RAINSCREEN

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1. RAINSCREEN

1.1 RAIN PENETRATION

Rain penetration is one of the oldest problems building owners have had to deal with, yet it still occurs all too frequently. The penetration of rain can not only damage interior finishes and materials, but it can also damage the structure of the walls themselves.

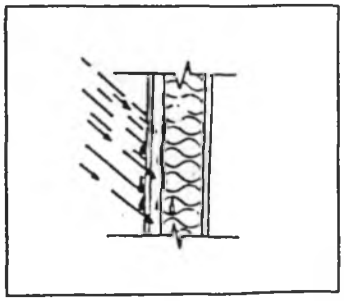
A notable reference on the topic of rain penetration is Canadian Building Digest CBD 40 "Rain Penetration and its Control", by Kirby Garden. This document was published in 1963 and is one of the earliest references on the rainscreen principles. In fact, the term "Open rainscreen" was coined in this paper. The following discussion on rain penetration is based on the information contained in CBD 40.

Rain penetration results when a combination exists of water at the surface of the wall, openings through which it can pass, and a force to move the water through these openings. The elimination of any one of these three conditions could prevent the occurrence of rain penetration. While wide roof overhangs may help to shelter the walls of a low-rise building, it is not likely that rain will never reach the walls. Therefore one of the remaining two conditions must be eliminated to prevent rain penetration.

The face seal approach attempts to eliminate all the openings in the wall through which water can pass. However, the materials used to seal all these openings are exposed to extremes of weather and to movements of the building. Even if the problems of job site inaccuracies and poor workmanship can be overcome and a perfect seal can be achieved, the in-service weather conditions will eventually cause the deterioration and failure of these seals, creating openings in the wall through which water can pass. Unfortunately, these openings can be extremely tiny and difficult to identify, so that even an extensive maintenance program may not keep the building free of openings.

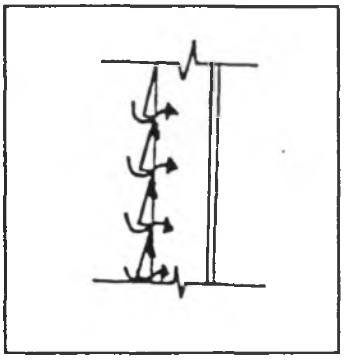
The alternate approach to controlling rain penetration is to eliminate the forces which drive or draw water into the wall. There are typically considered to be four such forces: kinetic energy, capillarity, gravity and wind pressure differences. Each of these forces is explained below.

Kinetic Energy



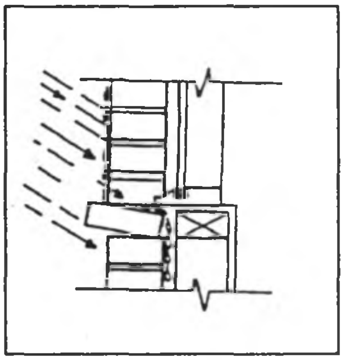
For a wind driven rain storm, rain droplets can be blown directly into large openings in the wall. However, if there is no direct path to the interior, the rain droplets will not pass deeply into the wall. Where large openings, such as joints, are unavoidable, the use of battens, splines, baffles or overlaps has been successful in minimizing rain penetration caused by the kinetic energy of the rain drops.

Capillarity



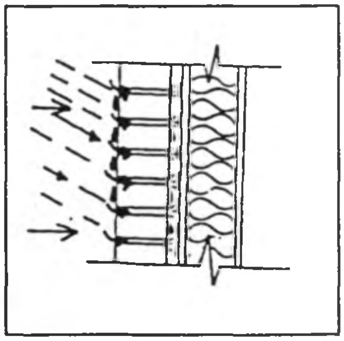
Due to the surface tension of water, voids in a material will tend to draw in a certain amount of moisture until the material approaches saturation. If capillaries pass from the exterior to the interior, water can move through the wall due to the action of capillary suction. While partial water penetration of a wall by capillarity is characteristic of porous cladding material, the introduction of a discontinuity or air gap can prevent through-wall movement of water.

Gravity



The force of gravity will cause water to move down the face of the wall and into any downward sloped passages into the wall. To prevent gravity induced movement through joints, they are typically designed to slope upwards from the exterior. Unintentional cracks or openings are more difficult to control. If there is a cavity directly behind the exterior face of the wall, any water that does flow through the wall will then be directed downward, by gravity, on the inboard face of the exterior wall. At the bottom of the cavity, the water can then be drained back to the outside through the use of sloped flashings.

Air Pressure Difference

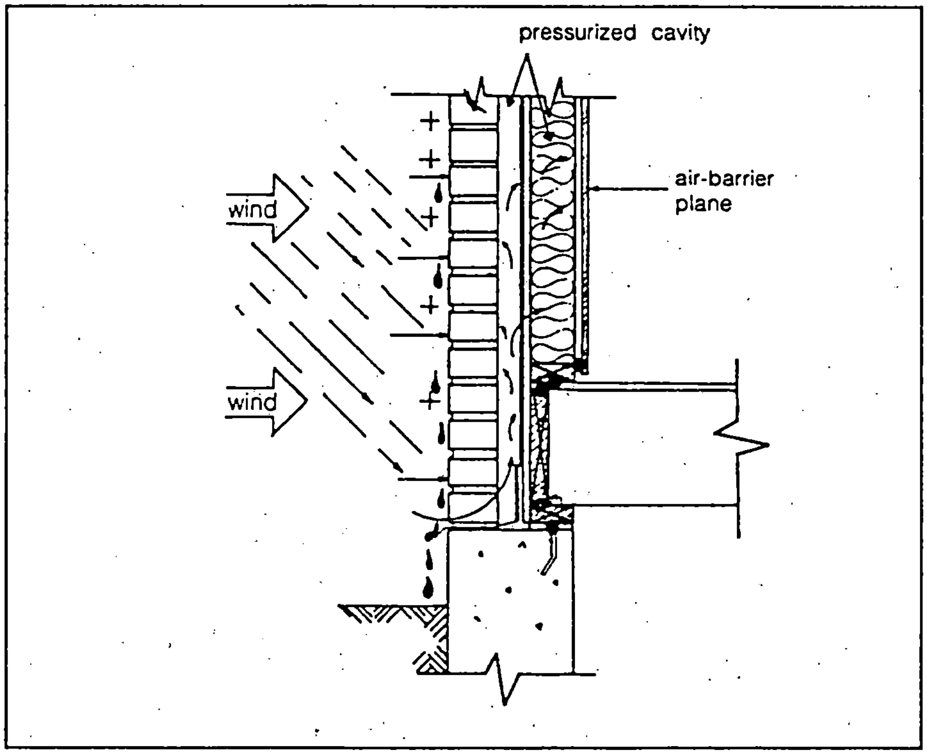


An air pressure difference across the wall of a building is created by stack effect, wind and/or mechanical ventilation. If the pressure on the exterior face of the wall is higher than on the interior of the wall, water can be forced through tiny openings in the wall. Research has shown that the amount of rain moved through the cladding by this mechanism is the most significant. This force can be eliminated or reduced by the use of the pressure-equalized cavity. This concept is discussed in detail in the following section.

1.2 PRINCIPLES OF PRESSURE EQUALIZATION

The theory of the pressure equalized cladding is that it neutralizes the air pressure difference across the cladding (caused by wind) which causes water penetration (the wind). It is impossible to prevent wind from blowing on a house but it is possible to counteract the pressure of the wind so that the pressure difference across the exterior cladding of the wall is close to zero. If the pressure difference across the cladding is zero, one of the main forces of rain penetration is eliminated.

A rainscreen wall incorporates two layers on wythes separated by an air space or cavity. The outer layer or cladding is vented to the outside. When wind blows on the building facade, a pressure difference would be created across the cladding; however, if the cavity behind the cladding is vented to the outside, some of the wind blowing on the wall enters the cavity, causing the pressure in the cavity to increase until it equals the exterior pressure. This concept of pressure equalization presupposes that the inner wythe of the wall is airtight. This inner wythe, which includes an air barrier, must be capable of sustaining the wind loads in order for pressure equalization to occur. If there are openings in the air barrier, the pressure in the cavity will not equalize and rain penetration may occur.



A further advantage to consider is that the wind load will not be imposed on the exterior cladding. Potentially, it is possible to design the exterior cladding of a rainscreen wall to be much lighter than it has been traditionally and thus economies in construction could be realized.

The concept of pressure equalization is readily understood when steady-state conditions are considered. However, the wind is dynamic and the exterior wind pressures impinging on a building facade are in a constant state of flux. Previous research has shown that there is typically a time lag between the application of the exterior load and pressure equalization in the cavity. As a result of this time lag, a pressure difference does occur across the exterior cladding. For the rainscreen concept to be effective, this time lag should be as short as possible. Therefore, when we examine the performance of a rainscreen wall, one of the primary factors considered is the time to equalization. Another is the load distribution on the exterior cladding. The higher the load, the higher the driving force moving rain to the interior, and the longer the time to equalization, more rain is likely to penetrate.

Some rain penetration through the exterior cladding can be tolerated because the cavity should be designed to drain. However, it is still desirable to the overall function of the wall to minimize any penetration of rain. Therefore, the "ideal" rainscreen wall would equalize instantly and the exterior cladding would never experience any wind load. In reality, this is almost impossible to achieve. We therefore expect rainscreen walls to have a short equalization time and small proportion of the peak wind load on the cladding.

At first consideration, the time to equalization seems a reasonable intuitive question. The most simplest definition would be the length of time required after application of an exterior load for the cavity to attain the same pressure. However, from our research, it was found that while the pressure across the cladding may approach zero, the equalization follows exponential decay and therefore never occurs. It may be more appropriate therefore to define the time to equalization as the time it takes for the cavity to reach a certain percentage of the applied load or the difference between the applied load pulse and the response load.

1.3 FACTORS AFFECTING PRESSURE EQUALIZATION

There are a number of wall parameters that affect the rate at which pressure equalization will occur, including:

- leakage area of the air barrier system
- area of vent openings
- cavity volume
- stiffness of the air barrier system
- stiffness of the cladding
- sealing of cavity perimeter (compartmentalization)

The rate of the applied load and the magnitude of the applied load will also affect the time to equalization. Each of these factors is discussed below.

1.4 THE AIR BARRIER SYSTEM

If the air barrier is perfectly tight, when a pressure is applied to the wall, all air entering the cavity through the vented cladding will remain in the cavity to cause the pressure in the cavity to increase.

If there is leakage through the air barrier, air will move from the cavity to the interior of the building, and equalization does not occur. The ratio of the air pressure difference across the wall to the air pressure difference across the cladding will depend on the relative tightness of the cladding and the air barrier. Ideally, the air barrier should not leak, both for the rainscreen to function to its maximum level and also to prevent the exfiltration of indoor air and the infiltration of outdoor air.

1.5 AREA OF VENT OPENINGS

Pressure equalization depends partly on air movement into/out of the cavity. The rate at which air can move through the cladding depends on the area of openings through the cavity. If only one small opening exists, equalization may be slow, whereas if there are many openings, equalization will occur much faster. Research has indicated that the area of vent openings required depends on the cavity volume and the stiffness of the cladding system and the air barrier system.

1.6 CAVITY VOLUME

A larger cavity will require more air to move into or out of the cavity to cause pressure equalization. Therefore, given the same area of vent openings, a smaller cavity will equalize faster than a larger cavity. Thus, in designing a rainscreen wall, consideration must be given to the proportion of vent area in relation to cavity volume.

1.7 STIFFNESS OF THE AIR BARRIER PLANE

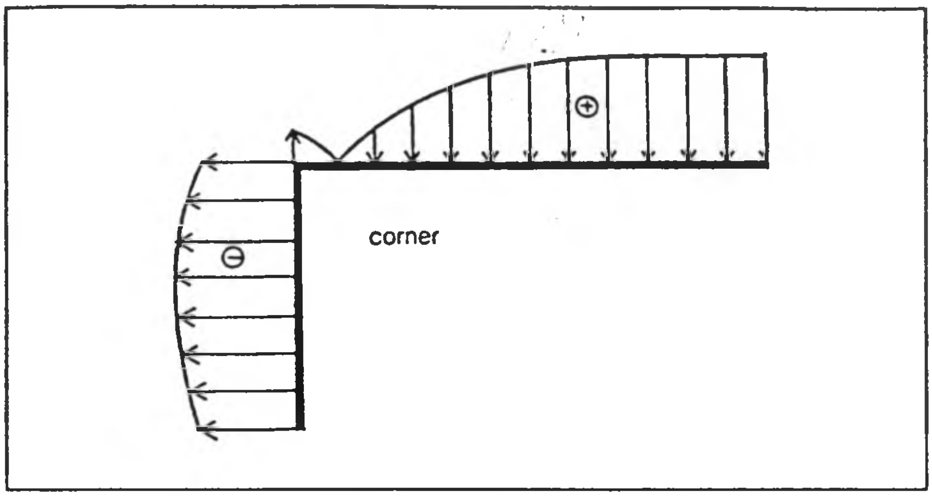
If the air barrier material is flexible and a positive pressure is applied to it, it will deflect. The result of this deflection will be an increase in the volume of the cavity and a larger volume takes longer to pressure equalize. Thus, the more flexible the air barrier, the longer it will take for the cavity pressure to reach outdoor conditions. This causes the cladding to experience dynamic loads. Therefore, in designing a rainscreen wall, the air barrier should be designed to be as rigid as possible.

1.8 STIFFNESS OF THE CLADDING

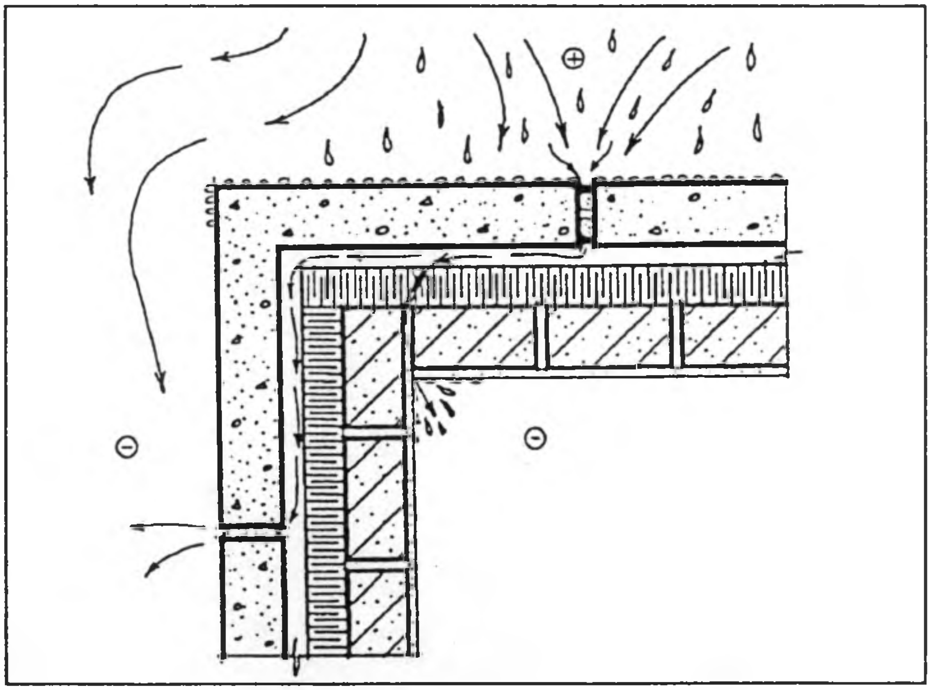
If the cladding is flexible, the cladding will deflect inwards, reducing the cavity volume, when a positive load is applied. Thus, the cavity will tend to pressure equalize faster than normal from the compression effects of the cladding deflection. But, the cladding deflection will cause the cavity pressure difference to linger longer. This characteristic of the cladding tends to dampen the gust loads on the facade. From the result of our pressure tests, it can be seen that a flexible cladding experiences a small but longer lasting air pressure difference.

1.9 COMPARTMENTALIZATION

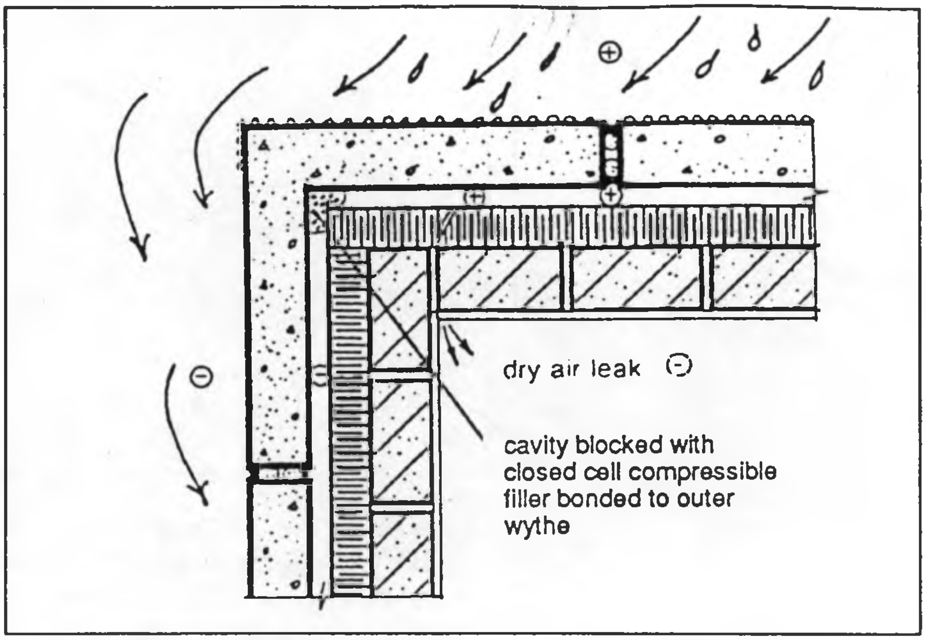
In designing a building with the rainscreen approach, consideration must be given to the pressure variations over the surface of the building. When the wind impinges on a building facade, it tends to flow around and over the top of the building producing variations in pressure on the surface of the buildings. In some areas the pressure will be negative.



If the cavity behind the cladding is continuous around the building, the pressures on the surface of the cladding may induce lateral air movement within the cavity from ingress of air at the front to exit along the sides and back. Air will move within the cavity from a region of positive pressure to the region of negative pressure at the sides of the building; as a result of this movement of air, pressure equalization will not occur within the stud cavity.



Therefore, it is important to "compartmentalize" the cavity. By Compartmentalization we mean dividing the wall cavity into smaller individual cavities through the use of strategically positioned, airtight seals. It is particularly important that these compartments do not extend around the corner of a building.



In addition it is important to note that compartment seals are not the same as baffles. Such techniques as stuffing fiberglass in a crack, or gluing rigid foam pieces that do not fit tightly is not satisfactory. A compartment seal may be an elastomeric membrane, a sheet steel angle, or foamed in urethane insulation.

1.10 WIND LOADING

Two conditions of wind must be considered with the pressure equalized wall, the steady state condition and the gust effect. While gusting presents a dynamic loading, it is the time average pressure over the surface which exhibits the most influence on rain penetration. For this reason, water penetration tests were conducted at a steady state pressure while the dynamics of gusting was examined for structural effects.

2. A SIMULATION MODEL

2.1 INTRODUCTION

To design a rainscreen wall the following physical parameters of the wall must be determined and they include; the volume of the cavity, the area of venting, the stiffness criteria of both cladding and the air barrier material and the leakage area of the air barrier system. It is also understood that the cavity volume is bound by compartment seals that must be leak proof.

To assist the designer, a simulation model can be used to determine the pressure equalization performance for the above noted features and characteristics. The simulation model developed predicts the pressure equalization behavior of a wall system in terms of structural air pressure load distribution and pressure equalization time. The simulation model was developed using the fundamental gas laws and basic equations of fluid dynamics.

2.2 DEVELOPMENT OF THE MODEL

The simulation model that follows was developed to simulate the behavior of a single cavity compartment, with one plane exhibiting cladding features and one plane exhibiting air barrier attributes. In all simulations it is assumed that the inside pressure is the reference pressure, and various loading rates and initial conditions of cavity pressure are chosen for the simulation.

Previous research has shown that the loading pattern typically exhibited by gusting wind most closely resembles a triangular pulse function. However, to simulate the behavior of the laboratory tests, the model uses an exponential equation to generate the loading on the wall. The rate at which the load is applied can be adjusted by changing the value of the exponent in the equation.

The response of the cavity pressure in a rainscreen wall is a function of the basic gas law:

$$P = \frac{nRT}{V} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (2.1)$$

where P = *absolute pressure (Pa)*
V = *volume* (m^3)
n = *no. of moles of air (moles)*
R = *gas constant (J/(mole .°K))*
T = *absolute temperature (°K)*

In the development of the simulation model, it was assumed that temperature would be constant; a value of 20 °C or 293 °K has been established as the standard condition. It was also assumed that the gas constant would not change significantly.

To understand how pressure equalization occurs, consider the situation where a positive pressure is applied to the wall surface. Pressure equalization will occur when the pressure in the cavity rises or falls to match the applied pressure. Movement of air into the cavity is one mechanism to increase the pressure in the cavity. The mass of air required to achieve equalization depends on the volume of the cavity. The rate at which equalization occurs depends on the rate at which the air can enter the cavity, which is given by the following equation:

$$Q = CA\frac{(2\Delta P)^n}{D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

where Q = *air leakage rate* (m^3/s)
C = *discharge coefficient (unitless)*
A = *total area of opening* (m^2)
ΔP = *pressure difference (Pa)*
D = *density of air* (kg/m^3)
n = *exponent (between .5 and 1)*

The rate of air flow into the cavity is constantly changing. As air flows in, the pressure difference across the cavity changes and the pressure difference across the cavity is the driving force which dictates the rate of air entering or leaving the cavity.

Another parameter that causes the pressure in the cavity to increase or decrease is related to deformation of the volume of the cavity. Depending on their rigidity (or flexibility), both the cladding and the air barrier will deflect under the applied load and will change the volume of the cavity. If the cladding deflects more than the air barrier, the cavity volume will decrease and the cavity pressure will increase without the flow of air into the cavity.

In actual situations, a combination of air movement and cavity volume change caused by deflections of the cladding and air barrier will occur. The program attempts to model these simultaneous occurrences. The resulting equation which must be solved takes the following form:

$$P_C = \frac{287 \cdot T \cdot [\, V_o \cdot d_e + (A_1 \cdot C_d \cdot T_s \cdot \sqrt{2 \cdot d_e \cdot (P_e - P_c)} - (A_2 \cdot C_d \cdot T_s \cdot \sqrt{2 \cdot d_e \cdot (P_c - P_i)}\,]}{V_o - k_1 \cdot (P_e - P_c) + k_2 \cdot (P_c - P_i)} \quad \ldots\ldots \quad (2.3)$$

where P_C = *absolute cavity pressure* (P_a)
T = *absolute temperature* (°K)
V_O = *initial cavity volume* (m^3)
d_e = *density of air* (kg/m^3)
A_1 = *area of cladding leakage* (m^2)
C_d = *discharge coefficient (unitless)*
T_s = *time interval (sec.)*
A_2 = *area of air barrier leakage* (m^2)
P_i = *interior pressure* (P_a)

k_1 = flexibility constant of cladding (m^3/Pa)
k_2 = flexibility constant of air barrier (m^3/Pa)

The resulting equation proved too unwieldy to analyze directly so it was divided into smaller segments and solved numerically through a computer program using an iterative procedure. A listing of the computer program will be found in Appendix A. The program is also available on computer diskette, with instructions for use, and will be provided by CMHC upon request.

2.3 INPUT PARAMETERS

When the program is executed, the following parameters must be input by the user:

Height of cavity (m)
Length of cavity (m)
Width of cavity (m)
Flexibility of cladding (m^3/Pa)
Flexibility of air barrier (m^3/Pa)
Vent area of cladding (m^2)
Leakage area of air barrier (m^2)

Each of these parameters is discussed below.

Height of cavity

This is the vertical dimension of the compartmentalized cavity of the wall.

Length of cavity

This is the horizontal dimension of the compartmentalized cavity of the wall.

Width of cavity

This is the width dimension of the compartmentalized cavity of the wall, i.e. the dimension of the space between the air barrier and the cladding.

Flexibility of cladding

This is the flexibility constant of the cladding. A flexibility constant equal to zero represents a rigid cladding which does not deflect under load, such as brick. The units are m^3/Pa and represent the volumetric displacement of a plane of materials subjected to a pressure difference.

Flexibility of the air barrier

This is the flexibility constant of the air barrier. A flexibility constant of 0.00005 m^3/Pa represents a very flexible material, such as 4 mil polyethylene film spanning 405 mm in a wood frame wall.

Vent area of cladding

This is the total leakage and vent area of the cladding. A typical value for an 8 ft. by 8 ft. brick wall vented at the head joints every 24 in. o.c. would be 0.0024 m^2.

Leakage area of air barrier

This is the total leakage area of the air barrier. This value should be zero or very close to zero.

There are a number of other parameters within the program. These parameters were assigned constant values and are described below:

Loading

The program was designed to simulate a wind loading pattern having an a saw tooth pulse of 1000 Pa for a total duration of 0.5 seconds from an absolute positive pressure of 100 000 Pa. Atmospheric pressure is assumed to be 100 000 Pa. The equation for the loading rate takes the following form:

$$P = 1000\, e^{-nt}$$

where $n = 5$
$t = \text{time (s)}$

Decreasing the variable n reduces the rate of change of pressure or decreases the rate of loading. A value of 5 was selected for the standard value of n because previous research indicated that this loading rate is most representative of a medium speed gust pressure change.

2.4 OUTPUT RESULTS

The output from the computer program is the following:

Column 1: Time (sec.)
Column 2: Exterior Pressure (Absolute wind pressure) (Pa)
Column 3: Cavity pressure (Pa)
Column 4: Cladding Load (Pressure difference across the cladding (Col 3 - Col 2)) (Pa)
Column 5: Air Barrier Load (Pressure difference across air barrier (Col 4 - Col 2)) (Pa)
Column 6: Cavity Volume (m^3)
Column 7: Air Mass (Mass of air in cavity) (kg)
Column 8: Vent Flow (Flow of air through cladding) (l/s)
Column 9: A.B. Leakage (Flow of air through air barrier) (l/s)

This data for the absolute wind pressure (EXTERIOR), the absolute cavity pressure (CAVITY) and the pressure difference across the cladding (CLADDING) are graphed for viewing convenience. The maximum cladding load is also indicated for convenience.

The data, for the graph, which are important to designers are the time to equalization and the peak load on the exterior cladding. These values can be obtained by scanning Column 3 of the data file. The peak load is easily discernible by scanning this column of data. It is somewhat more difficult to establish the time to equalization.

2.5 COMPARATIVE VALIDATION

To validate the simulation model, it was necessary to compare its output with the measured performance of other systems. The output results of significance are peak load air pressure difference on cladding and equalization time for a particular type and duration of wind gust. The output of the simulation model, was compared with the measured performance of a metal and glass curtain wall system. The performance of the latter was reported in a paper in the 1987 CSCE Centennial Conference Proceedings, May 19 - 22, 1987, or IRC/NRC reprint number 1547.

From the above noted publication, it was determined that the following features characterized the elements and geometry of the metal glass curtain wall tested. The volume of the cavity was 0.15 m^3, the area of leakage was 0.00023 m^2, no leakage through the back-pan, and an estimated stiffness of 0.000002 m^3/Pa for the glass spandrel and 0.000005 m^3/Pa for the back-pan. These parameters were input to our simulation model along with an exponential load exhibiting a 4000 Pa/sec decay. It will be noted from the comparison of the measured and computed results, that the results closely approximate each other. There is noted difference in the slope of decay but the peak loads and duration times are approximately the same under similar loading conditions.

Steady State Characteristics

The simulation model was developed primarily to simulate gust loading conditions. However, for steady state conditions, it was found by experiment, that the pressure distribution across the cladding (vinyl, stucco, brick) and the air barrier system (sheathing, gypsum) may be determined from the following equations.

$$CL = \frac{La^2(Pe-Pi)}{La^2 + Va^2} \qquad (2.5)$$

or

$$AL = \frac{Va^2(Pe-Pi)}{La^2 + Va^2} \qquad (2.6)$$

where CL = *cladding load (Pa)*
AL = *air barrier load (Pa)*
La = *air barrier leakage* (m^2)
Va = *vent area* (m^2)
Pe = *external absolute pressure (Pa)*
Pi = *interior absolute pressure (Pa)*

For example, if a sample wall has a .001 m^2 vent area through the brick weep holes, and it has .001 m^2 leakage area through the air barrier system, the wind load (Pe - Pi) of approximately 500 Pa would exhibit 250 Pa on the cladding and 250 Pa on the air barrier system. There would also be a flow of air corresponding to the actual size of the leakage, usually referred to as infiltration. It is to be noted that the flexibility or stiffness of the cladding or of the air barrier system is of no importance or consequence to the distribution pressures under steady state conditions, however, the deflections of the cladding components or air barrier systems under steady state loads may prove unacceptable.

Thus, the steady state pressure distribution in an exterior wall is easily determined from the known characteristics of leakage areas through the various systems in a compartmentalized wall, or can be obtained from field measurements of pressure and one other parameter, the leakage or vent area of the cladding, or the leakage of the air barrier system.

Dynamic Load Characteristics

Dynamic loads on the cladding and the resultant distribution of pressures within the wall is more difficult to predict and is the subject of our simulation model. First, to simulate a gust effect or transient load, experimental testing was conducted in a pressurized chamber by suddenly releasing the pressure by means of a special orifice valve and membrane to cause a rapid change in pressure. The rate of change of pressure of the chamber is set to fast, medium, or slow by means of various orifice sizes and membrane selection. The pressure drop/increase using this method was found to decay along an exponential curve and therefore could be analyzed and simulated.

While simulated gust pattern does not mimic wind behavior, it exhibits all the dynamics of wind effects, and for this reason was deemed suitable to validate the simulation model. Thus, the initial simulation model used an exponential load formula for this purpose. It is to be noted that the simulation now is executed using a triangular pulse load of varying amplitude and frequency. The model could also be modified to use a sinusoidal load of any frequency and amplitude.

A sensitivity analysis of the effect of the parameters is undertaken in the next section. While we believe that the model provides a good first approximation of the dynamic behavior of the cavity pressure for the noted characteristics, it should be compared with the results of other assemblies notably masonry cavity wall systems, precast sandwich wall panels, and similar structural components and elements to determine if size or scale effects exhibit a significant influence.

It is to be noted that the math model does not consider the resonance effects of the air in the chamber or the frequency response of materials in terms of possible dynamic oscillations of the mass of air or other components comprising the metal and glass curtain wall. Measurements made of the laboratory systems have indicated the cavity pressure decayed without any oscillatory behavior.

2.6 EXAMPLE SIMULATIONS

To demonstrate the use of the program and the effect of changing the input parameters, a number of example simulations were executed. First, some basic conditions were established. These would be typical of a brick veneer wall 2438 mm by 2438 mm with a 19 mm cavity and a concrete back-up wall. Both the cladding components and the air barrier system are assumed to be rigid. The value of the input parameters used in the simulation are summarized in the first line of Table 1. Then, each input parameter was varied as indicated in Table 1.

TABLE 1
INPUT PARAMETERS FOR EXAMPLE SIMULATIONS

Example	VOL m^3	PFX1 m^3/Pa	PFX2 m^3/Pa	VA1 m^2	VA2 m^2
Basic Conditions	0.1	0	0	.0001	0
Cavity Volume Increased	0.5	0	0	.0001	0
Cladding Flexibility Increased	0.1	5X10-6	0	.0001	0
Air Barrier Flexibility Increased	0.1	0	1X10-6	.0001	0
Cladding Leakage Increased	0.1	0	0	.0005	0
Air Barrier Leakage Increased	0.1	0	0	.0001	.0001

2.7 DISCUSSION

Parametric Analysis Increasing the initial volume significantly increased both the peak load on the cladding and the time to equalization. This result is expected because the larger volume requires that more air must be exhausted to attain equalization. However, the fixed vent area limits the rate at which the air can be exhausted from the cavity.

Increasing the flexibility of the cladding reduced the peak load on the cladding but increased the time to equalization. This is attributed to the elastic deformation of the cladding which cause the cavity pressure to follow the outside pressure. However, as the load diminishes, the deformed cladding will sustain a difference until it has returned to rest position.

Increasing the flexibility of the air barrier increased the peak load response on the cladding and increased the time to equalization.

Increasing the vent area (or the cladding leakage) reduced both the peak load and the time to equalization. This result was expected because more air could move out of the cavity in the same period of time.

Increasing the leakage through the air barrier decreased the peak loading and lightly increased the time to equalization. In this situation, the cavity pressure decays both outwardly and inwardly in the simulation to accelerate pressure equalization. In a pressure buildup condition, we could expect leakage through the air barrier to have the reverse effect.

The example simulations, although limited in number, demonstrate the sensitivity that model has with respect to each variable.

2.8 LIMITATIONS AND FURTHER DEVELOPMENT

Unpredictable results may be output from the simulation when the input parameters are not within realistic limits. The input parameters of leakage area and flexibility coefficient may be difficult to determine when trying to design a wall. More test data is needed to establish typical ranges for these parameters.

Further development of the model could include the following:

1) allowing user to input description of construction materials and let the computer generate the flexibility constants;
2) expand the simulation model to provide conditions using a steady state wind pressure;
3) expand user flexibility with respect to gust rate loadings;
4) develop a single number concept to define the peak load and pressure equalization; response for a rainscreen wall system;
5) expand the model to include a rain penetration index from the Climatic Data (Weather Index).
6) develop model further to predict rain penetration index for 15 min., one hour and four hour storms.