Air Pressure and Building Envelopes

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Abstract

Control of air pressure is key to several important performance aspects of the building system. Air carries moisture which impacts a materials long-term performance (serviceability) and structural integrity (durability), behavior in fire (smoke spread), indoor air quality (distribution of pollutants and microbial reservoirs) and thermal energy.

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.

1. Introduction

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)

2. Indoor Air Quality

A school located in Trenton, NJ provides a good example of using air pressure measurement techniques 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 Pascal's negative with respect to the crawl space (Figure 1). Furthermore, interior wall cavities were found to operate at 1 Pascal 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 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 Pascal.

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 Pascal's 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 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 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.

3. 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.

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). 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 Pascal's 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 Pascals. 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 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 Pascal's to the exterior. Under the second approach, approximately 275 L/s of outside air was required to pressurize individual floors 5 Pascal's 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 Pascal 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 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 Pascal's 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 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 9). A minimum 25 Pascal 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 Pascal's 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 Pascal's 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 Pascal pressure difference can be maintained.

4. 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 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 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 Pascal's 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 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 Pascal's 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.

5. 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 Pascal's (chosen by popular convention). The amount of air necessary to be exhausted from a unit in order to depressurize the unit 50 Pascal's 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 Pascal's 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 13, a simple building envelope is depressurized to 50 Pascal's 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 Pascal's 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 13 illustrates the presence of a well-defined pressure boundary across the attic ceiling.

In Figure 14, the building envelope is depressurized 50 Pascal's relative to the exterior and an air pressure difference of 25 Pascal's is measured between the interior and the attic. A pressure difference of 25 Pascal's also exists between the attic and the exterior since the total air pressure difference must equal 50 Pascal's. 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 Pascal's, and an extremely leaky attic ceiling would have an air pressure drop much lower than 50 Pascal's. In residential construction, with code compliant attic ventilation ratios (i.e. 1:300), insulated ceiling air pressure drops greater than 40 Pascal's are viewed as providing acceptable performance by the author when a building envelope is depressurized 50 Pascal's. 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 Pascal's relative to the exterior. Measurements ranged between 25 and 35 Pascal's 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 15, a more complex building envelope is depressurized 50 Pascal's 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 Pascal's 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 16, the building envelope is depressurized to 50 Pascal's relative to the exterior and an air pressure difference of 25 Pascal's is measured between the interior and the floor assembly. A pressure difference of 25 Pascal's also exists between the floor assembly and the exterior since the total air pressure difference must equal 50 Pascal's. 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 17 and Figure 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 Pascal's when the building envelope is depressurized 50 Pascal's relative to the exterior.

At this condominium development, air pressure measurements were taken across floor assemblies when units were depressurized 50 Pascal's relative to the exterior. Measurements ranged between 20 and 30 Pascal's 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 Pascal's (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 Pascal's 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 Pascal's 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 Pascals 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 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 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 Pascals 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 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 2 inch 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.

6. 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 Pascal's 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 Pascal's 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 Pascal 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.

Air handlers create air pressure difference in buildings in several ways including duct leakage and by unbalanced air flows. 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 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. 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.

6. Conclusions

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.

The key to understanding air flow is pressure. 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.

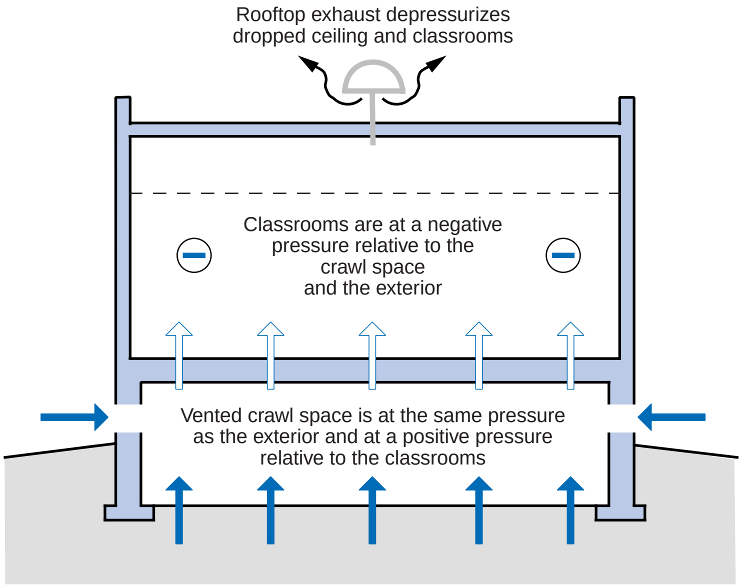


Figure 1

Problem Pressure Relationship

- The classrooms in this school operate at a negative pressure with respect to the crawl space

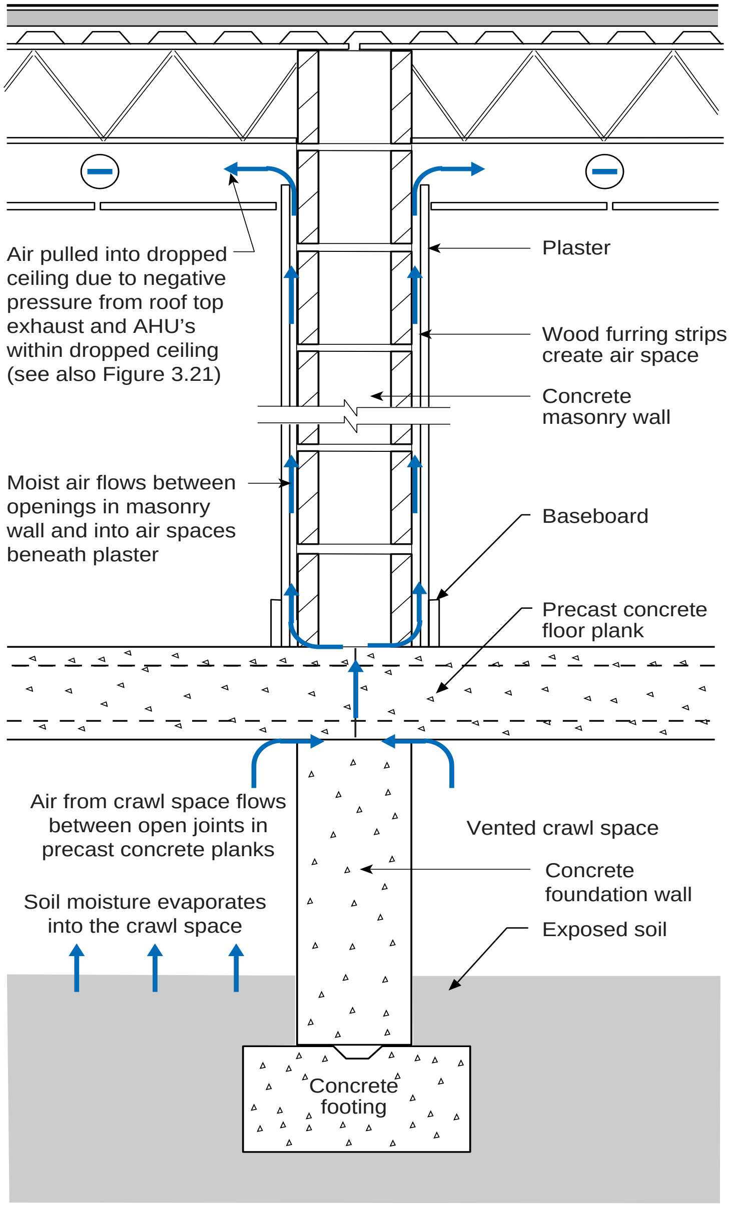


Figure 2

Moisture Movement

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

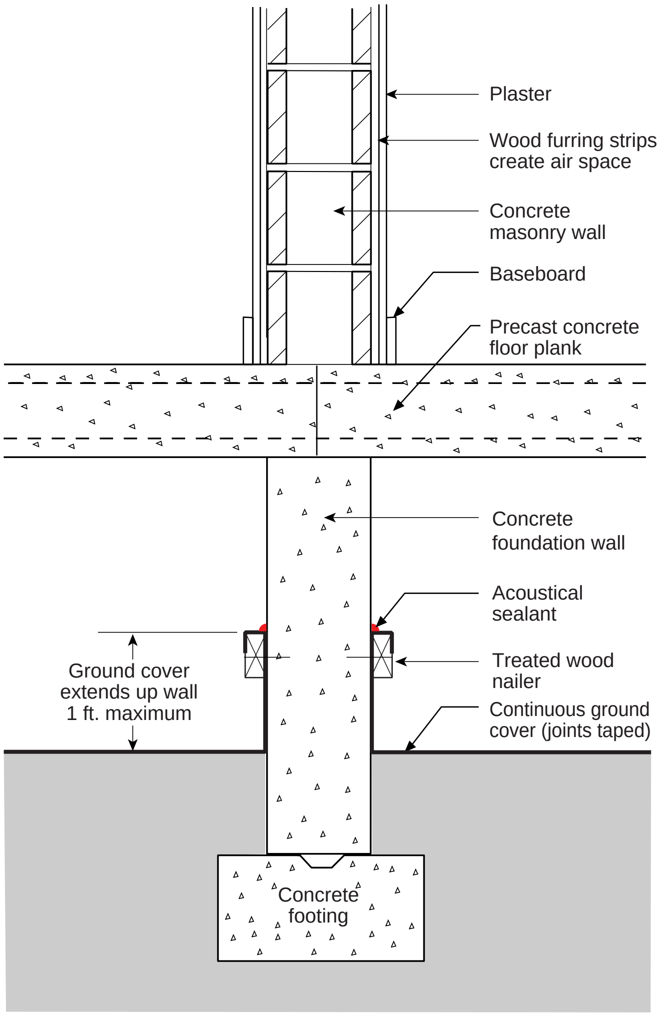


Figure 3

Ground Cover Installation

- This wall section illustrates proper installation of the polyethylene ground cover

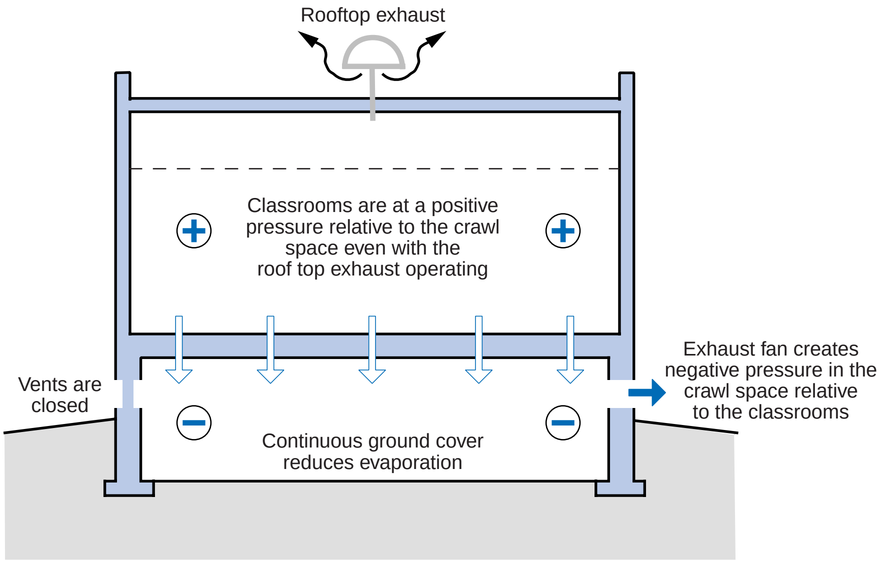


Figure 4

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

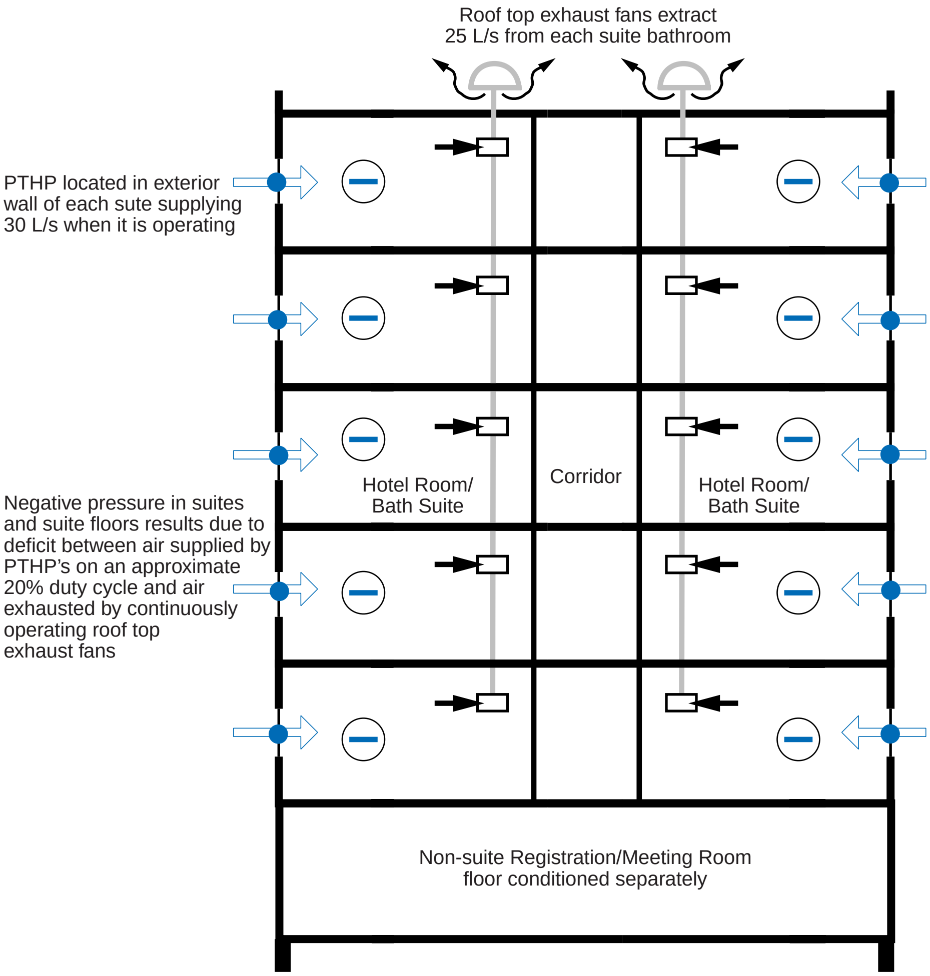


Figure 5

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.

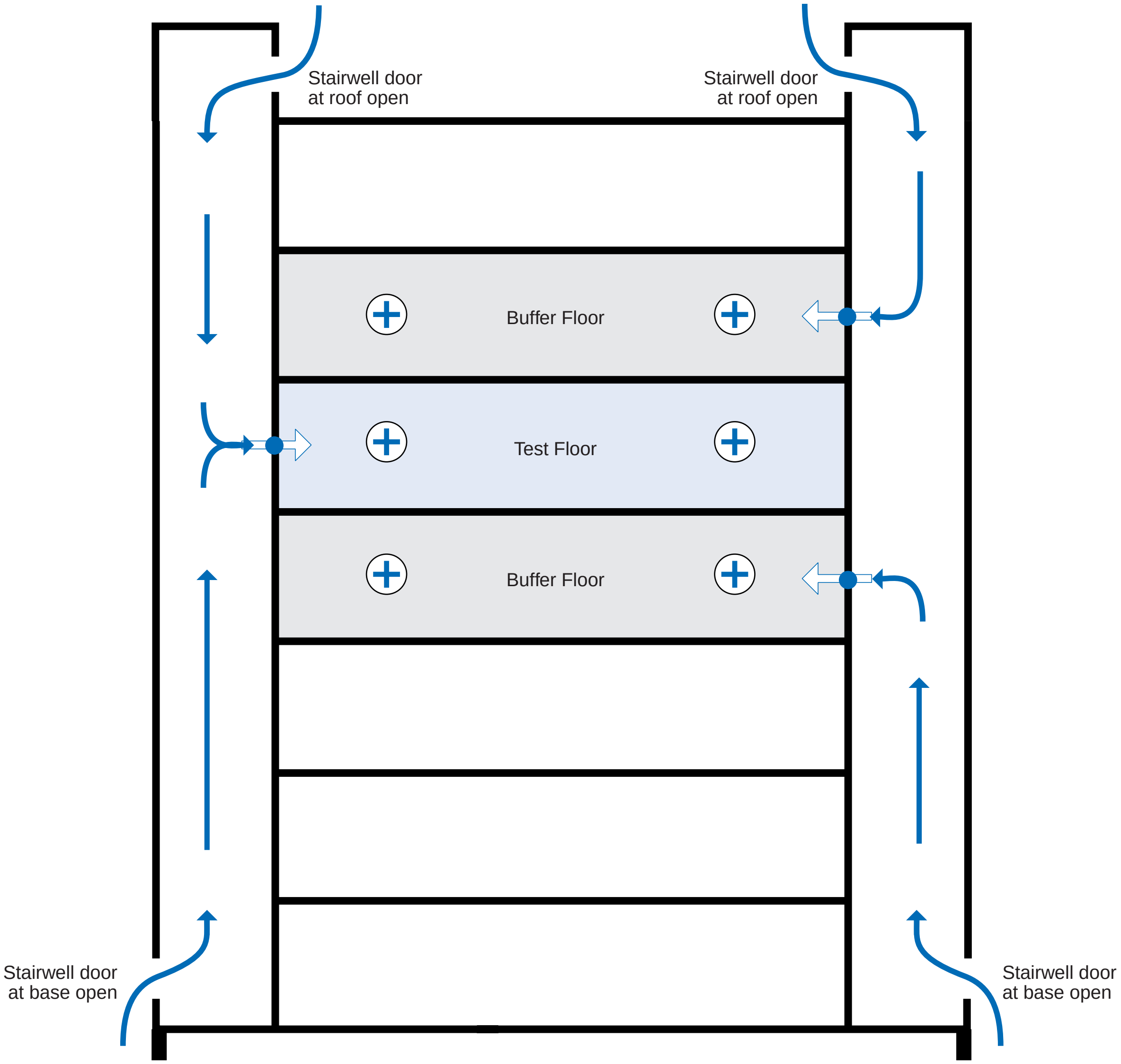


Figure 6

Air Leakage Test Zones

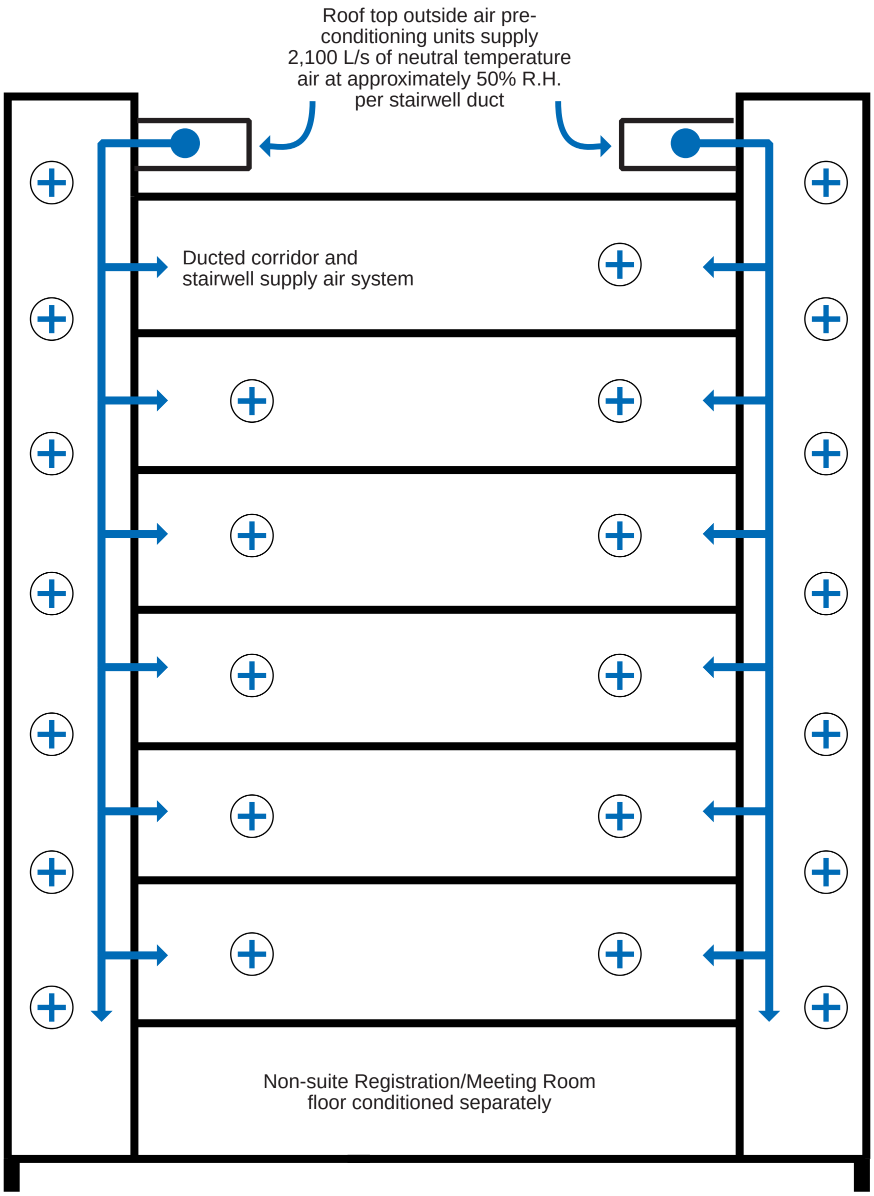
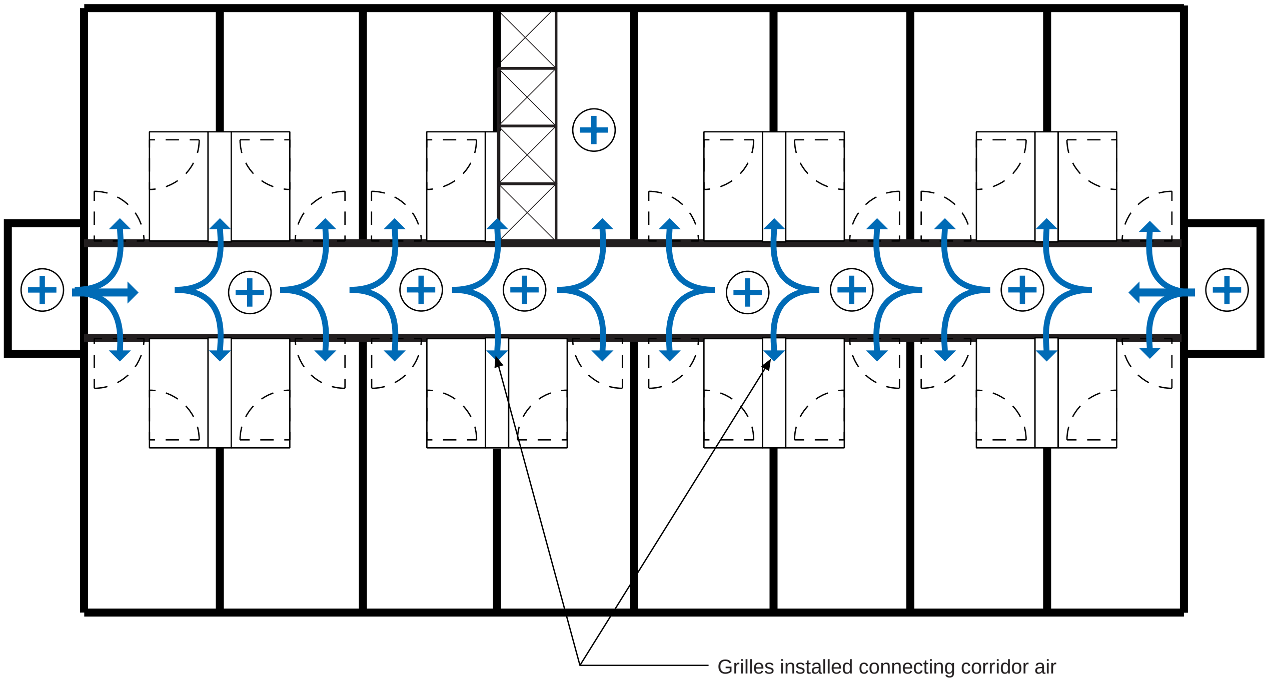


Figure 7

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



Grilles installed connecting corridor air pressure field to service shafts at each floor allowing extension of corridor air pressure field into service shafts

Figure 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)

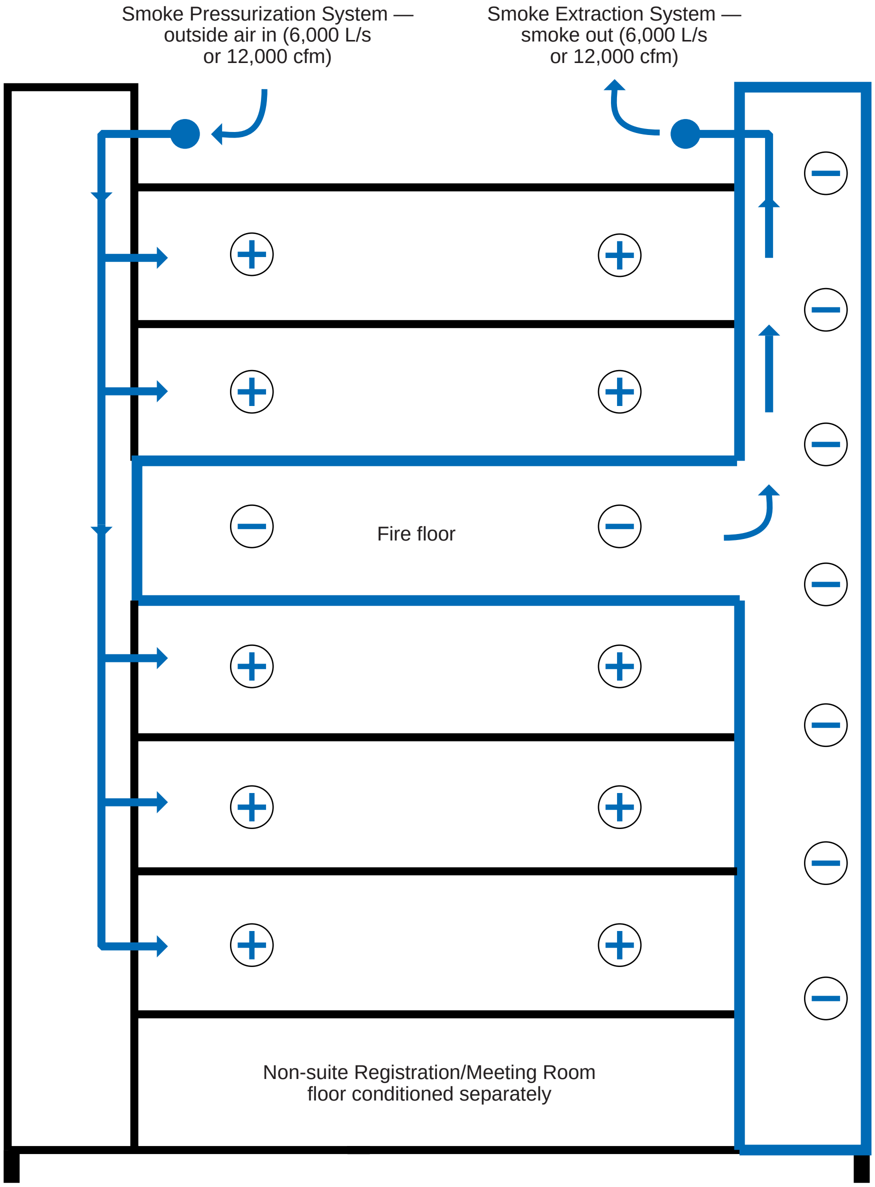


Figure 9

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

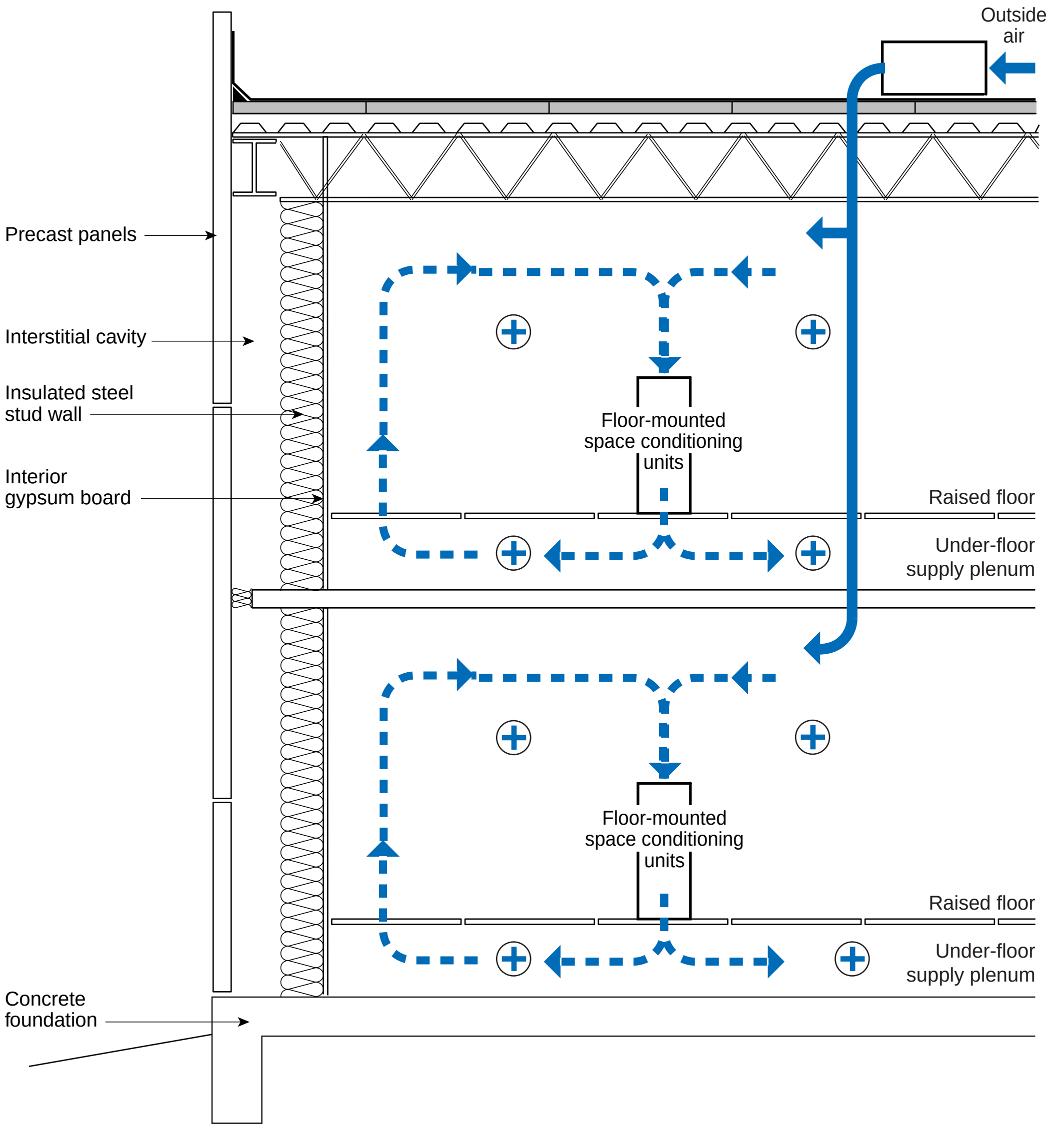


Figure 10

HVAC System as Designed

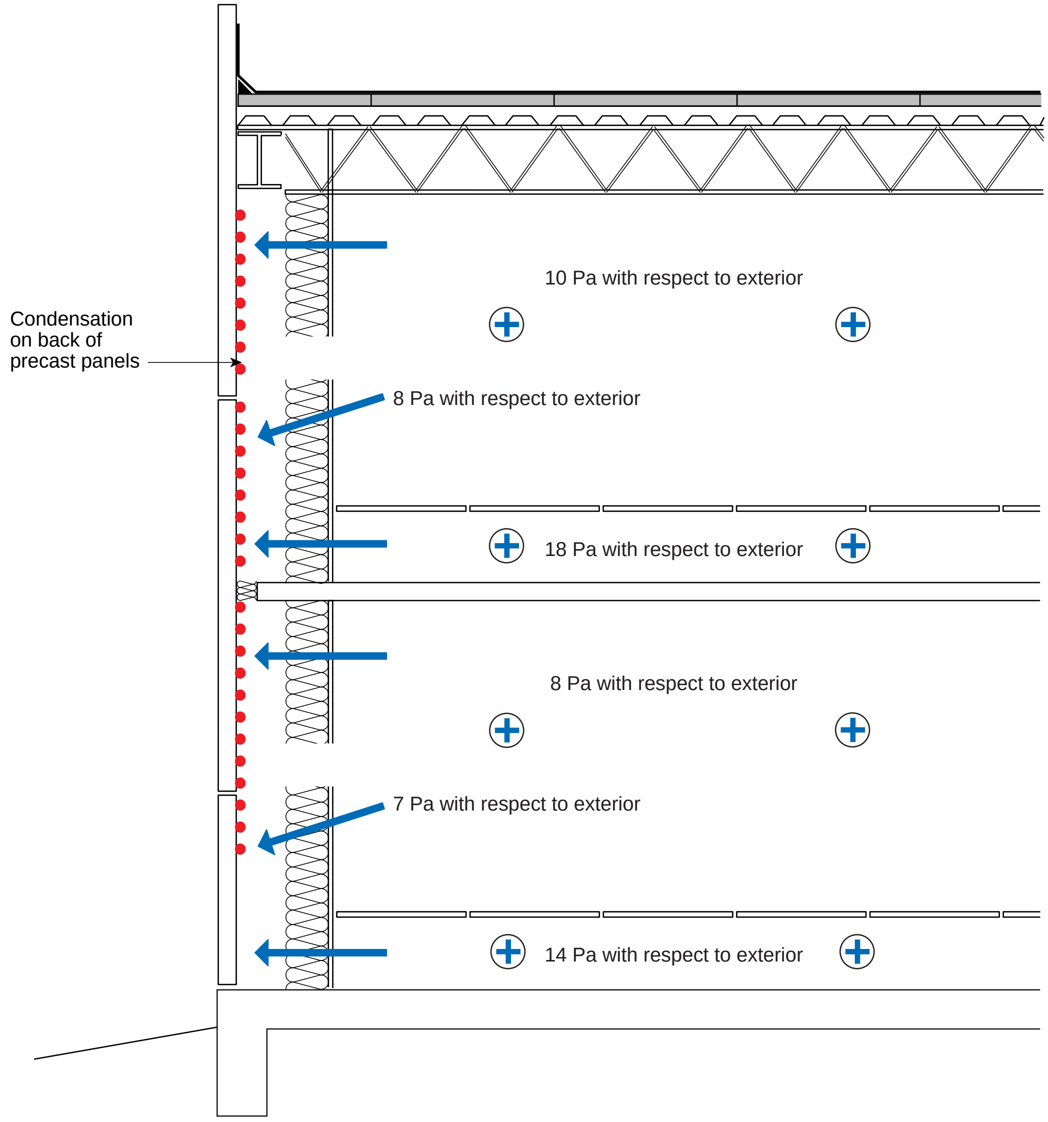


Figure 11

Unintended Pressurization of Interstitial Cavity

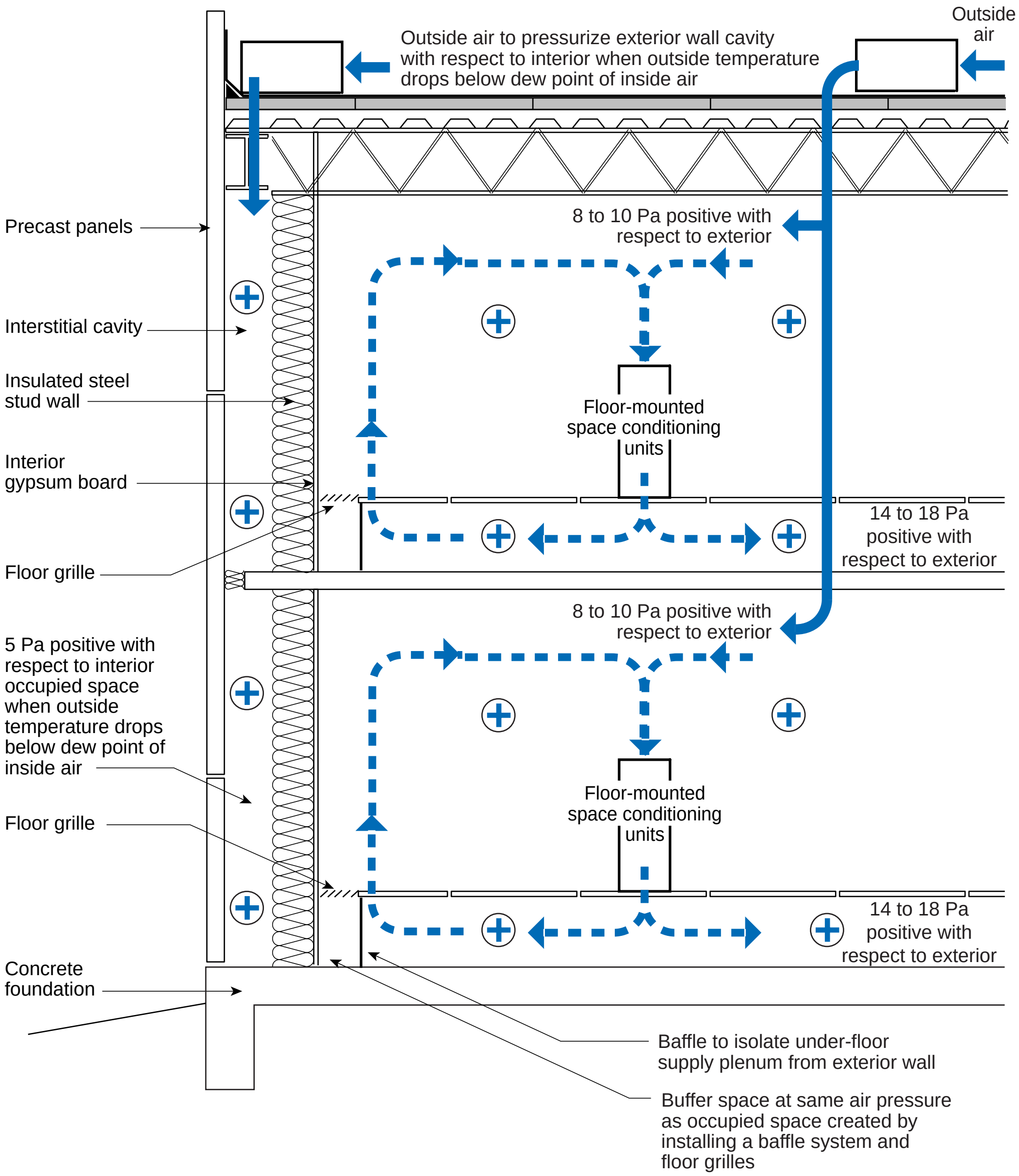


Figure 12
Modified Pressure Relationship

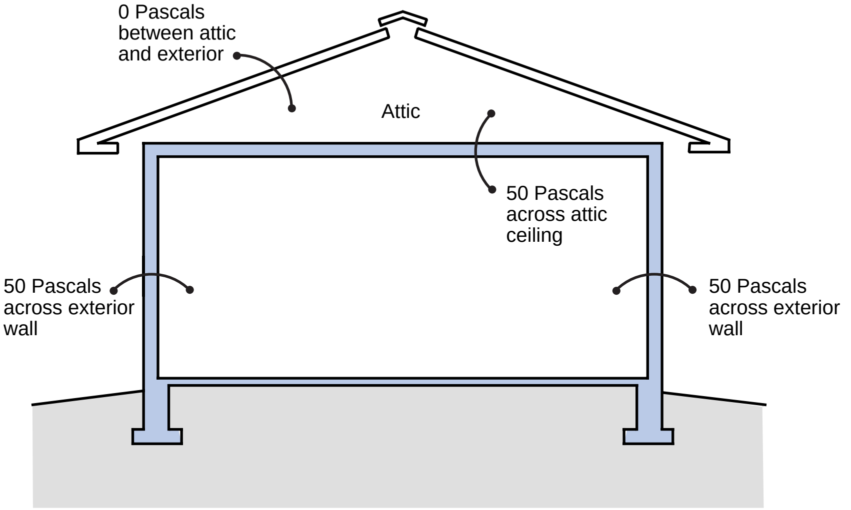


Figure 13

Well-Defined Pressure Boundary

- Pressure boundary defines effective building envelope environmental separator

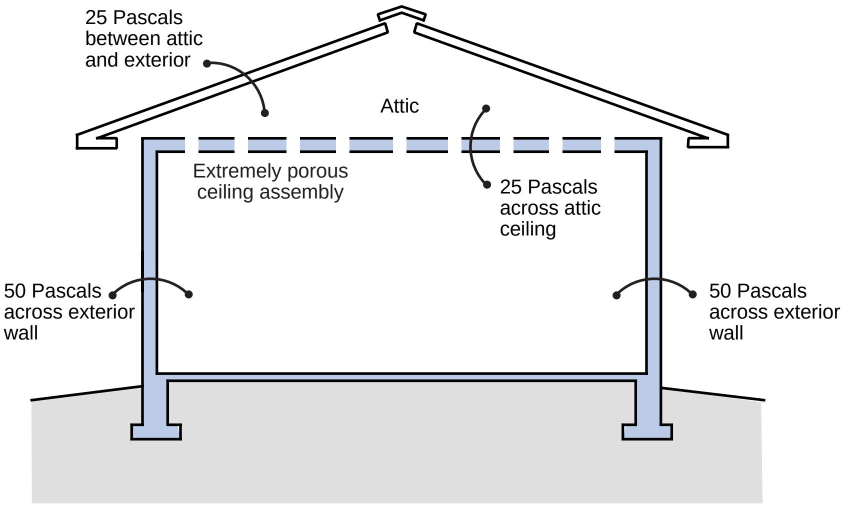


Figure 14

Poorly-Defined Pressure Boundary

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

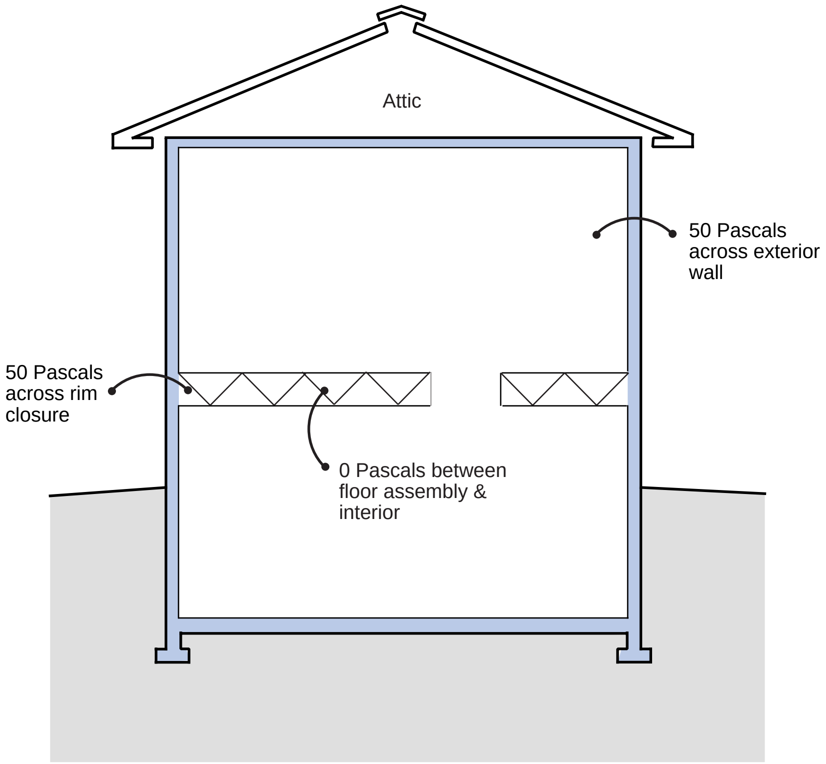


Figure 15

Tight Rim Closure

- Floor assembly “inside” well-defined pressure boundary
- Pressure boundary continuous at rim closure

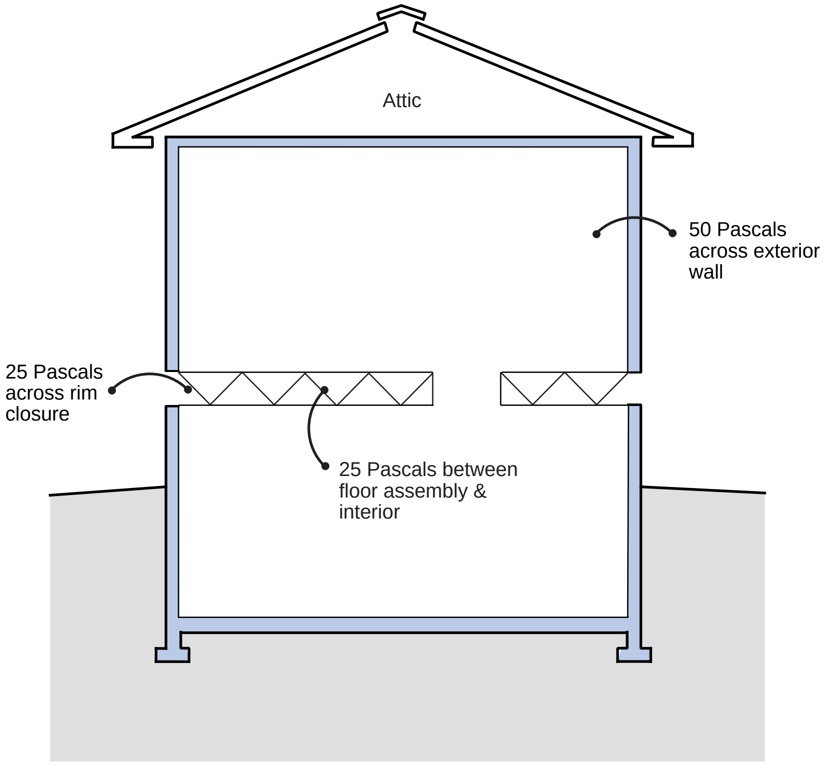


Figure 16

Leaky Rim Closure

- Floor assembly “outside” pressure boundary
- Pressure boundary not continuous at rim closure

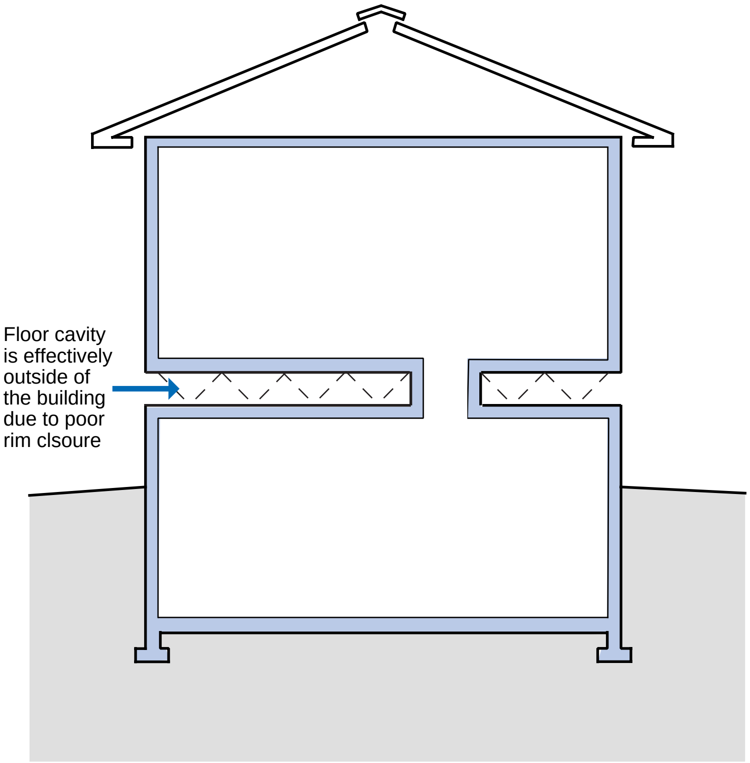


Figure 17

Pressure Boundary at Interior Floor

- Pressure boundary not contiguous with building envelope thermal boundary

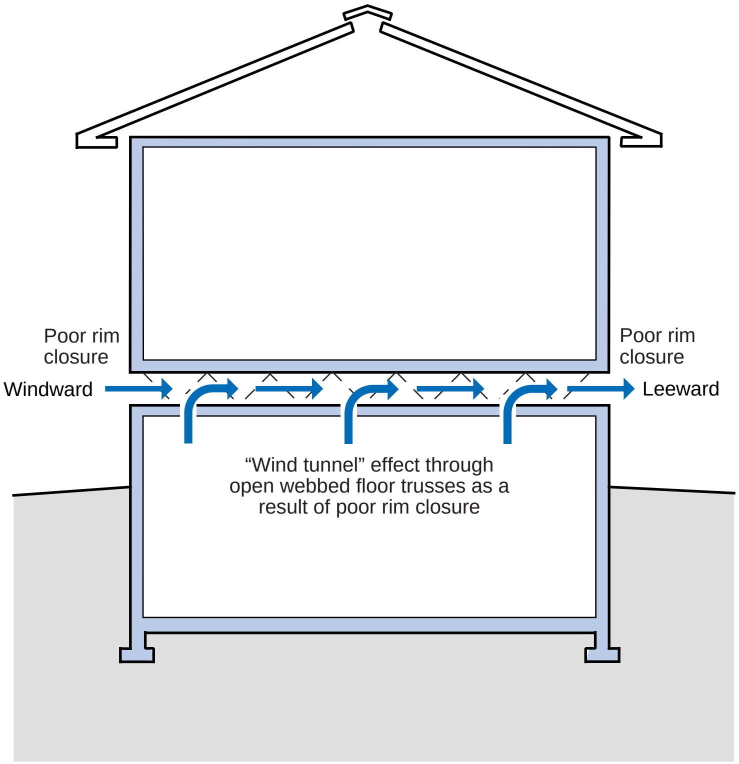


Figure 18

Wind Tunnel Effect

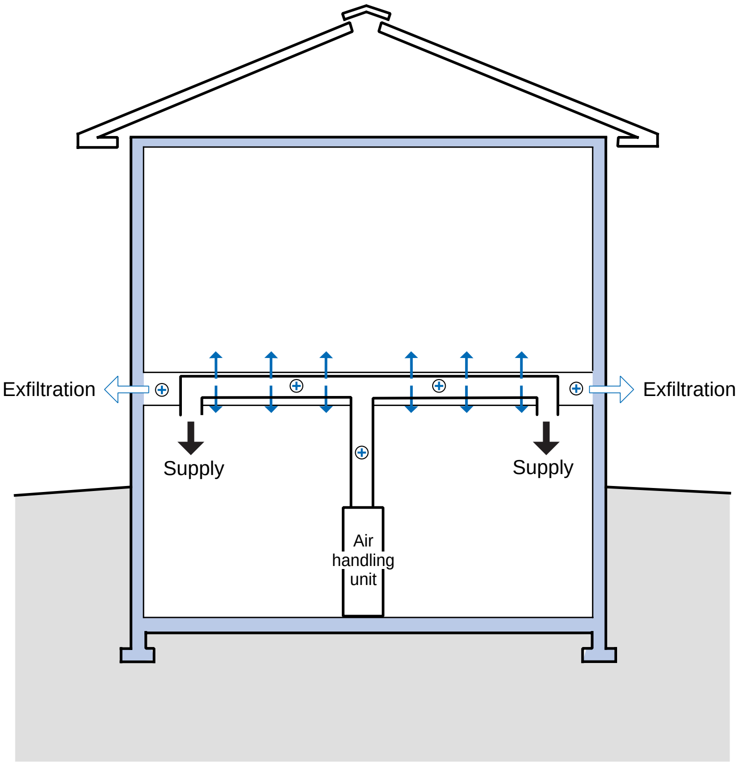


Figure 19

Supply Duct Leakage

- Leakage of supply ducts into floor space pressurizes floor space leading to exfiltration at rim closure

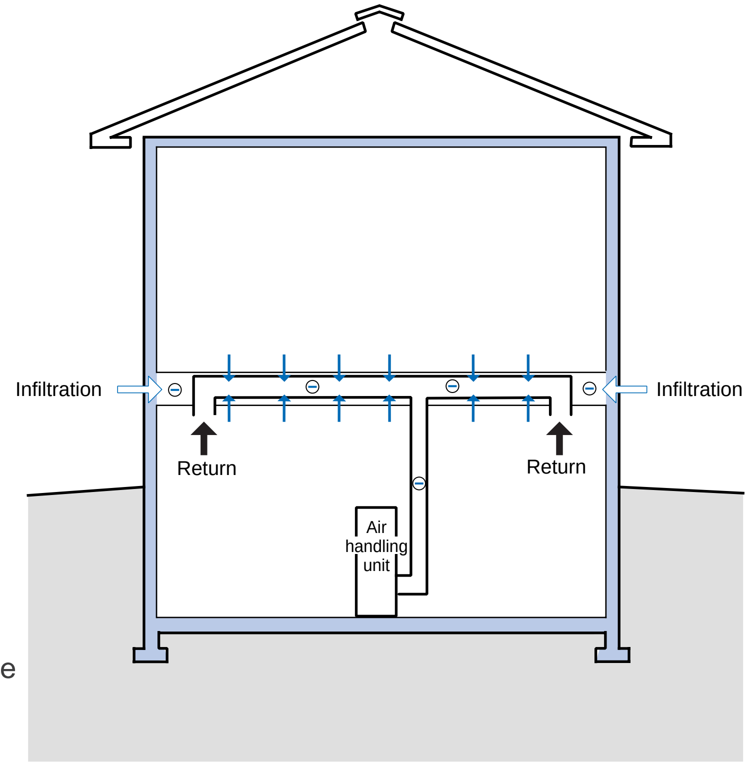


Figure 20

Return Duct Leakage

- Leakage of return ducts into floor space depressurizes floor space leading to infiltration at rim closure

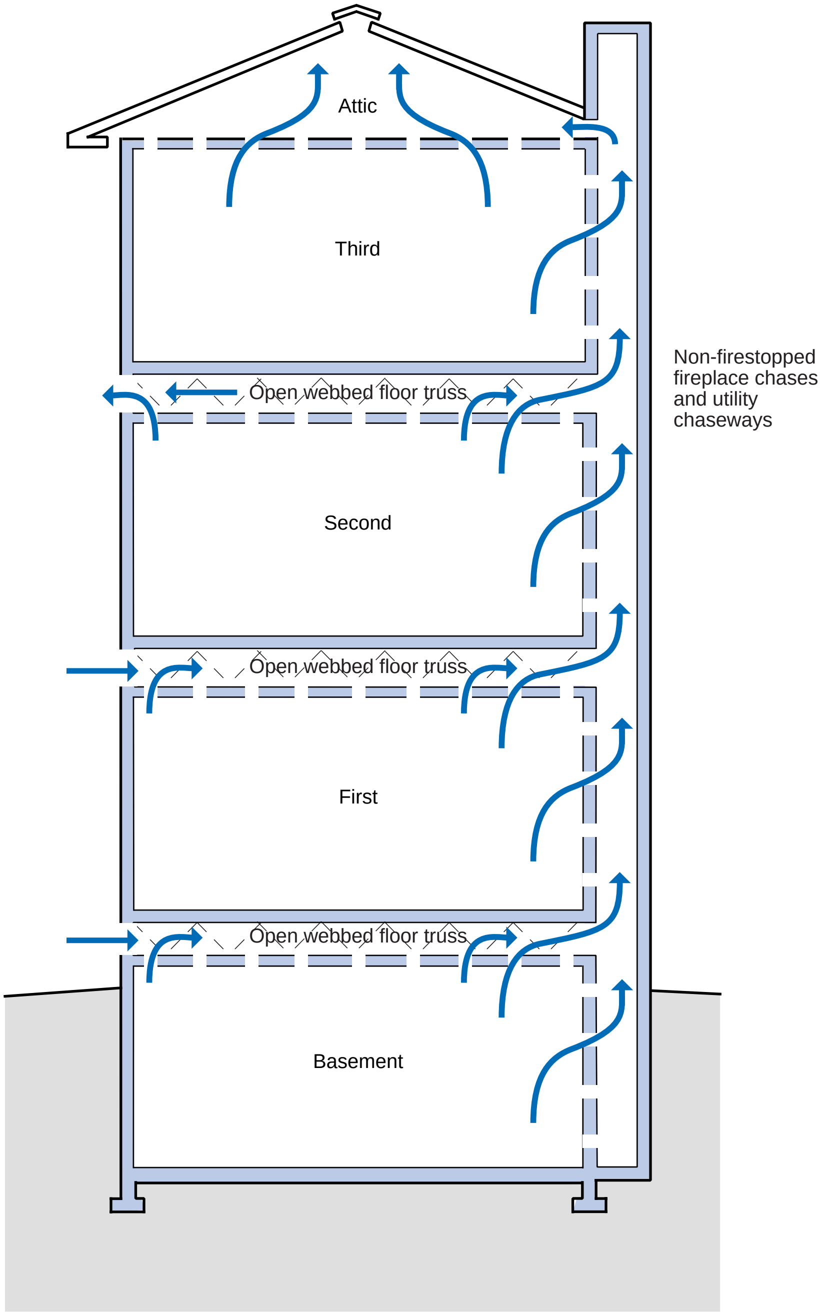


Figure 21

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

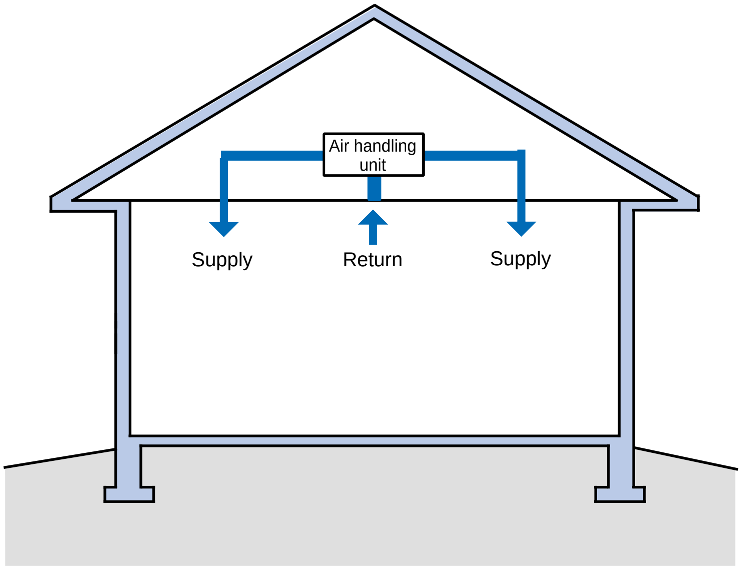


Figure 22

Unvented-Conditioned Attic

- The air handling unit is located in an unvented, conditioned attic
- The attic insulation is located at the roof deck