the development.

The ice damming and associated water damage occurred as a result of the ineffective ventilation of the underside of perimeter roof sheathing due to a lack of air flow pathways and/or blocked pathways coupled with excessive heat loss into the attic spaces due to air leakage from attic bypasses and leakage of heated air out of duct distribution systems particularly at boot/ceiling connections.

The leakage of the duct system when the air handlers are operating induces higher than typical driving forces across the building envelope. Furthermore, the construction and communication of the interstitial cavities, the party walls, and the attic spaces likely lead to stack effect air pressure driving forces in addition to the air handler induced air pressures. When stack effect air pressure differentials are combined with duct leakage/air handler induced air pressure differentials the combined driving forces and identified air leakage sites can easily account for the resultant complaints and problems.

The measurement of leakage through pressurization testing and air pressure measurements of interstitial spaces supports the hypothesis of pressure effects resulting from the air handling systems. The identification of air leakage pathways through visual observations, intrusive disassembly, and induced pressure differentials further supports the hypothesis.

In heating climates, where sufficient heat loss occurs at roof perimeters above insulated wall assemblies, ice damming can occur. The heat loss can melt snow on the roof causing melt water to run down over the roof overhang, where it can freeze forming a dam. The ice dam causes the water to back up and leak under overlapped shingles and through roof sheathing. This heat loss can occur from either a lack of thermal insulation where exterior walls intersect roof and attic assemblies, or from the leakage of warm air up and out of exterior and interior walls, attic bypasses and from duct leakage.

Air leakage from attic bypasses, exterior walls and air leakage out duct distribution systems as boot/ceiling connections resulting in high heat loss coupled with a lack of continuous venting and blocked rafter spaces at eve perimeters led to ice damming and the subsequent water damage. Observations revealed the lack of a continuous air space and perimeter eve ventilation as well as many rafter cavities blocked solid with wood framing. Temperature measurements between attic spaces and the exterior coupled with air pressure measurements and visual observations confirm the air leakage from attic bypasses, duct leakage and resultant high heat loss into the attic space.

Continuous soffit ventilation can be used to flush heat away from the underside of the roof assembly, preventing it from melting accumulated snow on the roof and thus controlling the formation of ice dams. For continuous soffit ventilation to be effective, a clear, continuous 50 mm air space should be provided at the roof eave perimeter. This is usually accomplished with carefully installed baffles at each truss bay. These baffles must be selected and installed in a manner which controls/prevents wind washing or the short circuiting of attic insulation.

In order to control ice damming it is also necessary to reduce heat loss into attic spaces. This means that air leakage from attic bypasses, interior and exterior walls as well as out of duct work needs to be reduced or eliminated. In addition, where roof geometry permits, additional thermal insulation may also be installed. However, this additional thermal insulation should not be installed at the expense of a continuous ventilated air space located above the insulation.

Rehabilitation Measures

The mechanism responsible for the ice damming and resulting water damage is ineffective ventilation of the underside of perimeter roof sheathing due to a lack of air flow pathways and excessive heat loss into the attic spaces due to air leakage from attic by passes and leakage of heated air through the building envelope and out of duct distribution systems. Therefore, addressing these factors can alleviate the ice damming complaints:

- Sealing all attic air leakage sites particularly at utility chaseways, party walls service penetrations, and the intersection of interior partition walls and sloped cathedral ceilings;
- Sealing all boot connections penetrating attic ceiling gypsum board;
- Providing continuous soffit ventilation and a continuous 50 mm clear air space above the roof ceiling insulation at the perimeter of the roofs; and
- Providing additional vent openings at roof ridge locations.

The mechanism responsible for the comfort complaints, high utility bills and freezing pipes is building envelope and mechanical system leakage as a result of the following factors:

- Large leakage openings connected to interstitial cavities/chaseways creating substantial air leakage pathways;
- Duct leakage induced air pressure differentials; and
- Stack effect induced air pressure differentials as a result of party wall leakage areas and interior air leakage pathways;

Therefore, addressing these factors can alleviate the comfort complaints, reduce the high utility bills and eliminate freezing pipes:

- Sealing all air leakage sites particularly at utility chaseways, party walls service penetrations, the intersection of interior partition walls and sloped cathedral ceilings, fireplace chaseways, rim joist assemblies, and the intersection of shed roofs/porch roofs and exterior walls;

- Sealing all boot connections penetrating gypsum board;
- Balancing the air distribution systems; and
- Insulating, sealing and heating the floors over garage spaces.

Discussion

This condominium development epitomizes the complex three-dimensional multi-layer, multi-cell, non-contiguous air flow analogue described initially in Figure 2.12. The diagnosis of the problems in this condominium development were significantly simplified through the use of series air pressure differential measurements and the measurement of the response of interstitial cavity pressures to the operation of air handling systems. Quantification of duct leakage, envelope leakage and cavity leakage was made possible using these techniques. This allowed the development of specific targeted rehabilitation measures.

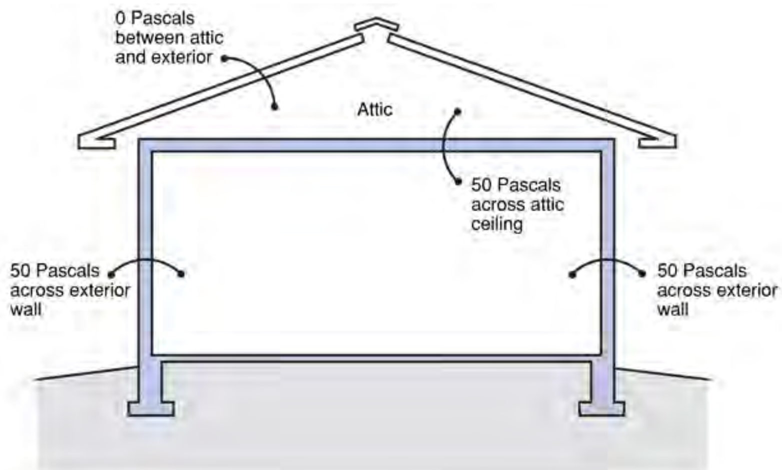


Figure 5.13

Well-Defined Pressure Boundary

- Pressure boundary defines effective building envelope environmental separator

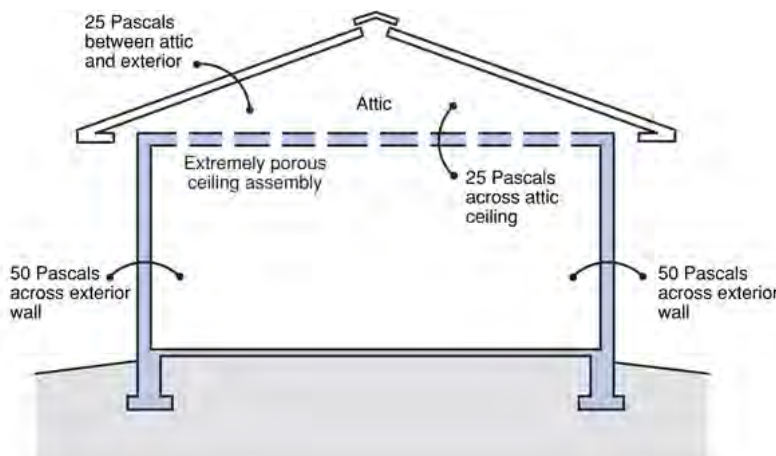


Figure 5.14

Poorly-Defined Pressure Boundary

- Pressure boundary poorly defined — ineffective at ceiling
- Pressure boundary not continuous at ceiling

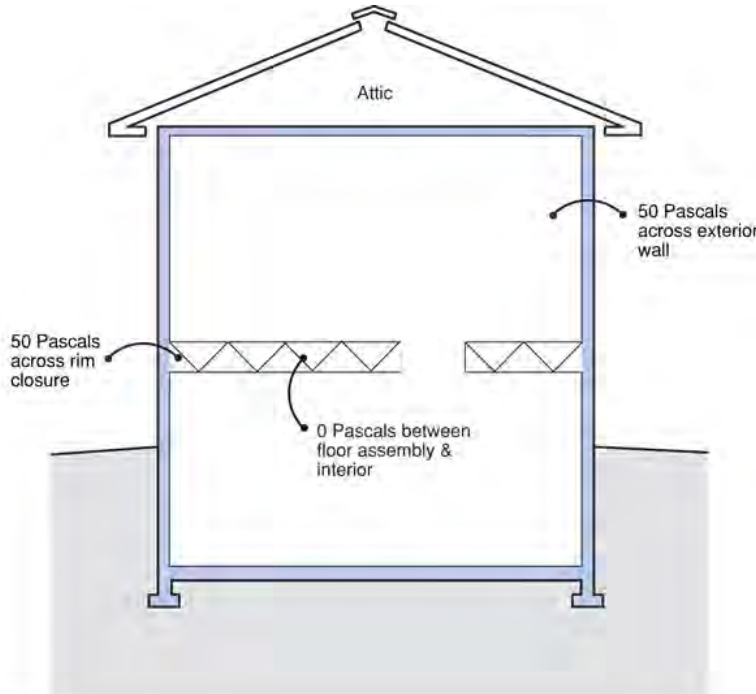


Figure 5.15
Tight Rim Closure
- Floor assembly "inside" well-defined pressure boundary
- Pressure boundary continuous at rim closure

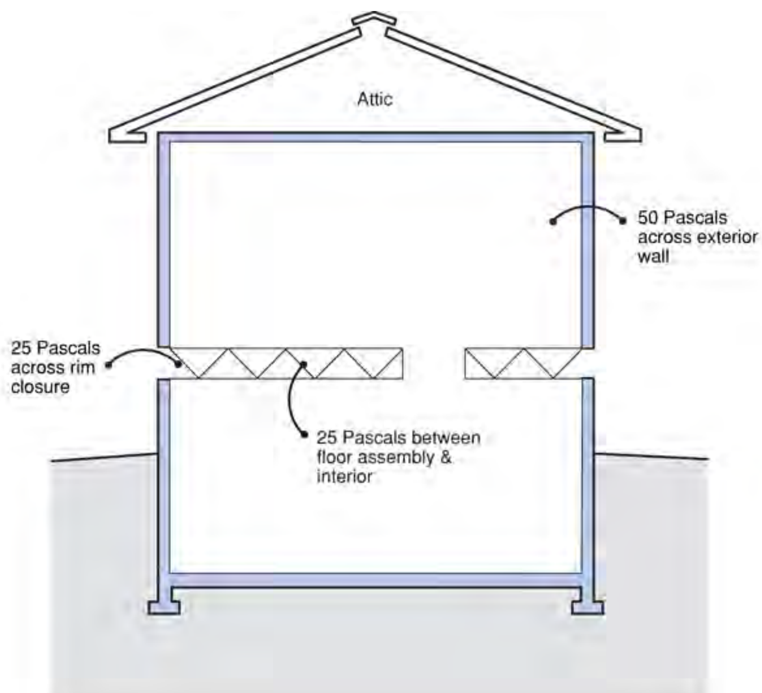


Figure 5.16
Leaky Rim Closure
- Floor assembly "outside" pressure boundary
- Pressure boundary not continuous at rim closure

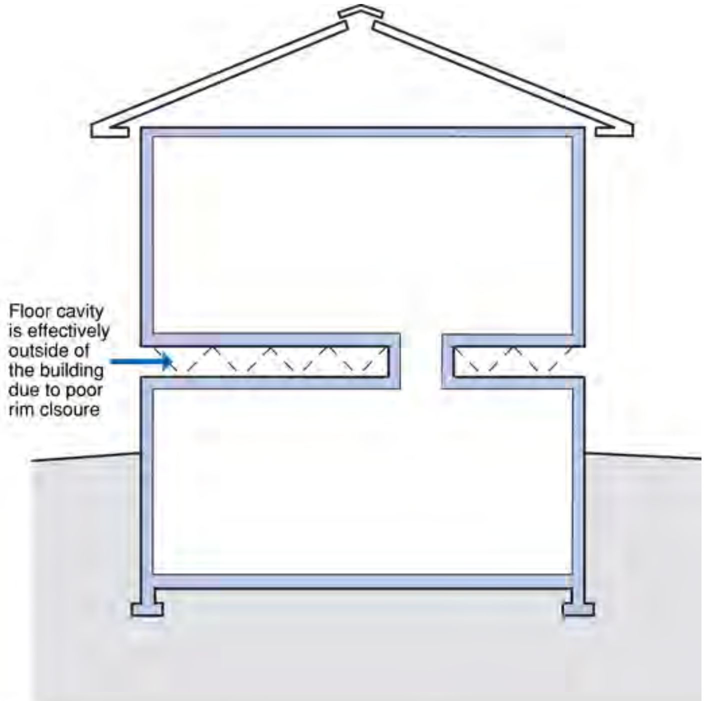


Figure 5.17
Pressure Boundary at Interior Floor
- Pressure boundary not contiguous with building envelope thermal boundary

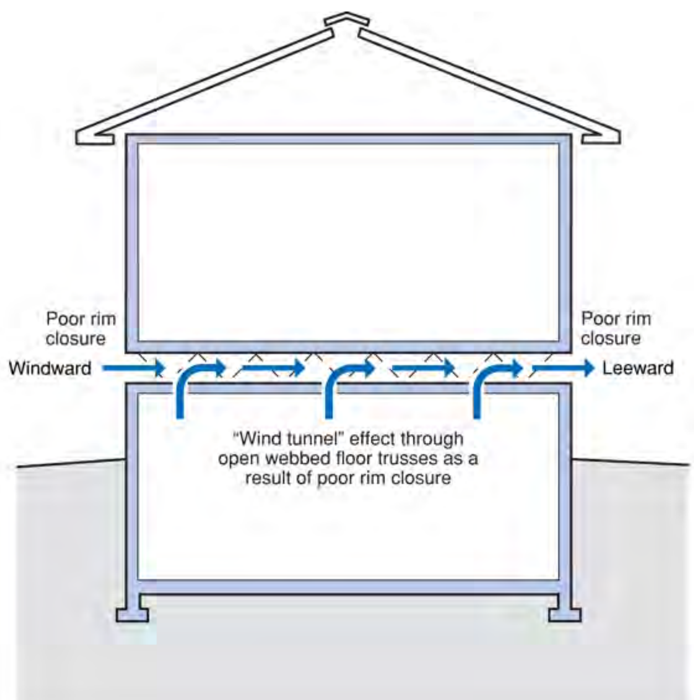


Figure 5.18
Wind Tunnel Effect

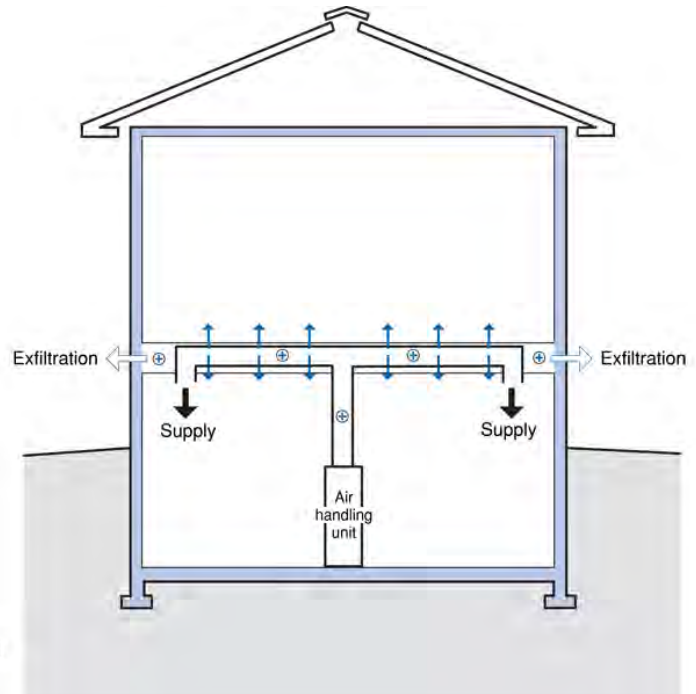


Figure 5.19
Supply Duct Leakage
- Leakage of supply ducts into floor space pressurizes floor space leading to exfiltration at rim closure

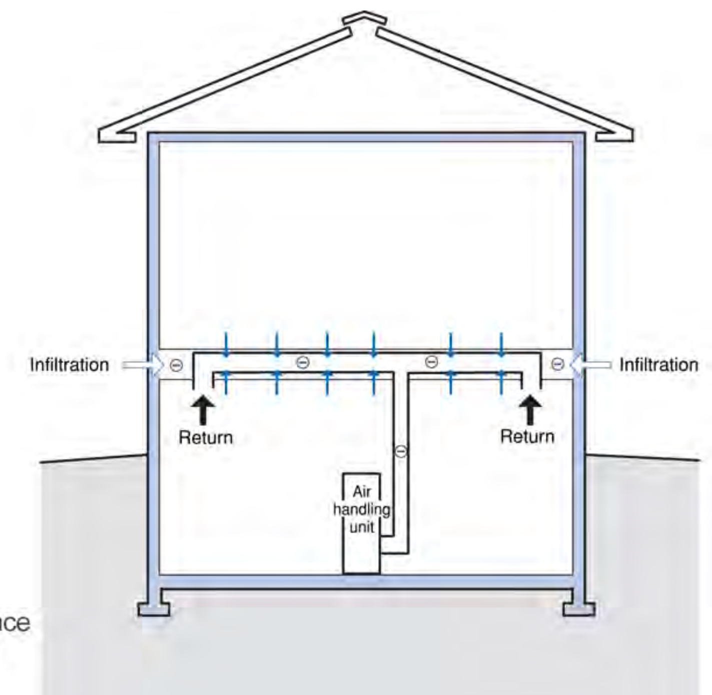


Figure 5.20
Return Duct Leakage
- Leakage of return ducts into floor space depressurizes floor space leading to infiltration at rim closure

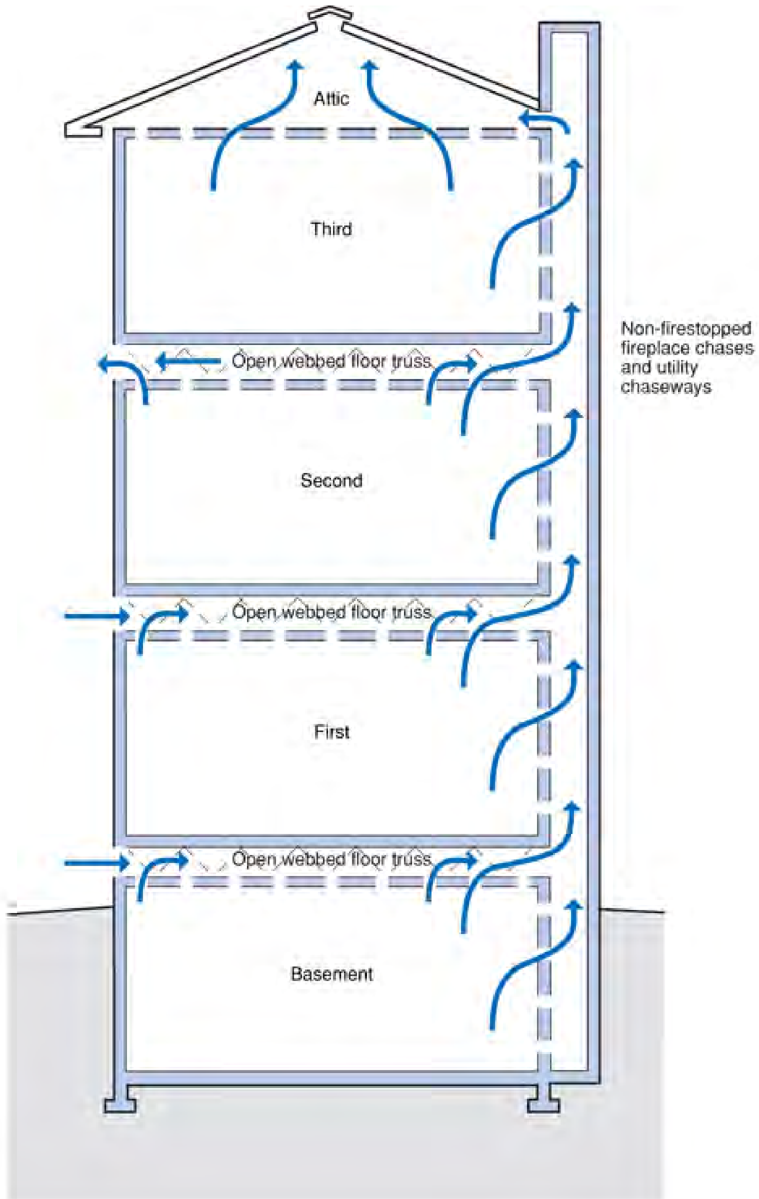


Figure 5.21
Combined Floor Paths and Pressure Drivers

- Vertical and horizontal communicationof open webbed floor trusses through fireplace and utility chaseways
- Pressure drivers are wind, the stack effect and the operation of the HVAC system

Operating Cost (energy)

A single family residence located in Las Vegas, NV provides a good example of addressing operating cost (energy) concerns by addressing duct leakage in two ways: sealing ducts or relocating the air pressure boundary. The effects of duct leakage on the building enclosure were determined by measuring the response of the interior building air pressure field to the operation of the air handling system.

Description of Facility and History of Problems

A homeowner began to complain about high utility bills. Electricity bills of over $275 per month were being reported for a 3-month period between June and the end of August.

The home is a recently constructed single family detached house, 200 square meters of floor area, one story in height over a concrete slab foundation. The exterior walls are wood framing sheathed with waferboard. The exterior cladding is painted stucco. Roof construction is wood sheathing installed over wood trusses. The roof assembly is vented in compliance with the 1:300 ratio. Interior cladding is painted gypsum board.

The space conditioning system is a forced air high efficiency heat pump. The air handler is located in the attic. Most of the supply and return ductwork is located in the attic. Exhaust fans are installed in bathrooms. A recirculating range hood is installed in the kitchen area. A fireplace is installed in the living room with tight fitting glass doors and exterior combustion air ducted directly to the firebox.

Investigation and Testing

Visual examinations, temperature measurements along with smoke pencil and air pressure differential testing using a digital micromanometer were the principle means of investigation.

The home was visited during a cool period in mid September. Exterior temperature was measured at approximately 25 degrees C. Exterior relative humidity was measured at 50 percent. Interior temperatures were taken at several locations in various rooms in the house. Interior temperatures ranged from 22 degrees to 26 degrees C.

A smoke pencil indicated that air was being forced out of the building at living room windows when the air handler switched on, suggesting that the living room operated at a positive air pressure with respect to the exterior. Smoke pencil readings also indicated that air was exiting from most bedroom windows. This was confirmed when the digital micromanometer was used to measure interior living room and bedroom air pressures relative to the exterior. When the air handler was operating the living room would rise to 3

Pa positive relative to the exterior. When the air handler was not operating, the living room and the bedrooms would come to a neutral air pressure with respect to the exterior.

Air pressure measurements were repeated under various conditions of interior doors being opened and closed. Not much difference in positive pressurization was noted with the opening and closing of bedroom doors.

A slight increase in air pressure of 1.5 Pa occurred in the master bedroom (relative to the main body of the house) when the master bedroom door was closed. With all interior doors in either the open or closed position, the building operated under an approximate 3 Pa positive air pressure relative to the exterior when the air handler was on.

When the air handler fan was switched on, but with the compressor not functioning, noticeably warm air was being supplied from a few of the supply registers. Discussions with the homeowner indicated that it was very difficult to cool the building during hot weather.

Conclusions

The operation of the air handler draws hot air from the attic into the return side of the air handler causing the entire building enclosure to become pressurized. When this hot air is introduced into the return side of the air conditioning system, cooling efficiencies are significantly reduced. The air conditioning load is significantly increased by the introduction of this hot air.

As discussed previously, air handlers create air pressure difference in buildings in several ways including duct leakage and by unbalanced air flows (see Figure 3.15 and Figure 3.18). In this example, return leaks appear to be dominating, as the building enclosure operates at positive air pressure with respect to the exterior when the air handler is operating.

In this example, the effect of bedroom door closure was not substantial. Return side leakage was shown to be present by virtue of the fact that the building enclosure went to a positive air pressure when all interior doors were open and the air handler was operating. The lack of effect of bedroom door closure was demonstrated by very little change in air pressure occurring when interior doors were opened and closed.

Air in the attic is typically much hotter than the exterior air due to the effect of solar radiation. When this air is drawn into the return side of the air handling system, it is not unusual to experience a significant drop in performance. Eighty percent and greater reductions in efficiency and capacity are common. This typically manifests itself in substantially increased utility bills and comfort complaints. Houses are unable to be maintained at cool temperatures.

Rehabilitation Measures

The air pressure relationship in this building should be altered. This can be done two ways. In the first way, the return side leakage of the air handling system can be repaired. Attic bypass leakage (openings around the outside of ducts) should also be repaired as part of this strategy. The strategy can be summarized as follows:

- Seal all return leaks in ductwork and the return plenum using mastic. Seal the opening around all ducts penetrating the attic ceiling. Seal openings along top plates.
- Provide transfer grills to facilitate air flow from bedrooms to the main return grill. Pressure balance house (check air pressure relationships, avoid negative air pressure after return side leaks are repaired).

In the second way, the air pressure boundary can be relocated. Under typical conditions, the pressure boundary in a vented attic is the attic ceiling gypsum board. This typically leads to problems, such as in this example, where the duct work and air handler are located external to the pressure boundary in the vented attic. An unvented conditioned attic can be constructed where the pressure boundary becomes the roof deck (Figure 5.22). In this manner the pressure boundary now encloses the duct work and air handler.

Roof ventilation is sealed and thermal insulation is moved from the attic ceiling to the underside of the roof deck. Transfer grilles are installed in the attic ceiling connecting the attic space to the main level of the house. These grills equalize air pressures and facilitate the flow of air throughout the house. In this manner the attic space becomes a conditioned space. Air leaking out of the supply ducts is no longer lost to the outside. Air extracted from the attic space is no longer drawn from the outside. Additionally, the duct work and air handler are now exposed to room temperatures rather than the extreme temperatures in vented, unconditioned attic spaces.

After a building enclosure with substantial return system leaks is repaired using the first approach, supply system leaks can become the dominant effect (see Figure 3.15). Supply leaks can lead to depressurization of building enclosures and serious health effects from the spillage and backdrafting of combustion appliances and mold growth from infiltration of hot, humid air into interstitial cavities in humid climates. Air pressure relationships should be retested after all repair work is completed in order to prevent the overlooking of adverse pressure effects.

Discussion

The response of the building interior air pressure field to the operation of the air handling system identifies the problems associated with the installation of the HVAC system. An understanding of the relationship between the air conveyance system air pressure field and both the interior air pressure field and the exterior air pressure field allows the development of the second strategy for rehabilitation – the relocation of the air pressure boundary.

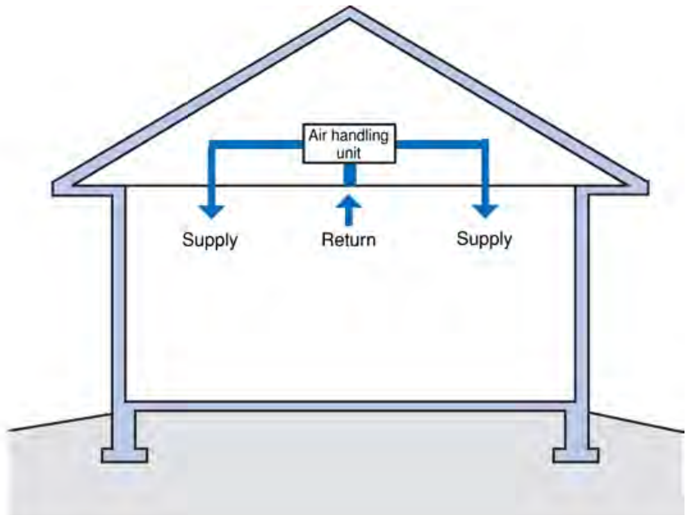


Figure 5.22
Unvented-Conditioned Attic
- The air handling unit is located in an unvented, conditioned attic
- The attic insulation is located at the roof deck

VI Conclusions

Air Pressure Control

In order to design and build safe, healthy, durable, comfortable and economical buildings we must understand air flow. Air flow carries moisture which impacts a materials long-term performance (serviceability) and structural integrity (durability), behavior in fire (spread of smoke), indoor air quality (distribution of pollutants and location of microbial reservoirs) and thermal energy.

Air flow in buildings is a complex, time dependent, three dimensional flow network where successful quantification of flows has been difficult. In order to improve the understanding, predictability and analysis of this complex flow network system, more complex relational models are necessary – and more effective use of available analytical tools are necessary. The development of more complex relational models and more effective use of available analytical tools has been the focus of this thesis.

This thesis makes the argument that the key to understanding air flow is pressure. Furthermore, that the key to developing the necessary more complex relational models is also pressure. And finally, that the key to effectively utilizing the sophisticated available analytical tools is pressure. It also logically follows that control of air pressure should be one of the significant factors in whole building system performance.

Air pressure affects the interrelationships between mechanical systems and the building envelope. These interrelationships are significant and involve numerous disciplines including architecture, structural engineering, mechanical engineering, fire protection, acoustics, and interior design. The cross disciplinary nature of the relationships make them easy to overlook, yet these relationships must be understood to avoid costly mistakes.

The design and construction of the building envelope (the walls, roof and foundation) significantly affect the design of the heating, ventilating and air conditioning (HVAC) systems. At the same time, the design, installation and operation of the HVAC system affects condensation and moisture accumulation within building cavities, rain penetration, pollutant migration, and the durability of the building envelope.

The strategy to control air pressure in the building includes eliminating the largest openings and holes. Additionally, it includes controlling the air pressure fluctuations generated by the building mezzoclimate, indoor climate, microclimate as well as the HVAC system operational conditions. To control the air, you must first enclose the air. When you enclose the air, you must control the mechanical system.

An element neglected in the traditional analysis of the air pressure fields in buildings is the effect of pathways and microclimates created by external cavities and interconnected internal cavities communicating with HVAC systems. This issue can be addressed at the diagnostic stage, the design stage or the rehabilitation stage.

Design

One manner to address the problem of the interconnected internal cavities is to compartmentalize them and disconnect them from the HVAC system. Another option is to deliberately connect the cavities (the interstitial air pressure field) to the occupied space (interior air pressure field) with openings, pathways, grills, etc. in order to reduce the air flow in the cavities by reducing or eliminating the air pressure differential driving force ("bleeding the pressure"). These strategies can best be implemented at the design stage – but are also equally valid during rehabilitation or renovation.

Compartmentalization of high rise facilities for smoke control and energy control is a common design approach (ASHRAE, 1997). This approach can be extended to interconnected cavities. For example, the problem identified in Figure 3.22 showing the linkages among the component pressure fields at dropped ceiling areas can be addressed using two strategies: employing a buffer space that isolates the dropped ceiling thereby creating a "compartment" (Figure 6.1) or directly ducting the return system eliminating the negative pressure in the dropped ceiling coupled with installing grills in the dropped ceiling thereby extending the interior air pressure field to the underside of the roof assembly – "bleeding the pressure" (Figure 6.2).

A similar approach can be used to address the problem illustrated in Figure 3.23. A return duct sleeve can be attached to the face of the unit directly connecting the return grill to the air handling unit. Adding grills through the gypsum board finish extends the interior air pressure field to the face of the rigid insulation effectively eliminating one of the interstitial cavities (Figure 6.3).

Deliberately pressurizing or depressurizing interstitial cavities is also a powerful approach for both new design and for rehabilitation. Both approaches were previously described in Figure 5.4 and Figure 5.12 respectively.

Finally, extending the pressure field to enclose air conveyance systems can be utilized to minimize the effect of duct leakage (Figure 5.22). This is a variation of the approach already described in Figure 6.2 and Figure 6.3.

Diagnostics

One of the most powerful diagnostic techniques available to enhance the understanding of air flow in buildings is the use of perturbation. This involves imposing a controlled change to the air pressure field by altering an air flow or by altering an opening and observing the response of the building air pressure field in magnitude and direction of change. This approach is powerful in that it can be used to overcome background “noise”(the typical fluctuations of building air flows and building air pressures.

Monitoring the response of the building air pressure field to the operation of the mechanical system is one of the most common and powerful uses of the perturbation approach.

A deliberate alternative intervention can also be imposed and compared to the effect of building operations. The advantage of this approach is that the timing of building analysis is not dependent on the occurrence of the “critical condition”. Investigators don’t always have the luxury of waiting for the critical condition to occur.

In this approach the laboratory is the field, and the key is to get the building to reveal itself to you. Sometimes the building needs to be pushed or kicked a little in order to get a response. Passive approaches often don't work very well or quickly. By creating change in a controlled manner and measuring the change, the interactions of the building envelope and the mechanical systems can be established — usually quickly and accurately.

The approach developed in the thesis measures the effect of perturbation or controlled change after the building has responded to a new equilibrium. With ultra fast pressure transducers (quicker than 10 readings per second) it may be possible to observe the pressure response of the building dynamically. Perturbations cause a pressure disturbance or pressure front to propagate through the building system.

Observing the rate and modulation of the pressure disturbance or pressure front as it propagates through the building system may yield useful information such as the specific locations of discontinuities such as unintentional openings due to missing fire stopping or ineffectual compartmentalization. This effort could be the subject of future work.

Analysis

The complexity of real buildings requires more complex relational models. These models must take into account the interconnected nature of the increasingly common non-contiguous complex three dimensional flow paths present in modern buildings. The focus of this thesis has been the development of such a relational model.

The relational model developed in this thesis can be used to configure existing analytical models to reflect the reality of the modern building. The modern building is presented in this thesis as consisting of multi layer building envelope assemblies interconnected to numerous void spaces and service chases often incidentally coupled to the operation of HVAC systems.

Existing analytical models used in building analysis have been limited in their application and accuracy due to the level of detailed input information relating to building construction assembly leakage and mechanical systems.

The gaps in available information can be "filled-in" by using the concept of perturbation in conjunction with existing network analytical models. By perturbing the building air pressure field and measuring the response, the pressure response can be used to "tune" the analytical models by apportioning leakage areas. This approach extends the range of applicability and accuracy of the models.

This approach represents an alternative pattern of analysis: developing the flow field, the leakage areas and the flow relationships from the measured building pressure field - the air pressure regime within and surrounding the building. This thesis argues that determining the characteristics of the building pressure field directly is considerably easier than determining the flow path resistances.

At present, network analysis and perturbation cannot be used to solve the interstitial flow, pressure and leakage regime. Network analysis and perturbation may suggest that such flows exist, but the complexity and workmanship dependence of the interstitial flow, pressure and leakage regime requires direct measurement. This thesis presents the case that the boundary conditions of the interstitial regime can be defined analytically (the boundary conditions being the building flow, pressure and leakage regime), but that the pressures and flows within the interstitial spaces cannot be predicted with certainty using analytical means.

The development of a computer-based apportioning approach meeting a convergence criteria may provide predictability to interstitial flows, pressure and leakage regimes. A numeric module developed for this task likely could be added to existing network analytical models and should be the focus of future work.

Analytical micro models of interstitial assemblies can also be developed and tuned by direct field measurements of interstitial air pressures and flows in the same manner as the macro models. The micro models can be expanded or incorporated into analytical macro models that address the entire building flow and leakage regime. The effect of the micro flows or interstitial regime on the general building regime can be modeled. In other words it is possible to go from the small to the large analytically. However, it does not appear to be possible to go in the other direction. It does not appear to be possible to generalize the interstitial regimes. They are often purely a local phenomena.

Further Research

Several areas of further research have been identified and could be pursued as a result of the work in this thesis.

- A computer-based apportioning approach could be developed and added to existing analytical network models. Such a numeric module would allow the use of pressures as inputs. The thesis work used a tedious manual method for apportioning leakage areas using very simple building examples. Complex buildings require complex multi-zone models. Manual methods of apportioning leakage areas are impractical in such cases. Computerized apportioning methods may hold the promise of providing unprecedented quantifiable accuracy in air flow analysis.

- With computer-based apportioning of leakage area it may be possible to provide predictability to interstitial flows, pressures and leakage regimes. Experimental work measuring simultaneous interstitial cavity pressures with local flow or leakage area perturbations could be coupled with detailed analytical models using computer-based apportioning to explore this possibility.

- The dynamic response of the building and building assemblies due to a perturbation might yield the location and type of discontinuities and connections in interstitial air pressure fields and flows. Observing the rate and modulation of a pressure disturbance or pressure front as it propagates through the building system might identify specific locations of ineffectual compartmentalization, unintended openings, or accidental links to HVAC systems.

- Building automation systems could be developed that track the building pressure field over time and identify problems when they occur due to pressure field changes. Pressure field measurements could be used as feedback mechanisms to control automated HVAC systems. Although this feature currently exists in some hospitals, data processing facilities and laboratories, low cost generic systems could be developed for hotels, schools and office buildings. These systems could be coupled with specific, local interstitial air pressure field measurements and control approaches that could be incorporated in new design and construction approaches.

- Commissioning protocols for commissioning building air pressure fields could be developed. These protocols could be linked to the previously described building automation systems and HVAC control feedback mechanisms.

- Experimental work determining quasi-steady state interstitial air pressures and leakage regimes could be coupled with enhanced heat, air and moisture (HAM) analytical models enhancing the predictability and accuracy of the analytical models. Linking a network model such as CONTAM96 with a moisture model such as WUFFI or MOIST should be possible. CONTAM96 could be modified to contain a numeric module for apportioning leakage areas (as previously described) and also be configured to address interstitial air pressure fields. In this manner CONTAM96 could be used to provide the inputs of leakage areas and pressures to WUFFI or MOIST.

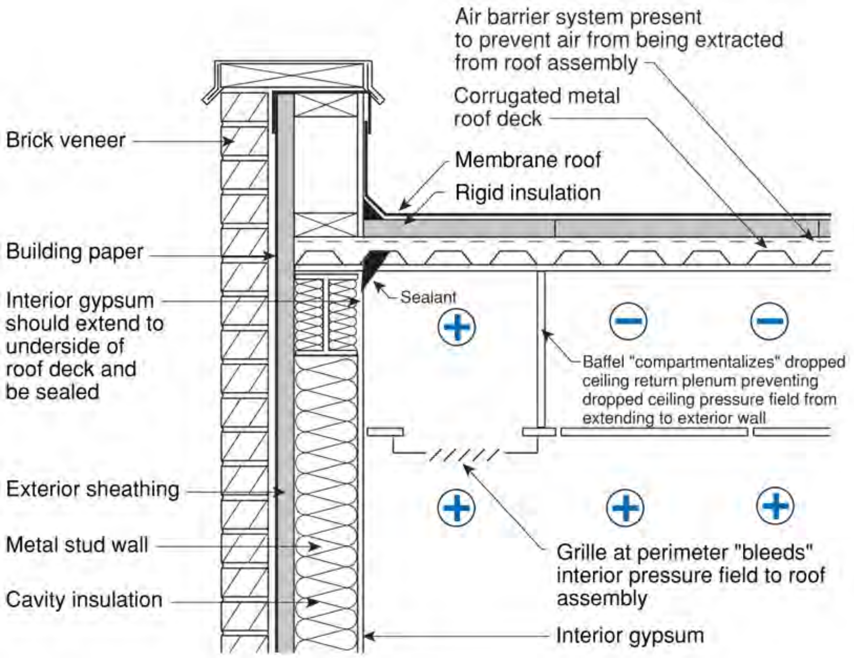


Figure 6.1
Compartmentalizing Dropped Ceiling

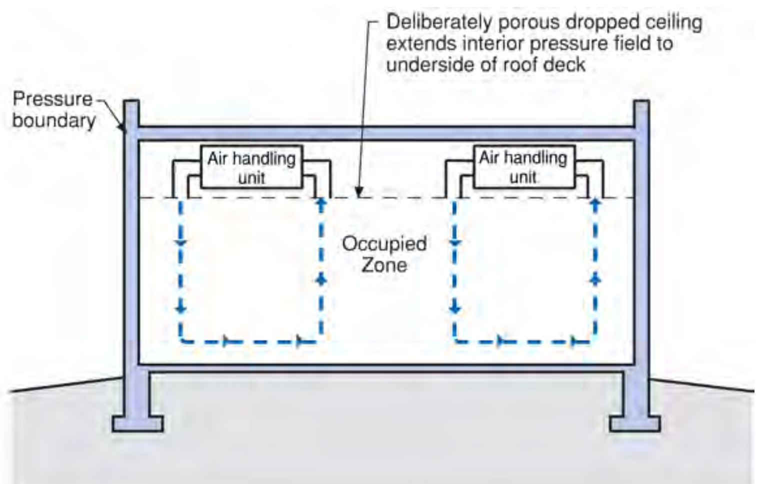


Figure 6.2
Elimination of Dropped Ceiling in Return Plenums

- Ducting return and supply eliminates negative pressure in dropped ceiling

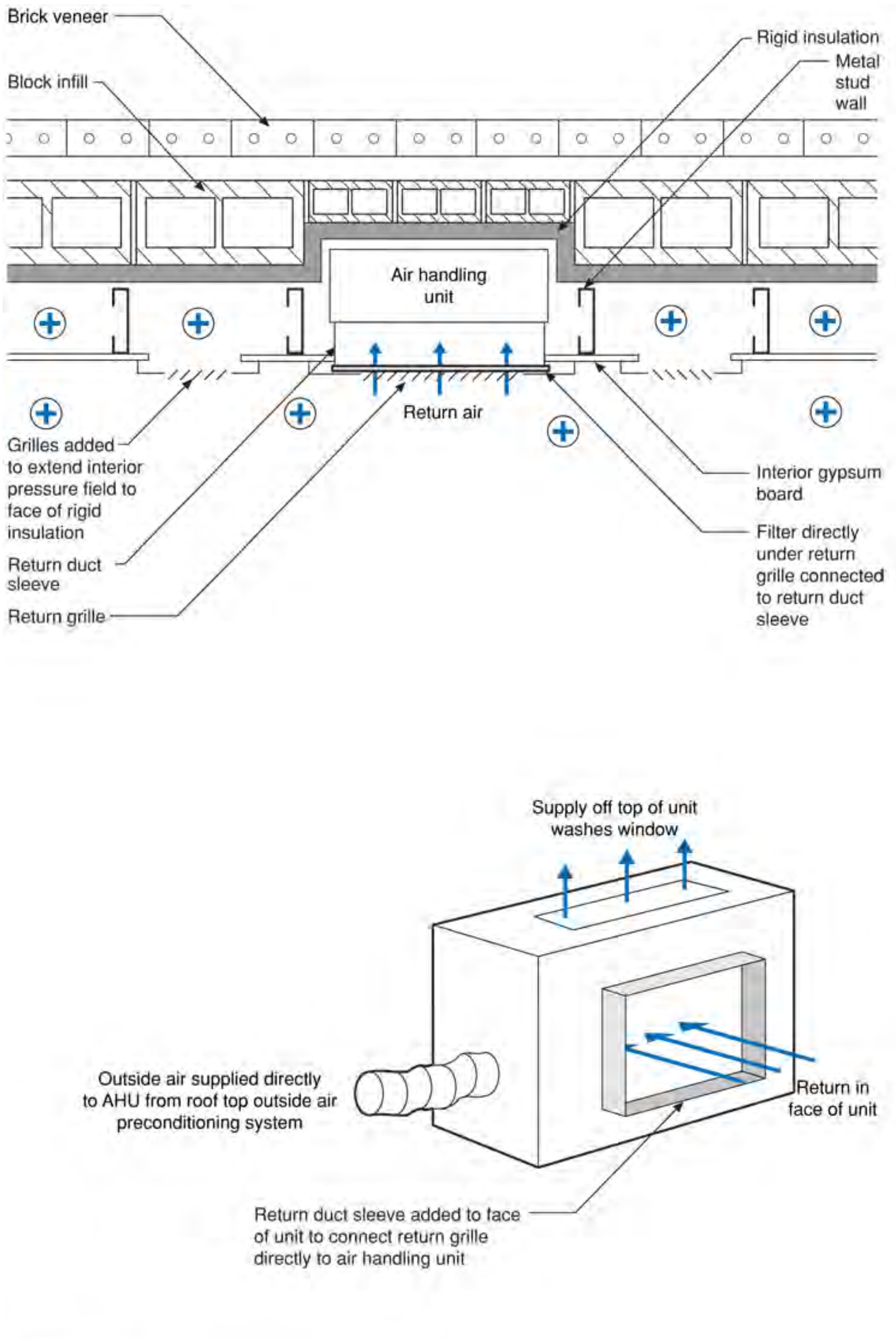


Figure 6.3
"Bleeding" Pressure Fields

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Appendices

Description of CONTAM96 Analytical Models

The appendices contain the details of four CONTAM96 analytical models. CONTAM96 is a network model developed by the National Institute of Standards and Technology (NIST), Building and Fire Research Laboratory, Gaithersburg, Maryland, 20899.

The airflow calculations in CONTAM96 are based on the algorithms developed in AIRNET (Walton, G.; Airflow Network Models for Element Based Building Airflow Modeling, ASHRAE Transactions, Volume 95, Part 2, Atlanta, 1989). The algorithms are based on the conservation of mass and the air flow rate from zone to zone as a function of the pressure drop along the flow path.

Flows are evaluated by assuming steady-state conditions. The analysis requires the solution of simultaneous nonlinear algebraic equations. An adaptation of the Newton-Raphson method is used to solve the nonlinear problem by an iteration of the solutions of linear equations.

Conservation of mass at each zone provides the convergence criterion for the Newton-Raphson iterations. A constant under-relaxation coefficient is used to accelerate convergence. Sparse matrix methods are used to reduce the storage and execution time requirements. A skyline solution process is used.

Newton's method requires an initial set of values for the zone pressures. These are obtained by a linear approximation relating the flow to the pressure drop.

The models in the appendices were configured to the relational models developed for the two buildings (Minneapolis House and Westford Academy). Information from depressuization tests and a manual iterative (trial and error) process were used to apportion leakage areas for both tuned models.

The apportioning process involved selecting a zone and altering leakage areas until the calculated pressure agreed to within approximately 0.5 Pa of the measured pressure in the zone. A subsequent zone was then selected and the process repeated until all zones were considered. When the altering of leakage areas in one zone caused divergence in another zone beyond the 0.5 Pa limit, the process in that zone was stopped, and the next zone was considered. The 0.5 Pa convergence criteria was arbitrary. The rationale for the 0.5 Pa criteria was the judgement that this represents the current practical limits for accuracy of interior pressure field zonal pressure measurements.

CONTAM96 Air Flow Analysis

The air flow rate from zone j to zone i, $F_{j,i}$ [kg/s], is some function of the pressure drop along the flow path, $P_j - P_i$:

$$F_{j,i} = f(P_j - P_i) \quad \text{(A-1)}$$

The mass of air, m_i [kg], in zone i is given by the ideal gas law

$$m_i = \rho_i V_i = \frac{P_i V_i}{RT_i} \quad \text{(A-2)}$$

where

V_i = zone volume [m^3],
P_i = zone pressure [Pa],
T_i = zone temperature [K], and
R = 287.055 [J/kgK] (gas constant for air).

For a transient solution the principle of conservation of mass states that:

$$\frac{\delta m_i}{\delta t} = \rho_i \frac{\delta V_i}{\delta t} + V_i \frac{\delta \rho_i}{\delta t} = \sum_j F_{j,i} + F_i \quad \text{(A-3)}$$

where

m_i = mass of air in zone i,
$F_{j,i}$ = airflow rate [kg/s] between zones j and zone i: positive values indicate flows from j to i and negative values indicate flows from i to j, and,
F_i = non-flow processes that could add or remove significant quantities of air from the zone.

Such non-flow processes are not considered in CONTAM and flows are evaluated by assuming quasi-steady conditions leading to:

$$\sum_j F_{j,i} = 0 \quad \text{(A-4)}$$

Flow within each airflow element is assumed to be governed by Bernoulli's equation:

$$\Delta P = \left(P_1 + \frac{\rho V_1^2}{2} \right) - \left(P_2 + \frac{\rho V_2^2}{2} \right) + \rho g (z_1 - z_2) \tag{A-5}$$

where

ΔP = total pressure drop between points 1 and 2
P_1, P_2 = entry and exit static pressures
V_1, V_2 = entry and exit velocities
ρ = air density
g = acceleration of gravity (9.81 m/s^2)
z_1, z_2 = entry and exit elevations.

The following parameters apply to the zones: pressure, temperature (to compute density and viscosity), and elevation. The zone elevation values are used to determine stack effect pressures. When the zone represents a room, the airflow elements may connect with the room at other than its reference elevation. The hydrostatic equation is used to relate the pressure difference across a flow element to the elevations of the element ends and the zone elevations, assuming the air in the room is at constant temperature. Pressure terms can be rearranged and a possible wind pressure for building envelope openings added to give:

$$\Delta P = P_j - P_i + P_s + P_w \tag{A-6}$$

where

P_j , P_i = total pressures at zones i and j
P_s = pressure difference due to density and elevation differences, and
P_w = pressure difference due to wind.

Appendix A: Minneapolis House Tuned CONTAM96 Analytical Model

This is a six zone model; the zones are the basement, first floor, and the four bedrooms (referred to as northwest, southwest, southeast, and northeast.) The flow rates for exhaust fans and blower doors, as well as the leakage areas for windows and doors, apply when the elements are open/in operation; otherwise, the flow/area is considered zero.

Basement zone (7940 ft^3/225 m^3):

- Leakage to outside: 160 CFM 50 (80 L/s); n=0.65
- Air handler flows: supply 190 CFM (25 L/s); return 190 CFM (95 L/s)

First floor zone (6700 ft^3/190 m^3):

- Leakage to outside: 155 CFM 50 (73 L/s @ 50 Pa); n=0.65
- Leakage to garage: 63 CFM 50 (30 L/s @ 50 Pa); n=0.65
- Leakage to basement: 700 CFM 50 (330 L/s @ 50 Pa) n=0.65
- Door to basement: 17.8 ft^2/1.7 m^3; C=0.65, n=0.65, 10 Pa
- Air handler flows: supply 310 CFM (146 L/s); return 610 CFM (288 L/s)
- Blower door fan: 730 CFM (345 L/s) constant volume model

Garage zone (4000 ft^3/113 m^3):

- Leakage to outside: 460 CFM 50 (217 L/s @ 50 Pa); n=0.65

Second floor hallway zone (1400 ft^3/40 m^3):

- Leakage to outside: 155 CFM 50 (73 L/s @ 50 Pa); n=0.65
- Open stairwell leakage to first floor: 40 ft^2/3.7 m^3; powerlaw model
- Air handler: none
- Ventilation exhaust fan: 90 CFM (43 L/s) constant

Northwest bedroom zone (1200 ft^3/34 m^3):

- Leakage to outside: 37 CFM 50 (17 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 318 CFM 50 (150 L/s @ 50 Pa); n=0.65
- Air handler: supply 80 CFM (38 L/s); no return
- Door: 17.8 ft^2/1.7 m^3; C=0.65, n=0.65 @ 10 Pa (to hallway)
- Window 1.0 ft^2/0.1 m^3; C=0.65, n=0.65 @ 10 Pa (to exterior)

Southwest bedroom zone (1008 ft^3/29 m^3):

- Leakage to outside: 56 CFM 50 (26 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 583 CFM 50 (275 L/s @ 50 Pa); n=0.65
- Air handler: supply 30 CFM (14 L/s); no return
- Door and window as per NW bedroom

Southeast bedroom zone (2885 ft^3/82 m^3):

- Leakage to outside: 175 CFM 50 (83 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 425 CFM 50 (200 L/s @ 50 Pa); n=0.65
- Air handler: supply 160 CFM (76 L/s); no return
- Door and window as per NW bedroom

Northeast bedroom zone (1176 ft^3/33 m^3):

- Leakage to outside: 46 CFM 50 (22 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 32 CFM 50 (15 L/s @ 50 Pa); n=0.65
- Air handler: supply 30 CFM (14 L/s); no return
- Door and window as per NW bedroom

Appendix B: Minneapolis House Standard Tuned CONTAM96 Analytical Model

This model is identical to the tuned model in terms of exhaust fans, blower doors, windows, doors, and stairwell leakage. However, leakage areas are modified as follows:

Basement zone (7940 ft^3/225 m^3):
- Leakage to outside: 243 CFM 50 (115 L/s @ 50 Pa); n=0.65

First floor zone (6700 ft^3/190 m^3):
- Leakage to outside: 122 CFM 50 (58 L/s @ 50 Pa); n=0.65
- Leakage to basement: 47.1 in^2/304 cm^2 @ 75 Pa; C=0.65; n=0.65

Second floor hallway zone (1400 ft^3/113 m^3):
- Leakage to outside: 47 CFM 50 (22 L/s @ 50 Pa); n=0.65

Northwest bedroom zone (1200 ft^3/34 m^3):
- Leakage to outside: 62 CFM 50 (29 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 31.6 in^2/204 cm^2 @ 75 Pa; C=0.65; n=0.65

Southwest bedroom zone (1008 ft^3/29 m^3):
- Leakage to outside: 53 CFM 50 (25 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 31.9 in^2/206 cm^2 @ 75 Pa; C=0.65; n=0.65

Southeast bedroom zone (2885 ft^3/82 m^3):
- Leakage to outside: 142 CFM 50 (67 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 32.0 in^2/206 cm^2 @ 75 Pa; C=0.65; n=0.65

Northeast bedroom zone (1176 ft^3/33 m^3):
- Leakage to outside: 61 CFM 50 (29 L/s @ 50 Pa); n=0.65
- Leakage to second floor hallway: 31.8 in^2/205 cm^2 @ 75 Pa; C=0.65; n=0.65

Leakage to the outside is determined by taking the total measured leakage of the building (730 CFM 50/365 L/s @ 50 Pa) and dividing it into thirds: basement, walls, and ceiling plane. Then, within those groups, the leakage is distributed by surface area proportions.

Leakage to the interior is determined by multiplying the areas of the demising partitions by an average leakage ratio. The 25 mm tall undercut of the bedroom doors is also added, which dominates the leakage to the second floor hallway.

Appendix C: Westford Academy Tuned CONTAM96 Analytical Model

This is a five zone model; the zones are Room 117, Room 119, Rooms 109/107/105, Rooms 103/101, and the main hallway with the open rooms. The flow rates for duct blaster fans and blower doors, as well as the leakage areas for windows and doors, apply when the elements are open/in operation; otherwise, the flow/area is considered zero.

Room 117 (2119 ft^3/60 m^3):

- Leakage to outside: 1200 CFM 50 (570 L/s @ 50 Pa); n=0.65
- Leakage to hallway: 1860 CFM 50 (880 L/s @ 50 Pa); n=0.65
- Door: 21 ft^2/2.0 m^2 C=0.65; n=0.5
- Window: 3.8 ft^2/0.35 m^2 C=0.6; n=0.5
- Blower door (from hallway): 680 CFM (321 L/s) constant volume
- Duct blaster (to exterior): 100 CFM (47.2 L/s) constant volume

Demising wall between 117 and 119

- Leakage: 800 CFM 50 (380 L/s @ 50 Pa); n=0.65
- Door: 21 ft^2/2.0 m^2 C=0.65; n=0.5

Room 119 (2119 ft^3/60 m^3):

- Leakage to outside: 1200 CFM 50 (570 L/s @ 50 Pa); n=0.65
- Leakage to hallway: 1290 CFM 50 (610 L/s @ 50 Pa); n=0.65
- Door and window as per Room 117
- Blower door (from hallway): 5327 CFM (2514 L/s) constant volume

Room 101/103 (1413 ft^3/40 m^3):

- Leakage to outside: 2800 CFM 48 (1320 L/s @ 48 Pa); n=0.65
- Leakage to hallway: 1300 CFM 48 (610 L/s @ 48 Pa); n=0.65
- Door and window as per Room 117
- Blower door (from hallway): 100 CFM (47 L/s) constant volume

Room 105/107/109 (6357 ft^3/180 m^3):

- Leakage to outside: 4100 CFM 32 (1935 L/s @ 32 Pa); n=0.65
- Leakage to hallway: 1500 CFM 32 (710 L/s @ 32 Pa); n=0.65
- Door and window as per Room 117
- Blower door (from hallway): 140 CFM (66 L/s) constant volume

Hallway and open rooms (3530 ft^3/100 m^3):

- Leakage to outside: 33,700 CFM 22 (15,905 L/s @ 22 Pa); n=0.65
- Outside door: 126 ft^2/11.7 m^2 C=0.65; n=0.5
- Triple blower door (to outside): 33,500 CFM (15,810 L/s) constant volume

Appendix D: Westford Academy Standard CONTAM96 Analytical Model

This model is identical to the tuned model in terms of duct blasters, blower doors, windows, and doors. However, leakage areas are modified as follows:

Room 117 (2119 ft^3/60 m^3):
- Leakage to outside: 24.5 in^2/158 cm^2; C=0.65; ΔP=50 Pa; n=0.65
- Leakage to hallway: 40.8 in^2/263 cm^2; C=0.65; ΔP=50 Pa; n=0.65

Demising wall between 117 and 119
- Leakage: 40.8 in^2/263 cm^2; C=0.65; ΔP=50 Pa; n=0.65

Room 119 (2119 ft^3/60 m^3):
- Leakage to outside: 24.5 in^2/158 cm^2; C=0.65; ΔP=50 Pa; n=0.65
- Leakage to hallway: 40.8 in^2/263 cm^2; C=0.65; ΔP=50 Pa; n=0.65

Room 101/103 (1413 ft^3/40 m^3):
- Leakage to outside: 45.8 in^2/295 cm^2; C=0.65; ΔP=50 Pa; n=0.65
- Leakage to hallway: 84.7 in^2/546 cm^2; C=0.65; ΔP=50 Pa; n=0.65

Room 105/107/109 (6357 ft^3/180 m^3):
- Leakage to outside: 63.9 in^2/412 cm^2; C=0.65; ΔP=50 Pa; n=0.65
- Leakage to hallway: 122 in^2/787 cm^2; C=0.65; ΔP=50 Pa; n=0.65

Hallway and open rooms (3530 ft^3/100 m^3):
- Leakage to outside: 55,922 CFM 50 (26,392 L/s @ 50 Pa); n=0.65