# Performance linkage approach: environmental control of buildings.

## Part 1: construction today

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# Performance Linkage Approach: Environmental Control of Buildings Part I: Construction Today

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## INTRODUCTION

THIS STATE-OF-THE art paper reviews the area of environmental control of buildings, outlines some research findings, and analyzes different aspects of the design process with a view to creating a comprehensive stage for the introduction of new ideas.

This paper underlines shortcomings in the current design process and highlights areas where the current design and evaluation processes must be improved to enhance innovation in the construction industry. Part II of this work (to be published in JTIBE) proposes improvements based on a holistic approach to the environmental control of buildings.

## RECENT CHANGES IN CONSTRUCTION

In the past, building envelopes were leaky and natural ventilation was relied upon to bring fresh air into buildings. Until the energy crisis of the late 1970s, energy was inexpensive. Our approach to environmental control of buildings has changed since that time.

Increased tightness of building envelopes, controlled ventilation, and air-conditioning systems are relatively recent additions to building technology. Recent trends to thicker thermal insulation in cold climates caused the pri-



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mary exhaust device, the chimney flue, to be used less frequently[1]. The trend toward using electric heating, heat pumps, and power vented sealed combustion furnaces has further eroded the role of a traditional active chimney. Chimney flues acted as exhaust fans which extracted great quantities of air from the conditioned space, reducing the moisture load acting on the building envelope. Less efficient chimney flues increased the indoor air humidity resulting in more frequent condensation on surfaces of windows or thermal bridges. More recently, the significance of this issue was reinforced by increased epidemiological evidence that links respiratory diseases to dampness (Robinson, 1992).

### Indoor Environment

Building enclosures have become significantly tighter, reducing the exchange of air between the indoor and outdoor environments.

The lower the air exchange, the less effective the dilution of pollutants in the indoor space. New consumer products increased the variety of pollutants in the indoor air. The reduced dilution caused concentrations of these pollutants to increase even further. These pollutants include moisture (from people and appliances), formaldehyde (from particle board and furnishings), volatile organic compounds (from carpets, paints, cleaners, and adhesives), radon (from basements, crawl spaces, water supplies) and carbon dioxide (from people).

It is important to recognize that relying on random leakage openings and the effects of wind and stack effects to provide the required air change does not ensure dilution when most needed. In small buildings, the variations in building airtightness are enormous. Leaky buildings are often two to three times leakier than tight buildings. Compounding these concerns is the difficulty in predicting how tight a building will be when built using conventional construction practices. In effect, for health reasons, mechanical ventilation is a requirement in all buildings, tall or small.

In some residences, the installation and use of indoor spas, hot tubs, and central humidifiers made moisture control more difficult. In commercial and institutional buildings, the installation of pressurized and humidified computer rooms and special use areas such as health clubs or copying/duplication rooms created additional environments that are hostile to humans.

These changes in construction processes introduced new considerations for materials.

[1]In the extreme, reducing the chimney's ability to exhaust products of combustion may lead to spillage of combustion products, backdrafting of furnaces and fireplaces, and associated health and safety problems.

## Material Considerations

Any material must be assessed in the context of a system. What is the function of the material? Can the material perform the function? What is the risk to the occupants, the building, and the environment? Extending this argument further, there are no truly benign materials, and nothing is completely risk free. However, risk can be managed. For example, a toxic material can provide significant benefits and pose little risk when used properly. The use of some damp-proofings on the exterior of a concrete or preserved wood foundation illustrates this point. An inherently toxic material provides substantial benefits to the system (moisture control) and does not pose a high risk to the occupants.

Concerns have been raised on how many synthetic agents impact the indoor environment. It has been voiced that "natural" or "green" materials should be used. However, many "natural" materials contain volatile organic compounds, are potent irritants, and pose hazards to health. Allergic reactions to the odors emanating from "cedar" closets and chests are common. As well, radium and radon are natural materials. Yet, nobody would suggest that these two "natural" materials be used in construction, though radon gas could be used in sealed glazing systems in place of argon, and radium could be used on thermostat dials to make them easy to read at night.

The risk to occupants is low if a particular agent remains in the building product and does not affect people through respiration and physical contact. In general, building materials which do not off-gas are preferable to those that do. Products which off-gas a little are preferable to those which off-gas a great deal. Less toxic alternatives should be used in place of more toxic materials. The principle of product substitution should be employed wherever possible.

For volatile organic compounds (VOC), the decay of their emission rate must be considered. For example, most interior paints contain significant quantities of VOC (solvents). They off-gas or evaporate very rapidly and leave behind a relatively "benign" surface. After some period, these materials pose little risk to most occupants over the rest of the service life. However, they may pose a real "risk" to the painters as an occupational hazard.

Superimposed over all of the specific concerns about material and product use on the interior environment of a building and the occupants, are the concerns relating to the local and global environment. Is it more appropriate to use a recycled material in place of a new material? Is the new material or product manufactured in a nondisruptive or least-disruptive manner to the environment? How much energy was used to make it?

These are all valid and important concerns. Sometimes, however, in pursuing one of the detailed concerns, we lose the bigger picture. For instance, a large embedded energy content is often voiced against the use of foam plastic insulations. Franklin Associates (1991) calculated energy consumption through each stage of a product's life cycle. This calculation included the energy input involved in acquisition of raw materials, materials manufacure, material waste, product and by-products manufacture, production waste, cost of transportation to the first buyer and a number of other variables. It was established that 50 Btu is used to manufacture 1 pound of polystyrene insulation.

Compare the embedded energy with that saved over a period of thirty years. With density of 1 lb/ft$^3$ (16 kg/m$^3$) and thickness of 2 inch (50 mm), one pound of insulation covers 6 square feet (0.04 m$^2$). With a seasonal temperature difference of 32°F (20°C) for a five month heating period and the thermal resistivity of the insulation of 3.5 ft$^2$hr°F/(Btu in), the energy saving is equal to (20 years × 5 months × 30 days × 24 hours × 32 degrees F × 6 square feet/3.5 × 2 inch) = 3 million Btu. It is evident that any type of thermal insulation is a "green product" in terms of the saved energy. The embedded energy is not a factor affecting the selection of thermal insulation.

As we highlighted above, to design a durable and cost-effective building shell, we must select materials with a view to their contribution in the subsystem. Evidently, the same approach should be used when selecting subsystems.

**Subsystem Considerations**

Discussing the architectural interior systems, Flynn and Segil (1970) listed four subsystems:

1. The site subsystems (wind diversion, sun shading, etc.) that provide an environmental context of the building (called here the mezzoclimate)
2. The building envelope
3. The subsystems that satisfy environmental and service demands
4. The subsystems that facilitate the distribution of energy to and throughout the buildings which together form a comprehensive environmental system

Flynn and Segil (1970) stated: "But rather than a simple correction of climatic deficiencies, the environmental control function of building must be oriented toward the more extensive sensory demands of various occupant activities and experiences. This occupant perceives light as the surface brightness and color; he absorbs heat from warmer surfaces and warmer air; and he himself emits heat to the cooler surfaces and cooler air. He responds physiologically to humidity, to air motion, to radiation and to air *freshness.* He also responds to sound. A major function of the building, then, is to provide for all the sensory responses concurrently—to establish and maintain order and harmony in the sensory environment."

Is this happening in the construction practice? Seldom. Today's processes of design, construction, and commissioning may appear better suited to the roles of construction professionals and building trades (each having an independent circle of responsibility and corresponding expertise), than to ensuring team communication with a view to satisfying the user's requirements. For instance, testing professionals specify very precise and detailed procedures which ensure constancy of material performance. Any piece of material that passed the test criterion is as good as the one that was originally tested. The result of the test itself, however, seldom describes the field performance of this material in a construction system (Bomberg, 1982). Only when enough data from the field performance has been collected and correlated with the test, can such a test have a judgment value for a designer selecting materials.

The code professionals write requirements that carefully describe traditionally proven solutions. Architects, structural engineers (who design the building shell) and mechanical engineers (who design the HVAC services), fire, acoustic, lighting, and material experts—are carefully trained in their respective professions with no common ground for understanding "how to establish and maintain order and harmony in the sensory environment" when developing design for the "durable and cost-effective building shell."

The current design process does not provide the facility for predicting performance of the new system during the design stage. Neither does it provide the means for an effective quality assurance that starts during the design and continues through construction, ending with the commissioning of the completed building.

## FACTORS AFFECTING THE DESIGN PROCESS

Before one can improve a process, one must understand it well. Our analysis must start at the beginning.

### User Requirements—The Starting Point of Design

Primarily, the building envelope provides a shelter from the outdoor environment to enclose a comfortable indoor space (Hutcheon, 1953). In doing so, the envelope must withstand many mechanical and environmental forces over its service life. These forces include climatic factors such as temperature, air, and moisture in their various forms. In climatic extremes, for instance the Canadian cold, the envelope must be well-insulated to provide the required level of thermal comfort. Other comfort considerations involve noise and fire and these functions must be achieved at a reasonable cost.

The user requirements listed in the first column of Table 1 are general. They must be, therefore, formulated as more specific design and performance requirements for which evaluation procedures may be developed and acceptance criteria established (Bomberg 1982). Table 1 highlights the point that one user requirement may result in a multitude of technical considerations which may or may not be expressed as performance characteristics. These requirements may be needed to define attributes of the factor that serve to attain a specified construction objective. To incorporate both the performance and the descriptive requirements that follow out of the user needs, we will use the term "performance objectives."

The performance objectives listed in Table 1 differentiate between time-independent and time-dependent effects. The latter are often called "durability" if the process causes a damage to the material, and "serviceability" if the process reduces the level of their performance in the building envelope.

Table 2 shows that damage caused by the time-dependent failure mechanisms prevails over other types of damage.

Table 2 indicates that time-dependent aspects account for 60% of the

*Table 1. User requirements and performance objectives for exterior walls.*

| User Requirements | Performance Objectives Time-Independent | Performance Objectives Time-Dependent |
|---|---|---|
| Space separation | • strength and rigidity (deflection): utility loads, wind, impact loads | weathering and aging: *time dependent property changes* |
| | • relative movements and dimensional changes of materials | fatique, deformation: sealants, gaskets |
| | • vibration and noise: airborne noise and structural vibration | |
| | • aesthetic considerations: color and texture of the facade | weathering: *stain, discoloration* |
| | • risk and prevention of fire: combustibility, smoke development, toxicity, time for escape | |
| Environmental Control | • control of heat flow: heat gains and losses, thermal bridges | thermal deformation and stress |
| | • control of water: rain, ground water, condensation<br>• control of air flow: wind, stack effect, HVAC operation<br>• control of water vapor: air flow, diffusion and thermally driven | hygric deformation and stress, moisture accumulation leading to deterioration: corrosion, freeze-thaw, rot, efflorescence, mold, mildew, weathering, etc. |
| Cost | initial cost, maintenance and repair | life cycle cost |

*Table 2. Frequency of damage in German wall systems, from Gertis (1982).*

| Cause of Damage | Percent |
|---|---|
| Temperature | 13 |
| Restrained movement | 12 |
| Moisture | 9 |
| Deformations | 9 |
| Settlements | 7 |
| Creep | 6 |
| External climate | 4 |
| Total of the above | 60 |
| Other causes | 40 |

observed damage in the German study (Gertis, 1982). Similar observations may be found in the U.K. study by Harrison (1983). The durability considerations are the most difficult part of building envelope design and evaluation as they involve many different and interacting variables and as they depend on environmental and service conditions as well as period of service.

Incidentally, a popular concept of material being more durable or less durable is false in terms of logic. The useful life of the material in building envelopes depends on both the outdoor and indoor micro-climates, type of construction, and conditions of service. A small change in one of those variables may result in the material failure during the first year of use or a flawlessly performance for forty years. There are documented cases with continuous spalling clay-brick veneer enclosing unheated storage space in a building while the walls enclosing the heated space were undamaged through a long observation period.

It appears that design for durability may require many technical and cost considerations such as design of environmental control of the envelope, buildability, defects arising during construction, inspection (commissioning), maintenance, repair or replacement, and life-cycle cost of the structure. Judging from the types of failures listed in Table 2, it is evident that the designer needs more guidance on these issues.

## Predictability of Building Envelope Performance—A Historic Background

The relation between knowledge and predictability of the construction performance was examined by Hutcheon (1971) who observed that: "The knowledge about building, called, for convenience, *Building Science,* is valuable largely because it is useful in predicting the outcome or the result of some building situation. The situation may be real, if the building already exists, or may be posed in a hypothetical way in the normal course of building design. Rational design is possible only when there is the capability to establish, each time a choice is made, the probability of a particular result."

Does the construction experience based on tradition promote rational design? The answer is only partially affirmative: "for tradition embodies prediction, embracing those things which have been shown by experience to produce a predictable result. Such experience very often has arisen from unintended, costly, full-scale experiments associated with failure of part or all of a building during or after construction."

But, there is a clear limit of the use of tradition: "Tradition has a great weakness in that it deals only with a way of doing something, without any contribution to understanding 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 or solution provided." There is the crux of the matter, and Hutcheon continues. "The experiments must be done if predictability is to be extended. They can be done more economically and with greater return if devised and carried out in a systematic series, which is, of course, research. They may be done in the laboratory as well as the field, often on model scale."

Then, would a laboratory testing provide a good means for achieving predictability of performance? Again, the answer is only partly affirmative. One must remember that the knowledge (the building science) was defined as a synthesis of the understanding and the experience. The advantages or disadvantages of testing must be analyzed in this context.

With knowledge about similar situations, one can identify key factors that influence the results and select tests that provide the needed information. When little is known, an elaborate test program may be needed. Cost may limit the research program to be undertaken, posing the risk that "in the absence of knowledge the choices made may fail to represent the service conditions in some important way. The single test, by itself, provides very limited information; it can be very effective when designed to provide some critical information in an otherwise adequate body of knowledge, like the final piece of a puzzle. Its value depends almost entirely on the relevant knowledge already available" (Hutcheon, 1971).

This discussion outlines *a paradox of knowledge and testing,* namely, to design a simple and effective test, a large body of knowledge is required; to develop such a body of knowledge, a large number of carefully planned, complex, and selective tests are needed. Addressing this issue, Bomberg (1982) postulated development of a series of interdependent ASTM tests, so-called blocks of test methods.

A particular difficulty relates to predicting long-term performance of new products. Not only because a manufacturer has little control over application of the building product, but also because evaluating the product durability may involve the outcome of several interactive and cumulative degrading effects. Hutcheon highlighted the limitations for such predictions: "This is exceedingly difficult for new materials and must be based entirely on the knowledge of the product and of related products and situations until supporting evidence from significantly longer periods of use becomes available. There is always great demand for accelerated durability tests, and these are very difficult to devise and to verify. Final verification must await the completion of a lifetime of service."

This discussion outlines *a paradox of durability evaluation,* namely, there are no methods of accelerating weathering and aging processes, there are methods either involving more severe exposure conditions or involving the theory of mechanical similitude. Extreme environmental conditions (e.g., elevated temperature), may accelerate some physical or chemical processes. Methods using the similitude theory may reduce the period of testing by altering properties of material or scaling geometrical relations, e.g., a transport process may be accelerated by changing the ratio of exposed material surface to its volume, as in the scaling factors to accelerate aging of foams (Isberg, 1988; Sandberg, 1990; Bomberg, 1990; and Christian et al., 1991).

Nevertheless, to relate the results from the so-called "accelerated test" to those in actual field conditions, one must either know the extent of "acceleration" obtained under the laboratory conditions in relation to the field conditions or the differences between the severity of the laboratory and field exposures with regard to all factors affecting the final outcome.

It becomes evident that to address prediction of long-term performance of a construction system, we need to develop a scientific basis "to assess the relevance of experience and thus to draw upon broader and more varied experience in the development of predictability" (Hutcheon, 1971). This aspect of research, aiming at enhanced understanding of general functional relations, has dominated building science of the 1970s.

The performance analysis (Wright, 1972; Blach and Christensen, 1976; Cullen and Sneck, 1980; Becker, 1985) was thought to be a panacea for enhancing predictability of performance for any system of the designer's choice. Despite concentrated efforts of many international groups, the performance analysis has failed to become a part of construction practice. Why? Perhaps, because it lacked a mechanism to combine the holistic and analytical approaches and could not produce a synergy between the two pillars of building science: engineering experience and understanding of scientific principles. Perhaps, because it did not recognize the dual nature in the process of design and evaluation.

## Addressing the Duality of Design Process

Designing for environmental control of the building envelope assembly compels professionals to integrate two very different conceptual processes. One extreme encompasses analytic thinking, involving testing and calculations; the other encompasses analog (lateral) thinking, based on broad experience and judgment based on understanding of what makes a building envelope function. On the analytical side is a complex array of tools, models, and data which describe the material, structural, and environmental factors relating to the building envelope. On the qualitative side is a sense of how a particular building envelope would function.

The design of an air barrier system offers an example of how the process of dual track and iterative design might work. The information flow may start with a search for suitable materials. Typical questions are asked about possible materials and their air permeability, their ability to be extended, their pliability, adhesion, and means of their attachment, connection, and support. The review would also address the long-term aspects of performance (material weathering and aging), stress, and deformations during service, and perhaps the projected costs of repairs and maintenance.

After making an initial selection, the designer then specifies the details such as intersections and joints between building elements (for example, foundations, walls, floors, windows, and doors). Then, to achieve satisfactory performance in these locations, the designer must ask further questions concerning the performance of the whole system, such as probable location of air leakage, rate of air leakage, its impact on vapor condensation, and possible damage (this issue will be analyzed later in text). Throughout the design process, the designer consults with structural, electrical, and mechanical experts to ensure that the selected materials will perform satisfactorily.

In addition, the designer reviews the buildability aspects such as material installation under different weather conditions, level of labor skill required for installation, accessibility to perform a sequence of tasks, and expected level of construction tolerance. Buildability, as the word suggests, reflects whether the design made on paper can be constructed with the resources available.

Even with the best design, the probability that no defects would develop during the service life of the building envelope is so low that some redundancy in the design becomes necessary. For instance, the plane of the air barrier system may be incidentally punctured, or poorly connected to some elements of the construction, for instance, windows. The designer must then evaluate whether "erroneous" moisture could be drained or dried out. How long would the drying process take and what effect would it have on other materials? Are these materials sensitive to moisture? Could the prolonged presence of moisture cause corrosion, differential movements, mold growth, or rot?

As many of these qualitative decisions (though based on experience) appear arbitrary, some people attempt to replace them with more "stringent" evaluation criteria. Consider an example of a vapor barrier.[2] A typical vapor barrier is required to have a permeance of no more than one perm, a unit that represents sufficient retardation of water vapor flow for traditional wood frame housing. For most building authorities, using a layer with 1.5 perms appears out of the question. Yet, calculations made with a complex model of heat, air, and moisture transport demonstrated that permeance values ranging from 0.2 to 7 perms are suitable for various combinations of materials and climatic conditions in Canada (Karagiozis and Kumaran, 1993). Ojanen and Kumaran (1996) showed that with an air barrier system controlling air flow, a vapor barrier with permeance of 3 perms would satisfy most locations in Canada. The latter requirement can easily be satisfied by a well-primed and double-painted drywall (without any special vapor barrier paint).

## DEFINING THE ENVIRONMENTAL CONTROL

### Defining Environmental Control

The design process should occur simultaneously on different levels. The building should be analyzed as a whole at the same time each of its components is analyzed. Environmental control must also be a part of this analysis if the interactions and trade-offs between control of heat, air, and moisture transports are to be fully realized.

### Interactions of Heat, Air, and Moisture Transports

Heat, air, and moisture transport across a building envelope are inseparable phenomena. Each influences the others and is influenced by all the materials contained within the building envelope. Often, we simplify the design process by ascribing control of each phenomenon to a particular material. The thermal insulation is to control heat transfer, and the air barrier is to control air leakage. Likewise, to eliminate ingress of moisture to materials, we use the rain screen and the vapor barrier.

However, each of these materials may perform different functions and influence several aspects of the overall performance. For instance, by controlling air leakage, the air barrier provides an effective moisture control. Simi-

[2]Changing the name to retarder may appear more scientific, but does not address the issue.

larly, by increasing temperature in the wall cavity, an external insulating sheathing reduces the intensity of vapor condensation in the cavity of a frame wall.

To ensure that all aspects of the building envelope perform effectively, we must deal with heat, air, and moisture transport collectively. In some ways, this approach represents a return to the thinking of sixty years ago, long before detailed performance analyses were routine. The difference today centers on improved standards and requirements concerning performance of the individual elements that make up the building envelope. So, while we preserve the basic approach of the past, we are now better able to apply the fundamental concepts first introduced in the 1930s.

### *AIR TRANSPORT—A LESSON FROM HISTORY*

Air transport represents a critical factor in environmental control. It underscores virtually all facets of environmental control as it moves both heat and moisture through the building envelope.

Our understanding of the performance of walls comes mainly from cold climates and primarily from the prairie regions of North America where the climatic extremes magnify any faults in the ability of building envelopes to maintain environmental control. Research on air leakage through frame walls, performed in the early thirties, led to the acceptance of building paper. The building paper reduced heat loss by limiting the passage of air and improved indoor comfort by reducing drafts, while permitting water vapor to pass to the outdoors. The building paper even reduced moisture damage to the walls by preventing wind washing (wind entering and leaving to the outside) which decreases the inner surface temperature. A weather barrier that permitted the wall to breathe became an important part of wall design.

At the same time, in the quest of thermal comfort, wall cavities became filled with insulation—first wood chips stabilized with lime, then shredded newsprint, and eventually, mineral fibre batts. Although water vapor passed through this thermal insulation as easily as through the air layer, the presence of insulation reduced temperature on the exterior part of the wall cavity causing interstitial condensation of water vapor.

A vapor barrier was then introduced on the warm side of the wall cavity to reduce ingress of vapor from the warm indoor space. Consequently, the walls of homes built in prairie regions in the 1930s already included the outside weather barrier and the inside vapor barrier.

### *THERMAL PERFORMANCE*

Assessment of thermal performance of the building envelope involves three considerations:

- quantity of heat transferred through the walls, windows, and other elements of the building envelope—energy
- reduction of thermal performance due to air flow through building envelope
- depression of temperature at the inner surface of the building envelope—effect on indoor environment and durability of building envelope

*THERMAL PERFORMANCE—ENERGY*

The heat transfer through the walls may be described with six levels of accuracy:

1. considering only the insulated area of the wall under the steady state conditions
2. considering only the unidirectional heat flow under the steady state conditions (parallel path model through the clear wall area)
3. considering multidirectional heat flow (clear wall area) under the steady state conditions
4. considering multidirectional heat flow through the whole system including corners, junctions, etc., under the steady state conditions
5. considering multidirectional heat flow through the whole system including corners, junctions, etc., under the transient heat flow conditions. No input from air and moisture flows
6. considering multidirectional heat flow through the whole system including corners, junctions, etc., under the transient heat, air, and moisture flow conditions. The transient air flow conditions are caused by multizonal air flows and interaction with HVAC equipment. The transient moisture conditions involve wetting and drying (rain, condensed moisture, etc.)

The first approximation considers only the insulated areas of the wall. For instance, a frame wall insulated with RSI 3.5 (R20) glass fiber batts is called an RSI 3.5 (R20) wall.

The second level of accuracy is not much better. An actual thermal resistance for each section is used. However, the model assumes no deviation of heat flow path through the wall, i.e., strictly unidirectional heat flow. With the area of thermal bridge[3] typically 2–3 percent, the increase in the overall heat transfer is very limited.

The third level of accuracy incorporates effects of multidirectional heat flows caused by thermal bridges. Kosny and Desjarlais (1994), discussing the

[3]Materials or elements having much higher thermal transmittance than the typical cross-section of the wall are called thermal bridges.

influence of architectural details on the overall thermal performance of residential wall systems, define clear wall area as the part of the wall system free of thermal anomalies such as corners, window and door openings, or joints with other structural elements. In the discussed case, because of the wood framing, the RSI 3.5 (R20) wall becomes an RSI 3.1 (R17.6) wall.

Historically, the shift from extensive measurements of heat transmission through the structures (Pratt, 1969) to computer calculations (Kosny, 1995) was slow. Discussion of whether measuring or calculating thermal performance of the structures is preferred took place in the mid 1980s (Wagner et al., 1984). The performance of wall systems with air spaces (Greason, 1983) or reflective insulations (Hollingworth, 1983) were overestimated by the calculations. The calculations, since they permitted analysis of both steady state and transient conditions, (Kuehn and Maldonado, 1984) ultimately replaced most full scale, steady state thermal measurements.

The fourth level of accuracy adds the effects of other thermal anomalies such as wall corners, wall floor junctions, while assuming that the steady state representation sufficiently describes the thermal performance of the building. Kosny and Desjarlais (1994) performed 3-D calculations for a one-story ranch house. The overall thermal transmittance of walls falls into three classes:

1. about the same or smaller than for the clear wall (EPS-forms and Larsen-truss walls)
2. about 10 percent larger than that of a clear wall (wood stud and skin panel wall systems)
3. about 20 percent larger than that of a clear wall (steel frame wall).

Knappen and Standaert (1985) presented a comparison between a one-, two-, and three-dimensional solution insulated with a 6-cm cavity insulation, double-glazed wall. The error of the one-dimensional estimate was 34 percent and the two-dimensional estimate was 16 percent in error. A similar magnitude of multidimensional effects was reported from field studies. For instance, Fang et al. (1984) reported that the effect of thermal bridges found in the buildings in Huron, Ann Arbor, and Anchorage increased thermal transmission by 10, 11, and 21 percent when compared to walls without thermal bridges.

The fifth level of accuracy in the assessment of thermal transmittance deals with the transient weather conditions and, thereby, induces the effect of thermal mass on heat loss from, or gains to, the indoor space. Normally, such a calculation is performed for a specific climate and construction type with a recognized computer model, e.g., DOE 2. While this approach may be used for both heating and cooling climates, the effect of building mass on annual heating energy requirements is normally of much smaller benefit in heating climates (Mitalas, 1979) than it is in mixed climates (European Passive Solar, 1986).

The sixth level of accuracy involves the effects of moisture. It is used only for durability assessment where coupling between thermal and moisture gradients may significantly affect distribution of moisture in the materials leading to loss of structural integrity or long-term performance.

Brown and Stephenson (1993) measured dynamic heat transmission characteristics of walls to confirm the data and procedures provided by the ASHRAE Handbook—Fundamentals. For all specimens, the measured and predicted frequency response agreed well. "On the other hand, the measured thermal resistance varied 45% to 90% of the predicted thermal resistance" concluded the authors. (The fact that results obtained from heat transfer models may or may not deviate from the measured values depends on a number of approximations in material properties and boundary conditions.)

The above discussion shows that the accuracy in determination of thermal transmittance may vary by an order of magnitude. What method should the designer use?

Actually, the designer needs two different methods. In the conceptual stage of design, a simple concept of thermal resistance (R-value) or its inverse (U-value) are sufficient, even though these concepts were developed for comparative purposes and may fail to describe the actual performance of some systems (e.g., slab-on-grade) or may be very imprecise for other systems.

A recommended approach for the conceptual design stage is to use a general equation:

$$R = (R_1 + m R_2)/(1 + m) \tag{1}$$

where: $R_1$ is the thermal resistance claculated from the parallel path model, $R_2$ is the thermal resistance calculated from the isothermal planes model, and $m$ is the parameter related to the contribution of the lateral heat flow component (as it depends on thermal properties and geometrical relations of materials in the construction assembly).

The unidirectional heat flow model was presented in this paper as the second stage of accuracy in R-value measurements. The isothermal plane model, which assumes a perfect equalization of temperature within each parallel wall section, is another limiting case. Equation (1) states that the thermal resistance of a wall is somewhere between these limits, approaching unidirectional heat flow (when $m \ll 1$) and uniform surface temperature (when $m \gg 1$).

There is a substantial amount of work relating either directly or indirectly to the $m$-factor in Equation (1). A Russian 1960s thesis analyzed different insulated and hollow blocks showing values of $m$ between 0.1 to 80 with the most probable $m = 2$. Therefore, if the difference between $R_1$ and $R_2$ is limited, some European standards use $m = 2$ (Plonski, 1965). Brown and Schwartz (1987) showed that $m = 1$ approximated most of the insulated wood frame walls. Garrett (1979) showed that $m$ varied from 1 to 1.7 between slotted lightweight concrete and dense concrete with foam inserts. Shu et al. (1979), Valore (1980), Valore et al. (1988) and Trethowen (1995) found that the isothermal planes model gives a much closer approximation to the measured $R$-values (i.e., a large $m$-factor) than the parallel path (zone) model ($m = 0$).

Equation (1) can best be used for engineering purposes with the following $m$-factor:

$m = 1.0$ for wood frame constructions and insulating masonry blocks
$m = 1.4$ for ceramic masonry blocks and sheet steel construction if the adjacent layer has thermal resistivity higher than wood (insulation)
$m = 1.8$ for concrete masonry blocks and sheet steel construction if thermal resistivity of the adjacent layer is equal to or lower than that of wood

For development of final contract documents, however, use of more realistic evaluating methods for assessment of thermal transmittance may be required. For instance, in mixed and cooling climates, one may require the fifth level of accuracy in assessment of thermal transmittance, since this level involves transient performance under specific climate and use conditions.

### *THERMAL PERFORMANCE—EFFECTS OF AIR MOVEMENT*

The second component of thermal performance—air leakage—relates to the rate of air flowing through the building envelope. This component is directly proportional to air pressure differences across the envelope and inversely proportional to the air-flow resistance of the building envelope.

While the air leakage component of energy is recognized, the reduction of thermal performance of fibrous insulations caused by air movement is often disregarded. How much air movement affects thermal performance of fibrous insulation depends on air pressures within the building element and its surroundings, air permeability of the insulation, and the airtightness of joints between materials and building elements. Bankvall (1986, 1986a) showed a dramatic reduction of the thermal performance of a mineral fibre batt exposed to air movement along the insulation surface coupled with the effect of workmanship on thermal performance of the wall system.

As Bankvall dealt with a hypothetical case of poor design and poor workmanship, Brown et al. (1993) studied a specific case of workmanship faults.

Each vertical corner of a wall cavity was partly unfilled (3 and 6% unfilled areas were selected for testing). Wind protection was applied on both sides of the mineral fiber insulation and no continuous and interconnected air spaces and gaps were simulated. These kinds of test conditions appeared to come closer to workmanship faults found in actual walls. Figure 1 shows that with a large difference in temperature, the reduction of wall thermal performance may be as high as 30 percent.

Silberstein and Hens (1996) analyzed the significance of proper design of ventilated air spaces. It is important to underline that, similar to wall construction, the roofing deck must also be constructed as an airtight structure. It was shown, that for an airtight roof deck structure and typical air velocities observed in ventilated cavities, the effect of air ingress into the insulation is insignificant.

There is no contradiction between the results of these two studies. Brown et al. (1993) stated: "Since the measured thermal resistance of walls with 0% defects agreed with predicted values, it is evident that the material is performing as expected; consequently, the issue of installation practice needs to be examined." The authors also stated: "It appears that the convective flow was initiated in the cross-section between the hot/cold pair of air gaps and then spread through the rest of insulation. A contributing factor is that the air permeability along the MFI product, the manufacturing plane, is much higher than across the product."

This explanation follows findings of Wilkes et al. (1991), who showed the significance of convection initiators on the onset of convection. This closes a loop between practice and understanding. The transition zone to fully developed natural convection in horizontal layers was already shown by Wilkes and Rucker (1983), but with the more recent research of Wilkes et al. (1991) and Brown et al. (1993) the role of convection initiators was first understood.

In practice, reduction in thermal performance of insulation caused by convective effects was observed at NRC by Wolf et al. (1966) on wood-frame walls and Sasaki (1971) on steel-stud walls. The latter paper discussed the effect of air gaps caused by a 6 mm lip on the flanges of the steel studs. Brown (1986), testing fourteen different configurations of sheet steel walls, indicated similar causes for poor performance of some of the tested sheet steel walls. Thus, not the findings on thermal performance derating, but enhanced understanding of this derating mechanism constitutes the progress of the last thirty years.

This example also highlights interactionMof environmental control with quality control and workmanship issues.

*THERMAL PERFORMANCE – CONFORT AND HEALTH*

The third aspect of thermal performance evaluation relates to the depres-

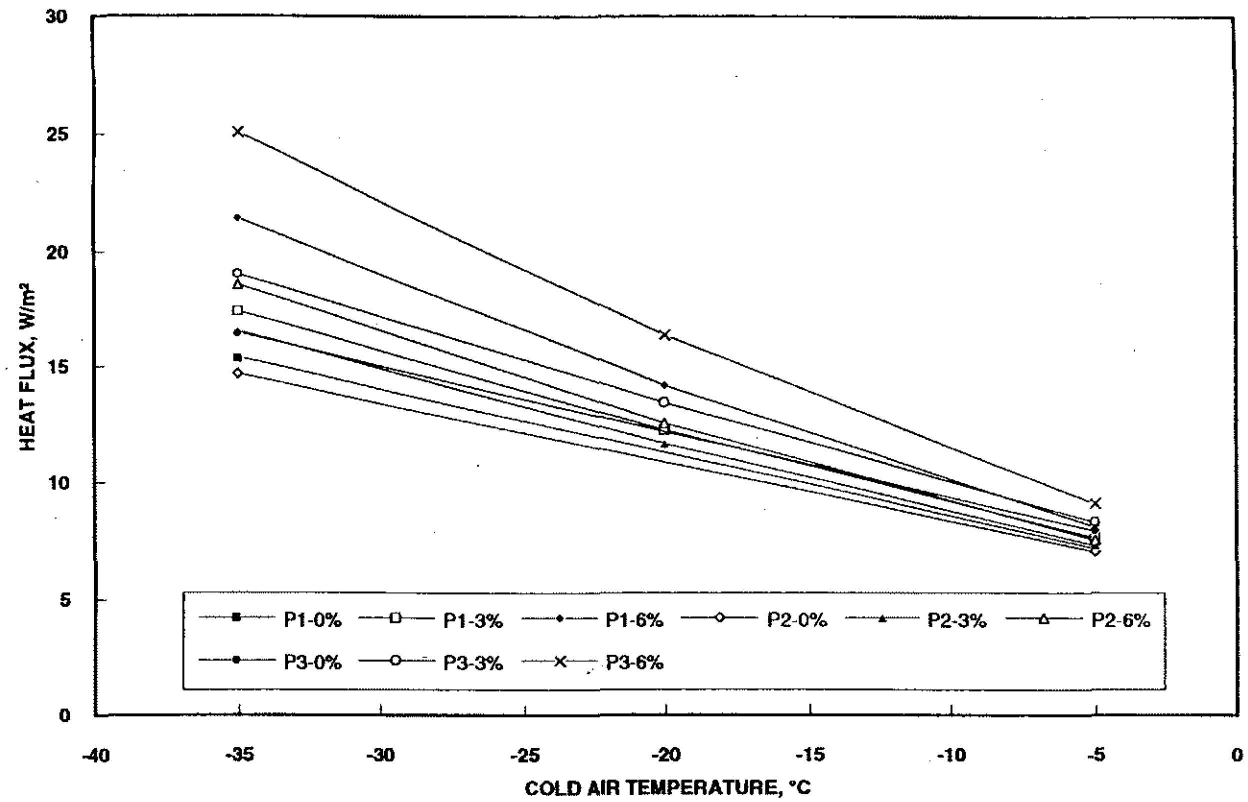


**FIGURE 1.** Increase in heat flux through the wall caused by workmanship faults along the studs. From Brown et al. (1994).

sion of temperature on the inner surface of a thermal bridge (TB). At these locations (in cold climate), lower thermal resistance reduces the surface temperature.

The following aspects of thermal and moisture performance of thermal bridges in external walls may need to be analyzed:

- depression of surface temperature for a TB located in the clear wall area
- effect of increased air film resistance on depression of surface temperature (for a TB located in a corner of walls and spaces with restricted air circulation)
- effect of thermal properties of the adjacent material layer on depression of surface temperature
- dust marking caused by surface temperature depression (aesthetics)
- moisture accumulation caused by surface temperature depression (effects of TBs on durability of the structure and health of the occupants, see later text)

### *MOISTURE EFFECTS—MATERIAL DURABILITY*

The building envelope must perform, retaining its structural integrity, while separating the interior and exterior environments. Of all environmental conditions, moisture poses the biggest threat to the integrity and durability of materials in building envelopes. Many construction materials contain moisture, most notably, masonry or concrete. These materials demonstrate excellent performance as long as the moisture does not compromise their structural or physical integrity. However, excessive moisture jeopardizes both the material and its functionality.

Consider, for example, the ability of a material to withstand, without deterioration, natural periods of freezing and thawing. As already mentioned, the frost durability is not a material characteristic, but a complex property which depends on the material, the construction system, and the environment. For instance, in one school building, only the outer surface of the external clay-brick protrusions showed freeze-thaw spalling. These protrusions were more exposed to driving rains and the surface temperature of the bricks was slightly lower, compared to the plain facade where no spalling occurred. Both of these conditions contribute to increased risk for freeze-thaw damage.

One may also observe interaction of temperature and moisture in other types of moisture originated damage, e.g., corrosion and mold growth. The rate of corrosion of metals exposed to air varies with both the surface temperature and air humidity (Grodin, 1993). Mold growth requires coincidence of both certain temperatures and humidities [temperatures above 5°C and relative humidity above 80% (Hens, 1992)].

**Indoor Environment: Comfort and Air Quality**

Ventilation is required for the health and comfort of the occupants. Ventilation is the process of removing and supplying air to and from the indoor space. Controlled ventilation is defined here as mechanically supplying outside air and exhausting inside air to maintain adequate indoor air quality (air change), and supplying air for combustion devices and air extraction systems (air supply).

Natural ventilation (infiltration/exfiltration driven by the stack effect and wind) through random and discrete openings such as operable windows, doors, ductwork, or holes is not adequate because of the lack of consistency of the driving forces. The instantaneous infiltration/exfiltration rates vary substantially due to the influences of wind pressures, stack pressures, and pressures induced by air-consuming devices. Thus, some areas of a house can have adequate air change at one moment, and inadequate at the next. The variation can be so substantial that the infiltration/exfiltration rates may be on the order of several hundred litres per second during a wind gust, and moments later, zero, if the wind suddenly dies down and the majority of the leakage openings happen to fall along the neutral pressure plane.

Mechanical ventilation involves the provision of a controlled driving force to remove and supply ventilation air through either deliberate, discrete openings or through random openings. This driving force can be provided on a continuous basis or, as necessary, to remove specified pollutants. Thus, to control indoor air quality, one may either provide sufficient ventilation to dilute the pollutants existing within the indoor space or control the rate of pollutants generated within the indoor space. Designers and builders have to decide whether to approach the IAQ through ventilation or through source control or both.

Sources can be controlled at the point of generation (point source control of pollutants/odors) such as the direct venting of combustion appliances and installation of range hoods in kitchens or by prohibition (exclusion) such as the regulation of formaldehyde adhesives in building materials, the banning of unvented kerosene space heaters, the requirement to store firewood outdoors, and the pressurization of crawl spaces and basements to exclude radon gas.

Pollutant concentrations are only one of the components defining the indoor environment of a building. The indoor environment also involves comfort factors such as temperature, relative humidity, and air velocity; physical stressors such as noise and lighting; psycho-social factors such as personal relationships, work stress; and, chemical, particulate, and biological concentrations. A further complication is often the difference between real and perceived indoor air quality by building occupants. The complexity of the interrelationships between the indoor environment, indoor air quality, and comfort factors is illustrated in Figure 2.

The relationships of factors shown in Figure 2 involve health, safety, durability, comfort, and affordability concerns as well as questions about construction performance (warranty).

## HVAC Considerations

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 all aspects of indoor climate and building envelope durability. Air movements induced by HVAC may affect pollutant migration, rain penetration, condensation, and drying of moisture within building cavities, i.e., the durability of the building envelope.

As long as buildings were leaky and poorly insulated, the extent/effect of HVAC systems (and air-consuming appliances) on air pressure fields was small. There was no need to understand air movement in the building, other than ensuring that a necessary supply of fresh air was provided. This is not the situation today. Now, we have well-insulated, airtight buildings and increased incidence of health problems (mold/microbial contamination) and deficient long-term performance (metal corrosion and other moisture originated deterioration). Air flow carries moisture which affects materials' long-term performance (serviceability) and structural integrity (durability). Air flow impacts the spread of smoke in a fire situation, distributin of pollutants, and location of microbial reservoirs (indoor air quality). Air exchange affects energy for space heating or cooling.

The key to all of these real or potential problems is the understanding of air pressure fields in the indoor and interstitial spaces of the building envelopes. Today, understanding the air flow in a building is a necessity. Air pressure gradients (differences in the indoor-air pressure fields), however small and difficult to measure, are needed to establish performance of the building as a system.

### *A STRATEGY TO CONTROL AIR PRESSURE*

A strategy to control air pressure in the building space includes the following steps:

1. Enclose the air space
2. Use controlled mechanical ventilation
3. Control air pressure fluctuations induced by HVAC system operational conditions

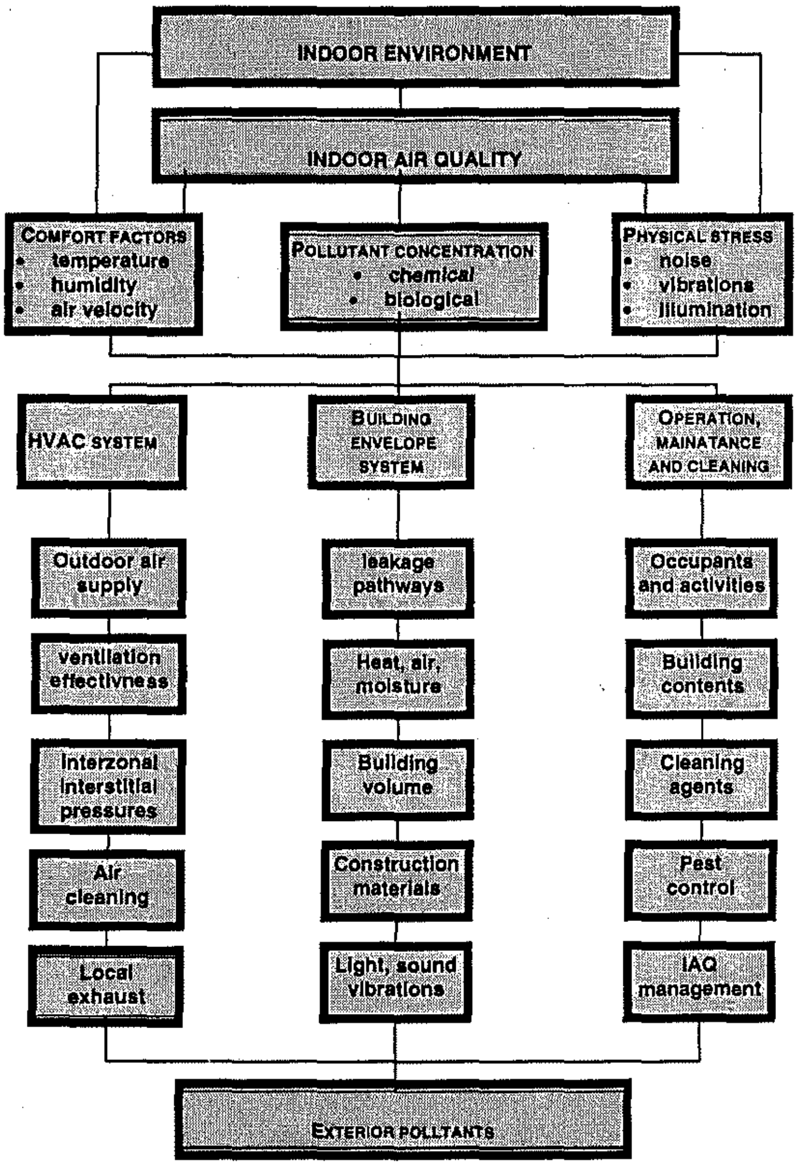


**FIGURE 2.** Factors affecting indoor environment.

4. Control air pressure gradients induced by HVAC system operational conditions
5. Eliminate interconnected internal cavities communicating with HVAC systems
6. Review building mezzoclimate for differences in wind and solar shading conditions

To control the air pressure field, you must first enclose the air space. To enclose the air space, one should use a mechanical ventilation system. Thus, a controlled mechanical ventilation system should be used anywhere, in small houses and in high-rises. The next step is to quantify the degree of air-tightness for any building envelope. The National Building Code of Canada (Swartz, 1995) made this requirement mandatory and provided *performance objectives* for the testing and evaluation of these systems.

While the need to control the pressure fluctuations (in time) and pressure gradients (in space) is recognized, the effect of pathways created by external cavities and interconnected internal cavities communicating with HVAC systems on performance of building systems is seldom mentioned. The significance of these elements, mostly neglected in the traditional analysis of air pressure fields, will be illustrated in the few examples selected from case studies (Lstiburek, 1992, 1994, 1995).

The following two examples involve the effect of pathways created by external cavities and interconnected internal cavities communicating with HVAC systems. The first one (Figure 3) involves a leaky return duct (actually it was the housing of an air handler) enclosed within an interstitial space. The second one (Figure 4) involves a plenum return ceiling communicating with an exterior wall.

Figure 3 illustrates a demising wall communicating with a leaky return duct in a building located in a hot, humid climate. The leaky return duct created a negative pressure. Since the cavity in the demising wall is connected with the furring space in the exterior wall, the interconnected cavities can extend the effect of the leaky duct for a great distance. In the actual case study, moist outside air was drawn into the building cavities even though the interior space was positively pressurized.

Figure 4 illustrates a plenum return ceiling which is not sealed at the exterior perimeter wall in a building located in a cold climate. Plenum return ceilings operate at negative pressures which may range from 1 to 2 Pascal (negative to the interior space) to 20 to 30 Pascal (negative to the interior space). When the plenum return ceiling is also negative to the exterior, outdoor air can be drawn into the plenum return through the exterior wall assembly. The error in the design shown in Figure 4 had caused additional problems as in the studied case, the exterior wall cavity was also connected

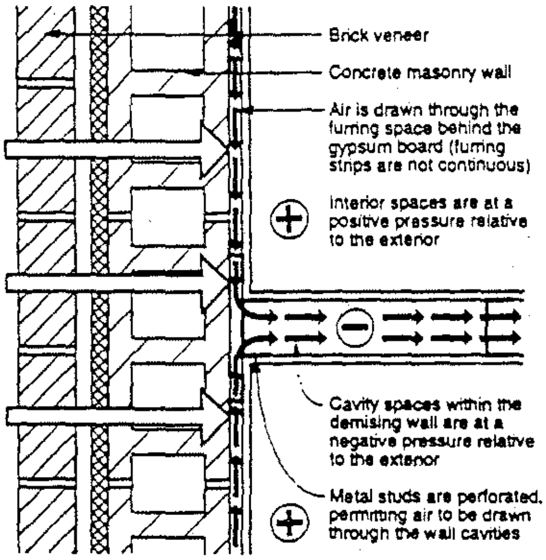


**FIGURE 3.** Negative pressure created by the leaky return duct draws moist external air into the wall cavity of the building located in hot and humid climate.

to the crawl space. Moisture and pollutants were drawn into the return air plenum.

Ducted distribution systems in conditioned spaces traditionally have not been thought to affect interior air pressures. They have been viewed as interior air circulation systems which move air from place to place within a conditioned space, with more or less a neutral effect on the pressure differences between zones within occupied spaces. Typically, entire building enclosures are designed to operate under slight positive pressures with pressurization achieved by providing more outdoor air supply than indoor air exhaust. This pressurization is assumed not to be affected by the interior air circulation systems.

*BUILDING ENVELOPE AND HVAC SUBSYSTEMS INTERACTION*

The following two examples illustrate the significance of ducted distribution systems on interior air pressures. The first one (Figure 5) involves the leakage of supply ducts installed in an exterior space (vented attic). The second one (Figure 6) involves the effect of closing doors in a facility with inadequate provision for return air.

Figure 5 illustrates a facility located in a hot, humid climate with leaky supply ducts located outside of the conditioned space in a vented attic. Air

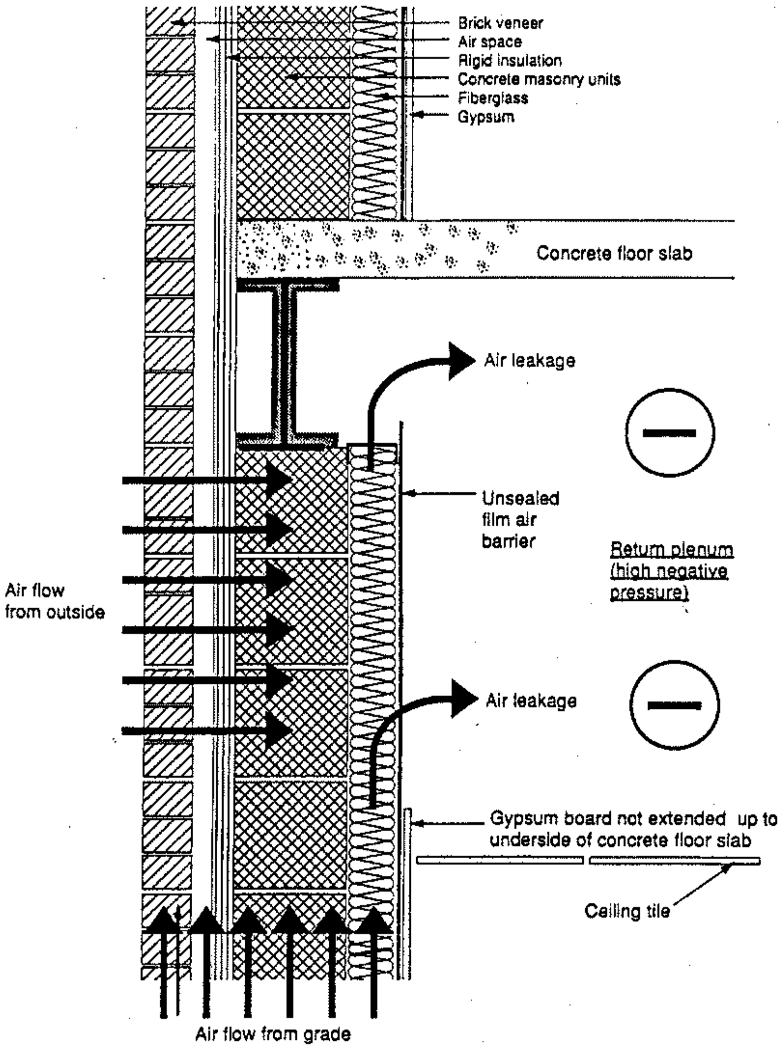


**FIGURE 4.** The exterior wall cavity was connected to foundation assembly. The error in design (unsealed internal gypsum board) permits drawing air from below grade to the return plenum.

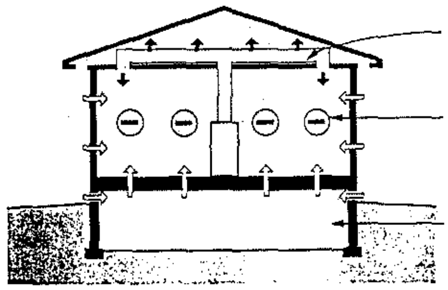


**FIGURE 5.** Negative pressure created in the conditioned space by leaky supply ducts located in the attic of the building located in hot and humid climate.

leaking out of the supply ducts depressurizes the conditioned space, inducing the infiltration of exterior hot, humid air.

Figure 6 illustrates a facility located in a cold climate with inadequate provision for return air. When interior doors are closed, individual rooms/spaces can become pressurized with respect to common areas. The common areas, in turn, become depressurized. If atmospherically vented combustion appliances (such as fireplaces and gas water heaters) are located in the common areas, the negative pressure in these regions can lead to spillage and backdrafting of combustion appliances. In the pressurized rooms/spaces, the forced exfiltration of interior (typically moisture laden) air can lead to condensation and moisture induced deterioration problems.

In most mid-rise and high-rise buildings, the stack effect air flows typically dominate the HVAC system air flows. Stack effects are shown schematically in Figure 7. Note that the majority of the air pressure drop is taken by the exterior building envelope at the top and bottom of the building. Air flows from the lower units and floors, up the elevator shafts, stairwells, and service penetrations to the upper units and floors. These stack effect induced

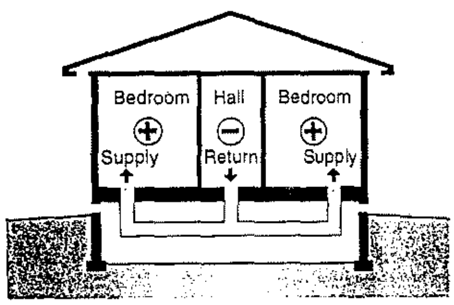


**FIGURE 6.** Pressure differences in the indoor space created by inadequate provision for return air when doors are closed.

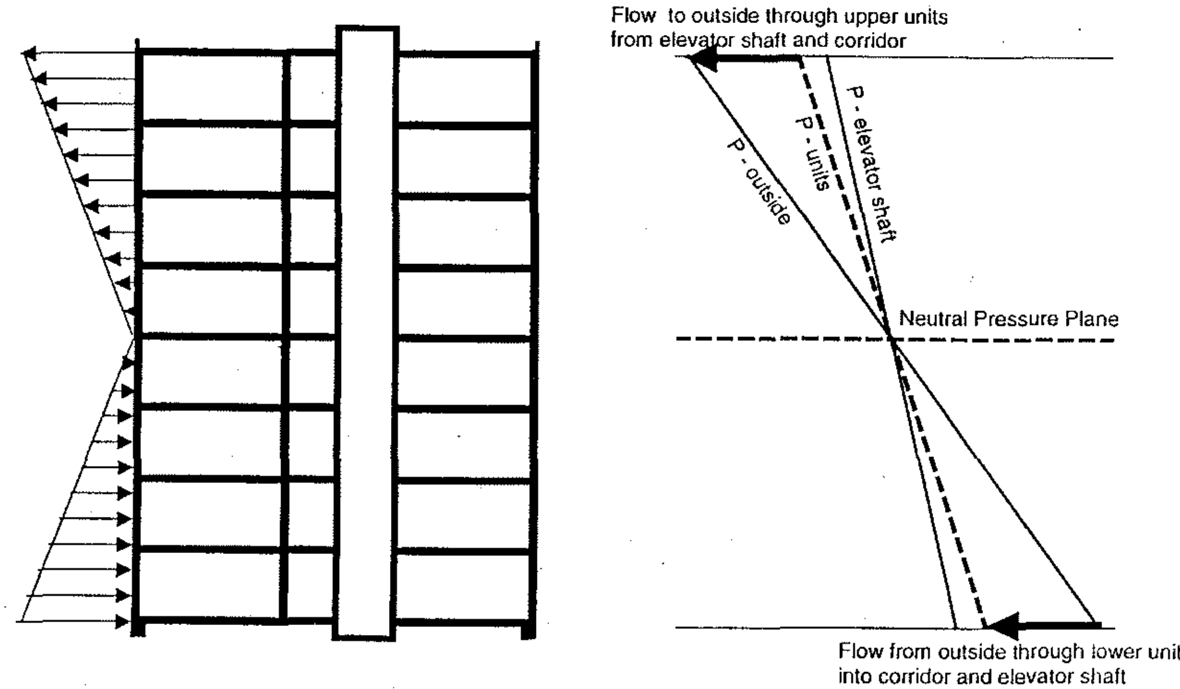


**FIGURE 7.** Air pressure distribution in a mid-rise building.

air flows are often responsible for pollutant migration, odor problems, smoke and fire spread, elevator door closure problems, and high thermal operating costs.

More desirable conditions are achieved by sealing units from corridors and by isolating corridors from elevator shafts (vestibules), air flows caused by stack effects are significantly reduced. The forces acting on this eight-story building have been reduced by "compartmentalization." In essence, this building behaves in a similar fashion to eight, one-story buildings located on top of each other. The pressure drops are now taken across the corridors and elevator vestibules, not the exterior building envelope. This results in a safer building with respect to smoke and fire control. Indoor air quality problems are reduced and energy efficiency is greatly enhanced.

Figure 8 illustrates a preferred controlled ventilation system for the eight-story tower. The key features are:

- Units are ventilated individually through exterior walls.

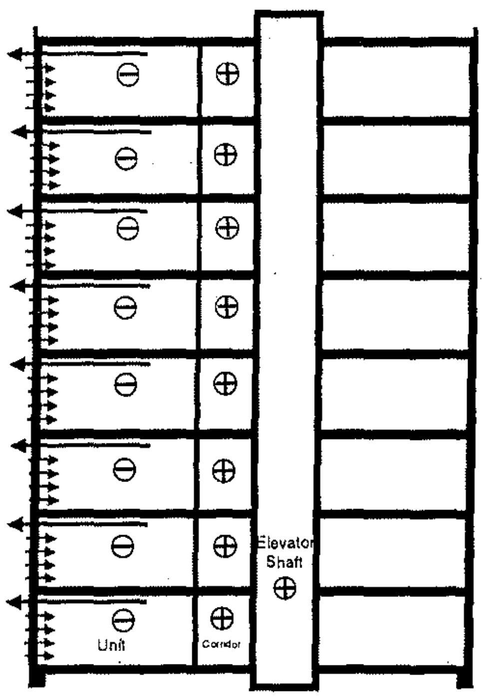


**FIGURE 8.** Air pressure distribution in a mid-rise building where units are compartmentalized, isolated from corridors and shafts and ventilated individually through exterior walls. Corridors and stairwells pressurized via smoke control system via fire alarm control.

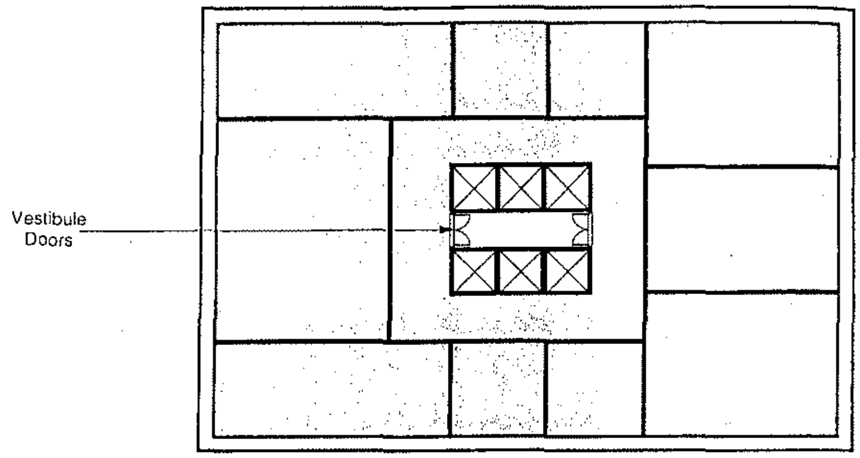


**FIGURE 9.** Shaded area is pressurized relative elevator vestibule and exterior wall interstitial cavities.

- Units are compartmentalized, isolated from corridors and shafts.
- Corridors and stairwells are pressurized via a smoke control system. The existing duct system for corridor air can be utilized.

In multi-story office buildings, compartmentalization was traditionally accomplished by placing elevator banks in vestibules which isolated them from the remainder of a floor. The vestibules acted similarly to air locks when the doors to the floor were closed, preventing air from rushing up the elevator shafts. The utilization of vestibules around elevator banks creates a circular or "donut" zone of pressure control (Figure 9) at each floor.

Duct leakage can inadvertently cause communication between seemingly isolated spaces. Figure 10 illustrates a storage space containing printed materials and an operating print shop. The storage space is maintained under a negative air pressure with respect to the rest of the facility by the operation of an exhaust fan. However, a return air duct passing through the storage space was found to be leaky, resulting in high levels of volatile organic compounds (VOCs) being drawn into the air handling system serving a neighbouring office space. The result—transmission of VOCs from the storage space to the office space via the HVAC system return duct leakage and health complaints in the office space.

Hallways and corridors can cause an extension of pressure fields throughout a building. A typical hotel room ventilation system may have a bathroom exhaust operating on a continuous basis via a rooftop mounted exhaust fan (which also serves for other bathrooms). Make-up air for this bathroom exhaust is typically provided through the exterior wall via a unit ventilator or packaged terminal heat pump (PTHP). In the studied case, the design assumed that 60 cfm out through the bathroom is offset by 60 cfm in through the unit ventilator or PTHP. Although the unit ventilator or PTHP does not run continuously, an intermittent imbalance of 60 cfm is not considered a problem.

However, consider the effect when thirty hotel rooms are on a single floor served by a single corridor. This corridor becomes a large duct connecting all rooms on the floor. If we have thirty exhaust flows of 60 cfm each operating continuously from each bathroom (1800 cfm of continuous exhaust from the floor), but unit ventilators or PTHPs only operating on a 20 percent duty cycle (i.e., 80 percent of the units per floor are not operating at a given time), the supply air flows are only 360 cfm (six operating unit ventilators of PTHPs at 60 cfm each). The flow imbalance per floor is 1440 cfm which is sufficient to depressurize the entire floor all of the time.

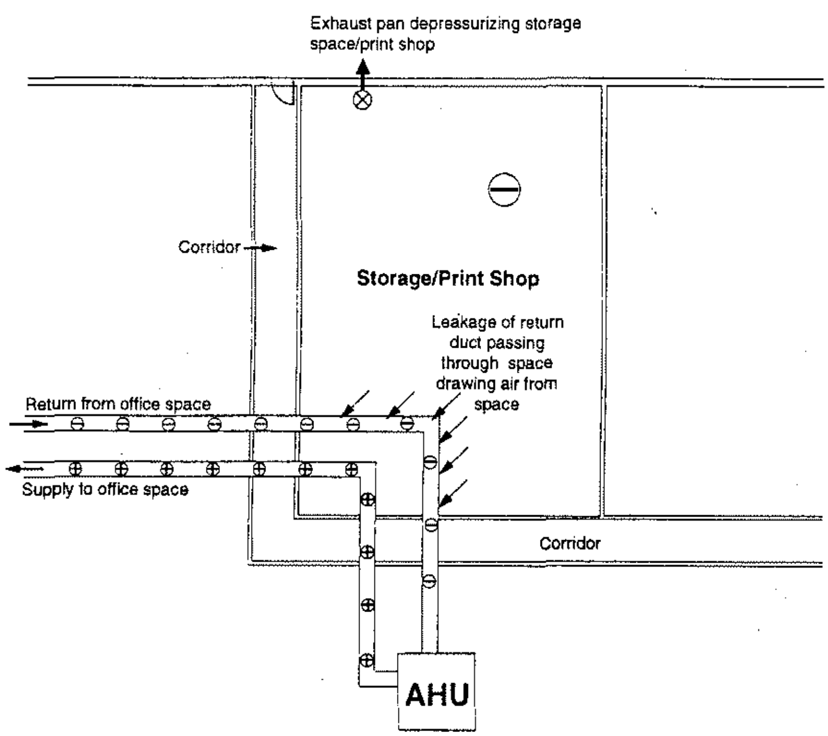


**FIGURE 10.** Duct leakage can cause communication between seemingly isolated spaces. In the case study, leakage from return duct passing through storage space/print shop introduced a pollution transfer despite an exhaust fan depressurizing this local area.

In hotel facilities located in hot and humid climates, the negative pressure field created in this manner is the single, most significant reason for mold, odor, and moisture damage. This observation highlights the fact that the air leakage/pressure relationship is the key to the interaction of the building envelope and the HVAC system. To design and build safe, healthy, durable, comfortable, and economical buildings, we must control the pressure fields.

## CONCLUDING REMARKS: THE URGENT NEED FOR INTEGRATION

To avoid material deterioration over the required period of service, a microenvironment within the building envelope must be controlled. To this end, one needs to deal with heat, air, and moisture transport collectively. As shown in the previous examples of vapor and air barrier, we need to mix the experience and judgment based on our understanding of how the building envelope functions with the analytical evaluation of selected performance factors (based on testing, computer models, and/or simplified calculations).

The above discussion showed that heat, air, and moisture transport across a building envelope are inseparable phenomena. In effect, to address interactions and trade-offs between control of heat, air, and moisture transports, the building system must be analyzed as a whole at the same time each of its components is analyzed. We often simplify the design process by examining these issues separately and ascribing control of each phenomenon to a particular material, yet somewhere in the design process, we must examine their interactions. Particularly significant are the interactions between the building envelope and mechanical systems. They impact health and safety (indoor air quality, smoke and fire spread), durability (moisture transport and accumulation), comfort (temperature, relative humidity, odors) and operation/maintenance (energy costs, minor and major repairs, housekeeping).

Current building codes stress the traditionally acceptable solutions while product evaluation based on tradition restricts the introduction of new construction products. This review highlighted limitations of the traditional approach and difficulties in developing accelerated testing of durability. Since the current design process fails to examine the relationships between input from disciplines: architecture, structural and mechanical engineering, fire protection, acoustics, and interior design, one needs to develop models of holistic approach to design and quality assurance of the environmental control function. Such models are proposed in the next paper.

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