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PREFACE

The Masonry Chair in Masonry Systems is a three million dollars endowed research chair funded by the Masonry Contractors Association of Alberta–North and the Government of Alberta's Access to the Future Fund. The inaugural chair holder is Dr. Y. Korany. An integral part of the mandate of the MCAA Masonry Chair is to develop and teach academic and professional courses in the design and analysis of masonry systems and masonry building envelopes. The ongoing and planned research projects under the Chair's mandate aim to remove the unjustifiable limitations imposed on masonry construction due to inadequate information, reveal the untapped capabilities of contemporary masonry, and drive innovation in masonry design.

The northern chapter of MCAA was formed on July 23, 1965 and represents both union and non-union contractors. Its mandate is to ensure quality masonry construction, maintain strong apprenticeship programs, and promote contemporary masonry through close collaboration with the University of Alberta.

The 3rd Masonry Mini Symposium is part of the graduate level course: *Behaviour and Design of Masonry Structures* that was taught in the spring of 2011. Course participants were asked to work in groups to write technical papers on topics relevant to masonry systems. They presented their findings to a panel of professional, engineers, architects, contractors, and building officials on the evening of April 7th 2011. This year's theme was masonry building envelope systems. In this report, the reader will find a compilation of the edited manuscripts of all papers presented during this event. The report is available to the public in PDF format through the online depository, Education and Research Archive (ERA) of the University of Alberta's Library.

Y. Korany

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ABSTRACT

The Art Gallery of Alberta, in the heart of downtown Edmonton, is located on Sir Winston Churchill Square, in the centre of the civic and arts public square. The existing Art Gallery was partially demolished to make way for the major addition to the complex. Designed by Randall Stout Architects of Los Angeles, the new art gallery is an 85,000 square foot state of the art facility and a premiere presentation venue for international, Canadian and First Nations art.

The building itself is a work of art. A prominent feature of the project is the Borealis, a striking ribbon of stainless steel that winds its way around and through the building's exterior.

Consideration of the extreme seasonal temperature fluctuations from winter to summer was critical to the design of this building. In addition, the complexity of the design required 3-D modeling to capture the architect's vision for this building. This paper will discuss some of the design issues associated with the environmental challenges of building in a northern environment as well as some of the methods used by the design team to visualize and detail the Borealis and various structure and building envelope components.

The Art Gallery of Alberta (AGA)

Originally known as the Edmonton Art Gallery, this was the only major institution in Alberta solely dedicated to collecting and exhibiting art. The existing 50,000 sq. ft. (4,600 sq. m.) facility was constructed in 1969 and consisted of a two storey rectangular concrete building with an exterior cladding system that was consisted of an exposed concrete exterior wall with stud wall, batt insulation, polyethylene sheet and gypsum board on the interior. Water leakage, air leakage and thermal bridging were evident in many areas of the building, creating numerous challenges to temperature and humidity control. This limited the Gallery's ability to attract the exhibitions it needed to achieve world class status. A new facility was required.

The design of the Art Gallery of Alberta began as an architectural competition. Architects from around the world submitted their concept for the facility. In the Fall of 2005, the submission by Randall Stout Architects Inc. of Los Angeles, California was selected and the design and construction process began (Figure 1).

The new AGA is an 85,000 square foot innovative gallery that will allow for presentation of national and international exhibitions and is a premier presentation venue for international, Canadian and Aboriginal art, education and scholarship. The $88 million gallery in itself is a work of art that will complement and complete the cultural precinct surrounding Churchill Square and solidify Alberta's Capital as a world-class city.

The Vision

The northern plains of Alberta and the Rocky Mountains and the curved North Saskatchewan River that flows through the heart of Edmonton were all inspirations used by the architect to develop the design. A free-flowing metal sculpture called the "Borealis" is a prominent feature of the building exterior and was inspired by the Aurora Borealis. The Borealis is a steel ribbon that floats around and through the building's main atrium space (Figure 2). In the architect's words:

> *"Transparent glazing planes and reflective metal surfaces animate the building, exposing the activities within and engaging people and art at multiple levels on both the interior and exterior. Selected to reflect Edmonton's dramatic weather patterns and the extreme contrast of the long days of summer and the short days of winter, these materials create a dynamic quality that allow the building to transform along with its natural surroundings. Not only does the building change throughout the day, it changes from season to season. More static building materials would not allow for this type of ephemeral connection between the building and the site. Crafted of patinaed zinc (mined and manufactured in Canada), stainless steel, and glazing, the building will have a timeless appearance and extraordinary durability in the northern climate."*

Figure 1: The Art Gallery of Alberta

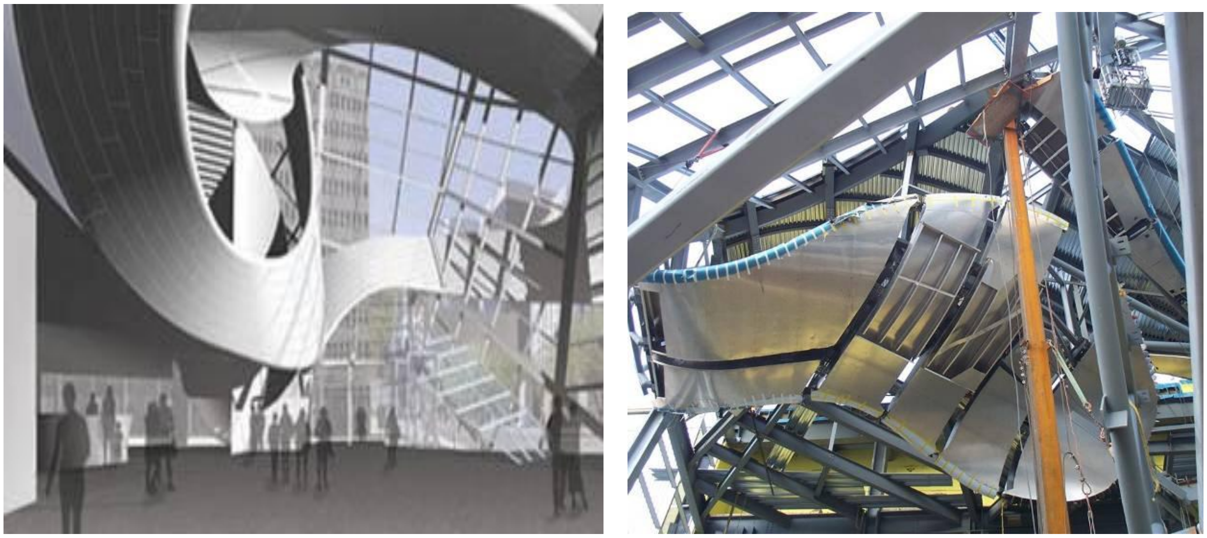

Figure 2: Interior image of Borealis (rendering (l) and under construction (r))

The Focus

The flowing form of the Borealis created challenges to the design and construction of the building. Our extreme seasonal temperature variations and exposure to snow and ice also complicated the design. The focus of this paper is to review the issues relating to the design of this unique and complex building and to discuss the assemblies used to enable it to perform in our northern climate.

By using established methods of envelope design, integration of the design and construction teams and some imagination, good building envelope solutions can be developed without compromising the architectural vision for the project,

The Design Process:

There were many challenges that were faced by the design team. Part of the design submission by RSA included salvaging portions of the existing concrete structure. This created a number of difficulties with as-built conditions and construction. Also, the mechanical systems were critical to ensure that the temperature and humidity controls in the gallery spaces were maintained. However, the focus of this paper is to examine the issues relating to the building envelope and primarily the Borealis.

Designing an envelope that accommodated the visual impact of the building, with its flowing curves and ribbon, while still achieving superior performance posed several challenges. These included:

- Complexity of the Design.
- Cold Weather Issues.
- Curtainwall Design.

Complexity of the Design:

Unlike traditional buildings, where rectangular three-dimensional buildings could easily be described using two-dimensional drawings to reflect plans and elevations, the complexity of this curved design required 3-D modeling (Revit, Rhinocerus, Catia and Tekla) to capture the vision of the architect. Without the use of computer modeling, the detailing of this facility would have been extremely difficult and likely riddled with conflicts between the various disciplines. All building design disciplines (architectural, structural, mechanical and electrical) as well as the cladding contractor and the structural steel fabricator worked to develop the 3-D models. Many of the team members had worked together on similar projects, therefore the learning curve was not significant.

The models generated during the design were invaluable in aiding with the visualization of the project (Figures 3 and 4). Computer modeling provided a tool that enabled the design and construction team to examine the various elements. Conflicts were located early in the design stage. Structural members, mechanical and electrical systems and cladding elements were overlaid and the model easily rotated to examine the building from virtually any angle. It was not uncommon to find a steel member that would protrude through the metal skin around the Borealis or to find areas where mechanical ducting would cut through the entire depth of a steel beam.

The geometry of the design was modeled into the programs and was directly transferred to the various steel trades for developing shop drawings and fabricating the members. Over 800 tonnes of structural steel were used on the project. Over 5,000 of these pieces were custom made and if the steel components were laid end to end would be over 12 km long. The computer models were of great benefit in the development of the shop drawings and fabrication of the steel. Similarly, the interaction between the highly variable shape of the Borealis with the curtainwall sections were also clarified by the models and allowed for the curtainwall trades to develop their shop drawings and fabricate their building components.

The integration of design and construction was started early in the project. A construction manager was retained and subtrades were engaged early in the design process to work with the design team. The building envelope consultant was also retained at the start of the design to provide input to the team. The interaction between the various groups was very important in the development of the project as potential difficulties with construction could be identified early in the process and incorporated into the design.

Since the designers and various trades were located in various parts of Canada and the United States, regular communication was achieved using Webex. This program allowed for the simultaneous viewing of drawings over the internet (Figure 5). Design issues could be reviewed and resolved over this virtual conference room, without the need for regular travel across the country.

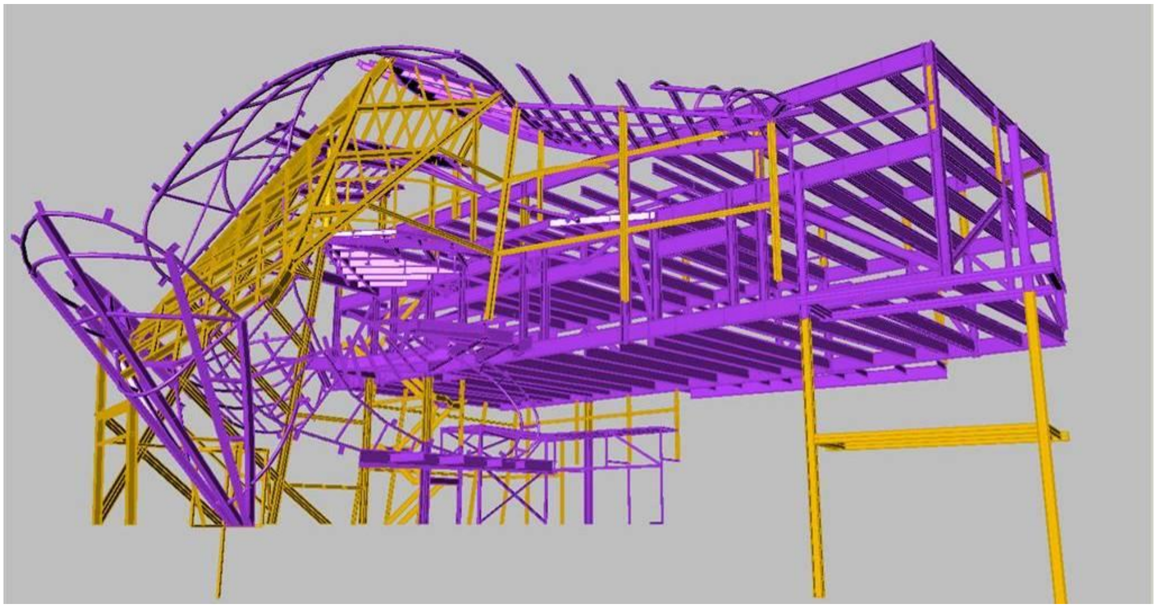

Figure 3: Model of steel framework.

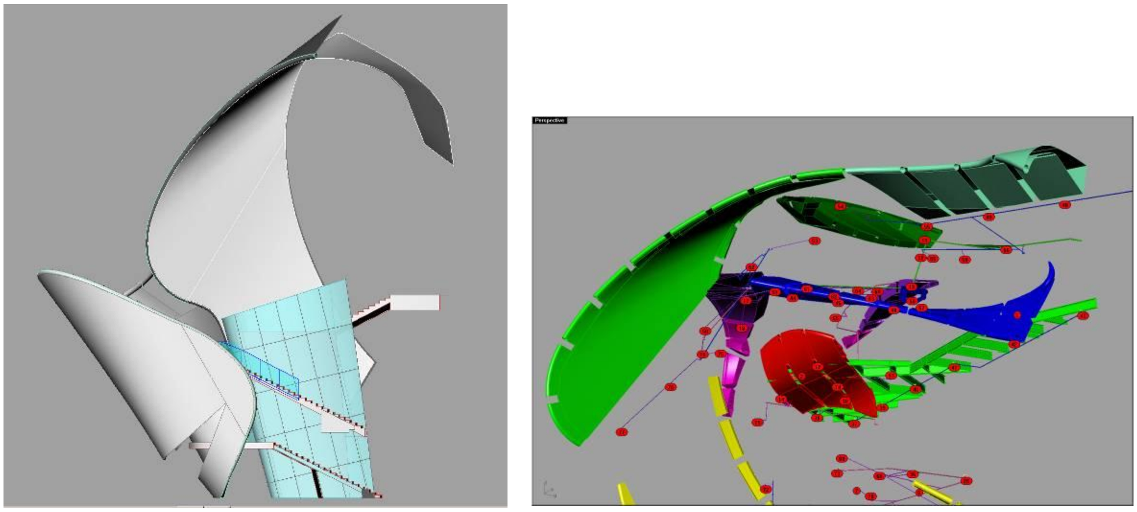

Figure 4: Views of Borealis and various components.

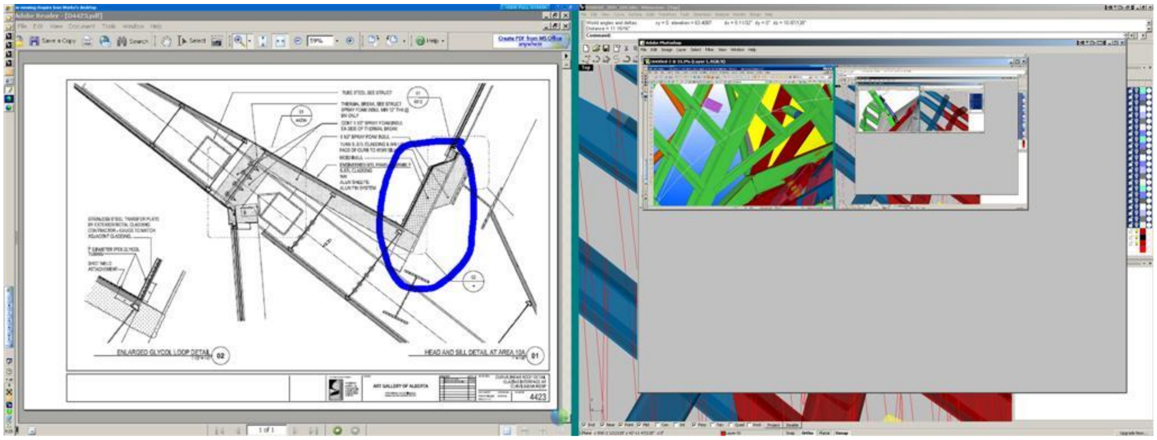

Figure 5: Typical view of screen during web conferences.

Cold Weather Issues:

Cold weather concerns over building envelopes, while a critical factor in modern building design, did not limit the architectural impact of the structure. Consideration of the extreme seasonal temperature fluctuations from winter to summer was critical to the design of this building. The environmental challenges of building in a northern environment included:

- Snow and ice.
- Thermal bridging and condensation concerns.
- Curtainwall details.
- Temperature effects on construction.

Snow and Ice:

The unique shapes of the exterior portion of the Borealis lead to concerns with the accumulation of snow and ice on the members (Figure 6). As the Borealis is located over the main entrance to the building, it was crucial that water, snow and ice not be allowed to fall onto the entrance space below.

Figure 6: Snow accumulation on Borealis during construction.

The Borealis forms a continuous ribbon flowing from the exterior through the curtainwall to the interior of the building. However, there is a small gap provided between the curtainwall and Borealis framing. This gap reduces the potential for water load on the curtainwall at these joints. In areas where the Borealis slopes towards the curtainwall, in addition to the gap, as noted above, gutters are also provided along the edge of the Borealis to collect and drain water.

Computer modeling was used to determine snow patterns on the Borealis. Based on the model, areas of snow accumulation were identified and a snow melt system incorporated into critical areas to reduce the risk of snow and ice collection on the steel surfaces (Figure 7). Heated gutters were provided in low spots to collect and direct water flow to the south-east, where the Borealis incorporates a snow chute into the design. The snow and water is drained to an internal sump and storm system located in the basement of the building. A glycol system (rather than electric) was selected as this would provide a more energy efficient system. Moisture and temperature sensors are incorporated into the design to provide the required control of heat to the assembly.

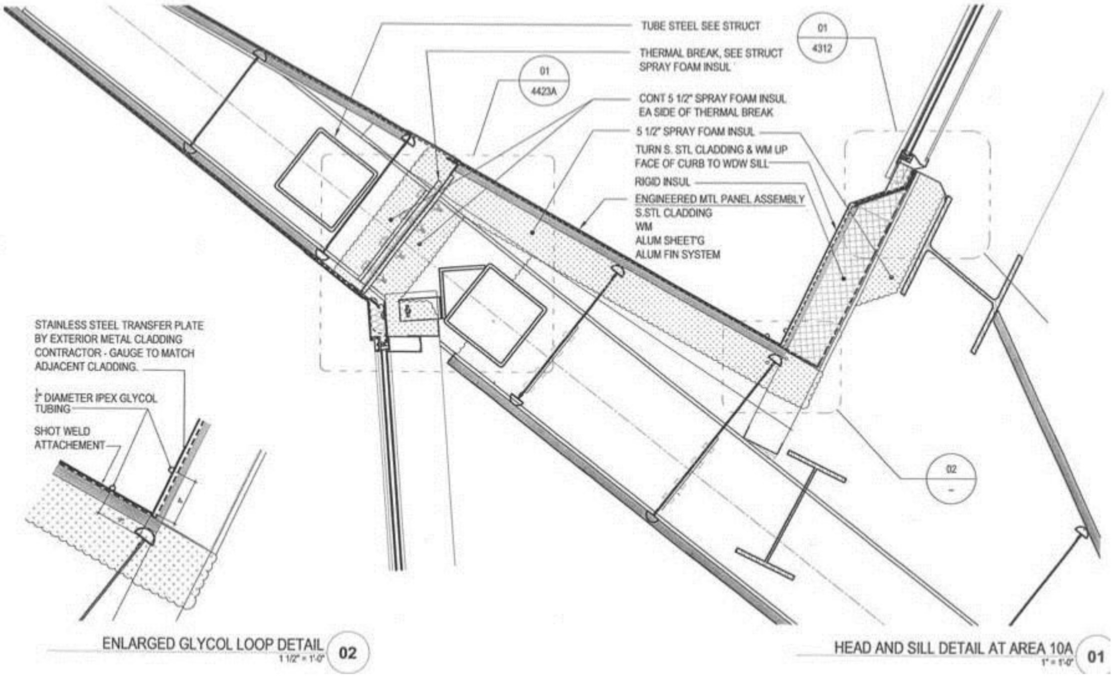

Figure 7: Details at snow melt gutter. Note thermal break detail.

The Borealis is cantilevered from the building and is formed using strips of stainless steel wrapped around prefabricated metal panels that span between the structural steel support members (Figure 8). The Borealis is not critical to the performance of the building envelope (with regard to the interior environment of the building) however, there was concern that water could penetrate the framing of the Borealis, resulting in accumulation of moisture inside the panels. Although drainage paths were provided to allow water inside the panels to exit, should water enter the Borealis cavity, this water could freeze in colder temperatures, resulting in the risk of overloading the members and/or the formation of icicles over the main entrances to the building. In order to reduce the risk of water penetration, the panels will be waterproofed prior to application of the finished steel cladding. The self-adhering sheet membrane will be sandwiched tightly between the metal liner and the exterior stainless steel cladding as the construction method of the metal skins did not permit a vented drainage plane.

Figure 8 Prefabricated Borealis panel prior to installation on building.

Thermal Bridging and Condensation Concerns:

One of Alberta's threats to building envelopes is its severe cold temperature. Leakage of warm, moist air from the interior into the cold exterior wall cavity can result in condensation within the building's exterior walls. This condensation builds up in the form of ice. Once warmer conditions occur, the ice melts, causing damage to interior finishes, and leaving stains, mould and eventually rot or corrosion. Remedial repairs can be costly. Also, the risk of damage to the artwork itself can not be tolerated.

The design of the building exterior cladding system utilized PERSIST (pressure equalized rainscreen insulated structure technique). The typical wall assembly is as follows (Figure 9):

- Zinc cladding on the exterior
- Metal backer (to support the zinc panels)
- Z-girts
- Semi-rigid insulation
- Air barrier/vapour retarder/waterproof membrane
- Interior back-up wall (concrete, block or metal stud wall).

A drainage cavity is provided behind the cladding to allow for any water that might penetrate the exterior cladding to flow down the wall and drain to the exterior.

This design allows for the air and water barrier to be continuously applied to the exterior of the building. The insulation will also be applied continuously, interrupted only at the locations of the Z-grits. With the escalating cost to heat or cool buildings, the improved performance of the building envelope through increased thermal resistance and reduced leakage is anticipated to result in long term energy savings to the owners. The exterior insulation also creates a warm structure that should exhibit reduced thermal movement during its life.

However, the cantilevered design of the Borealis creates areas where the structural steel framing pierces the building envelope (Figure 10). This creates thermal bridges where the steel passes from a warm conditioned space to the exterior of the building. In cold weather, this can cause the interior steel temperature to drop, increasing the risk of condensation on the interior spaces. As it was not reasonable to support the Borealis totally from the exterior, two measures were taken to reduce the thermal bridges.

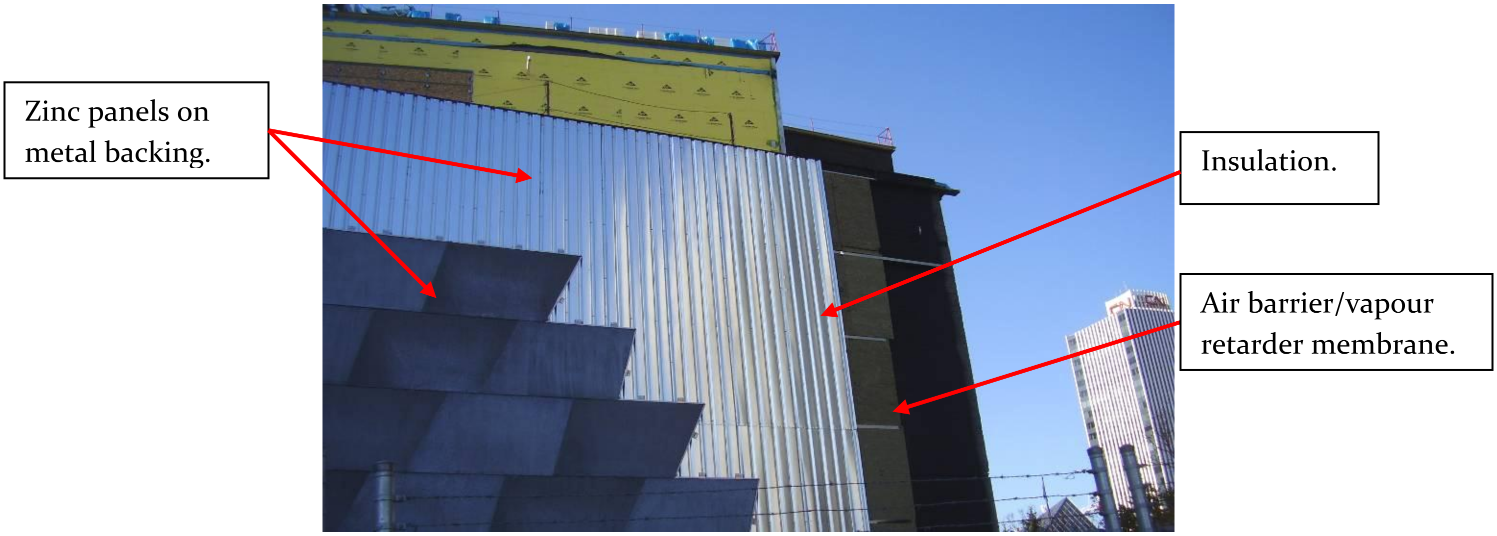

Figure 9: Wall assembly under construction.

Figure 10: Structural steel framing for Borealis.

Firstly, a thermal break was introduced in the structural steel members at the locations where they penetrate the building envelope. This thermal break was created by placing a piece of material with low thermal conductivity between the two pieces of steel. This material would have sufficient structural strength to withstand the superimposed loads and would need to be durable enough to withstand the environment to which it would be exposed. For this project, an oak spacer was provided (Figure 11). The oak was tested by the University of Alberta engineering department to determine its adequacy under load. Although the wood is not directly exposed to the elements, it was also protected with a liquid applied sealer to provide resistance to exposure to moisture.

Secondly, since there were still small thermal bridges created by the bolts used to fasten the sections together, there was a small risk that condensation could still form on the interior surfaces of the steel. To reduce this risk, the interior section of steel was sprayed with an air barrier, vapour retarder insulating foam for the first 400 mm to 600 mm of section adjacent to the exterior wall (Figure 12). The intent of the foam was to prevent the cooler steel in this area from coming in contact with the warm, humid interior air, thereby reducing the risk of condensation forming on the steel. A fire retardant coating will be applied to the foam to address fire code concerns.

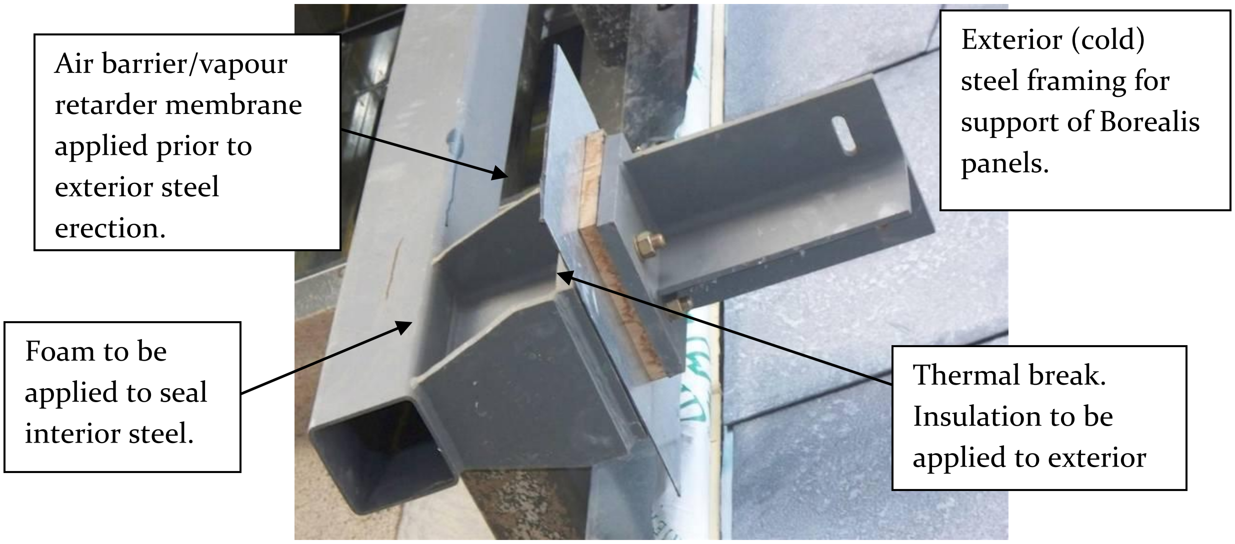

Figure 11: Oak thermal break at cantilevered Borealis supports.

Figure 12: Foam applied to exterior steel prior to panel erection.

Curtainwall Details:

A pressure-equalized, thermally broken, drained curtainwall system was used on all areas of the project. The glass was installed from the exterior and the exterior wall membranes were easily tied into the aluminum frames to provide continuity of the air barrier/vapour retarder.

The curtainwall system was sloped in many areas and to various degrees. In order to maintain adequate drainage of the system, custom aluminum extrusions were used. These extrusions were designed to keep the screw spline on the horizontal members flat and level at all times (rather than perpendicular to the frame section). By keeping the horizontal splines flat, drainage of the system to the exterior was maintained.

In areas where the glazing was sloped greater than 25 degrees from the vertical, a sloped glazing system was used. This incorporated horizontal condensation gutters on the interior and all horizontals were placed to direct water towards the vertical mullions where they would drain at the base of the verticals.

Temperature effects on construction:

Workmanship, detailing and product selection all play a role in how effective the design is. When building during winter, many of the products are moisture or temperature sensitive. Craftsmen must be aware of their product's limitations (such as applying caulking materials at the appropriate temperatures). Cold weather construction often requires enclosing the work space and heating the area to allow materials to properly cure. This can add cost to the project and extend the construction schedule. It is also important that consideration be given to using materials that can be applied and perform well in the extreme temperatures that occur from summer to winter months. With proper design, detailing and product selection, buildings can perform effectively under adverse weather conditions.

The construction schedule relied on much of the air barrier work being performed in the Summer and Fall of 2008, prior to the arrival of the cold winter temperatures. Also, the building utilized a significant portion of the concrete walls from the original building. These existing walls were cast with a rough plank formwork to create the finish desired at that time. This existing finished surface was very rough and would not accept a sheet membrane without considerable effort to smooth out the rough concrete. In order to accelerate the application of the air barrier/vapour retardant membrane and accommodate the existing rough surfaces of the concrete, a spray applied membrane was used (Figure 13).

The AGA was one of the first major applications in western Canada for this product and the membrane provided a continuous air barrier/vapour retardant membrane over the various wall assemblies. Joints and transitions were detailed using compatible sealants and self-adhering membranes prior to the application of the spray membrane. The overall finished thickness of the coating was 1 mm and the spray application enabled the contractor to apply a continuous coating over the entire wall surface. The bond between the membrane and substrate was excellent and the ease of application enabled the contractor to seal large areas of the project in a short period of time. Also, the membrane was not as sensitive to workmanship or surface preparation as there were no primers required and blisters or "fish-mouths" that are often seen on sheet membrane applications were generally not evident in the areas of the spray applied coatings. Digital thickness gauges and wet film gauges were used to regularly monitor the thickness of the coating.

Visual inspection was also performed to examine the uniformity and coverage of the coating. The membrane could also easily be repaired or additional material added as required.

Figure 13: Application of sprayed membrane.

CONCLUSIONS

The new Art Gallery of Alberta is a unique building, unlike any other in Edmonton. The complexity of the architectural design posed several challenges to the building envelope. However, by retaining the building envelope consultant at the start of the project, maintaining good design principles and engaging the construction manager and the various trades early in the process, effective details were developed and the building envelope for this facility. Regular inspection of the work also helps to reduce workmanship related problems during construction and contribute to the long-term performance of the building.

The building was open to the public in 2010.

ACKNOWLEDGEMENTS

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Design Principles of Building Envelopes

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Submitted: 13 April 2011

ABSTRACT

Masonry building envelope design is a complex and comprehensive process which is guided by the National Building Code of Canada (NBC). This paper provides a brief introduction of masonry building envelopes with an emphasis on the NBC code requirements, design principles and construction details. These principles include: heat transfer, air leakage, vapor diffusion, precipitation and sound transmission. Finally, a related design example and a case study will be provided.

Keywords: masonry, building envelope, design, construction, code.

INTRODUCTION

Masonry building envelope is one of the most conventional types of building envelopes in history and it still plays a vital and significant role in the modern building industry. There is no doubt that masonry building envelopes have numerous advantages: long life span, exceptional fire protection performance, relatively low maintenance costs and aesthetically pleasing appearance. Building envelope design is an important aspect of modern building design and it is a comprehensive and complex work for designers. It is essential that architects work in close collaboration with engineers on building projects in order to accomplish excellent designs of building enclosures, which are able to provide occupants with structural integrity, comfortable interior environment and energy efficiency.

The main objective of this paper is to present informative and instructive study on the whole process of masonry building envelope design which covers NBC requirements, design principles and construction details. Moreover, in an effort to provide further explanation regarding the above study, a case study and a design example are provided. However, only non-structural performance of masonry building envelopes is discussed in this paper, although the structural performance is equally important to the overall performance.

NATIONAL BUILDING CODE REQUIREMENTS

The National Building Code of Canada, developed by the Canadian Commission on Building and Fire Codes, is one of the model codes for regulating all aspects of design and construction of new buildings and major renovations in Canada. With regard to building envelope design, the related technical requirements are located in Part 3 (Fire Safety), Part 5 (Environmental Separation) and Part 9 (Housing and Small Buildings). The NBC requires that the building envelope shall possess plenty of capacity and integrity for resisting deterioration and loads, which are not only structural loads in nature, but also environmental loads such as rain water penetration and the flow of air, moisture, and noise.

Heat Transfer

The National Building Code of Canada requires that "the components or assembly of building envelopes shall include materials to resist heat transfer or a means to dissipate transferred heat in order to prevent adverse effects to the health and safety of occupants, the intended use of the building and operation of building services". NBC also stipulates that "the surface condensation on the warm side of building envelope, inside the wall assembly and at the locations of thermal bridges shall be minimized; and the convective airflow is required to be prevented by sufficient inherent resistance".

Heat transfer is a natural phenomenon in which heat energy moves through components of the building envelope from the outside to the inside during hot seasons and vice-versa during cold seasons owing to temperature differential between the two environments. There are three modes in the heat transfer process: conduction, convection and radiation (ASHRAE Handbook 2005).

Each material has its own specific thermal resistance (R-value). It is very important to choose appropriate material and wall assembly with relatively high thermal resistance R- value and create an optimal combination of multi-layer elements with various thermal resistances in order to prevent energy loss and reduce energy consumption.

Another purpose of choosing material with sufficient thermal resistance is to prevent substantial temperature drop which leads to condensation on interior surface of the wall. There is no doubt that the air inside an occupied building always contains moisture which comes from the occupant's activities: laundering, bathing, cooking, plants and humidifier, etc. The higher temperature can allow air to hold more water vapour. While the temperature of interior face drops below dew point, condensation will occur in the interior face of the building envelope. Thus, thermal resistance of building envelopes should also be determined based on the condensation requirement.

Another way to prevent condensation is to lower the relative humidity and the saturation temperature in order to maintain interior temperature above the dew point temperature and avoid condensation occurring.

Air Leakage

The National Building code of Canada requires that "an air barrier system in the building envelope shall be installed to provide the principle resistance to air leakage". With regard to selecting material, NBC requires that "materials intended to provide the principal resistance to air leakage shall have an air leakage characteristic (air permeability) not greater than 0.02 L/ (s-m^2) measured at an air pressure difference of 75 Pa". The air permeability is the property of material that measures the ability and rate of air flow through it. A material with high air permeability shall not be selected as the principle air leakage resistance through the building envelope. Table 1 shows the air leakage rate of some common used materials.

Table 1—Measured Air Leakage for Selected Building Materials (Source: Lux and Brown, 1986)

Material	**Average Leakage at a ΔP=75 Pa (L/s-m^2)**
0.15 mm (6 mil) Polyethylene	No measurable leakage
25 mm expanded polystyrene	4.7
12 mm fiberboard sheathing	1.6
Breather type building membranes	0.011 – 3.6
Closed cell foam insulation	0.001
Uncoated brick wall	1.6
Uncoated concrete block	2.1

As for the complete air barrier system, appendix A of division B of NBC lists the recommended air leakage rate for the air barrier system of building envelope given in Table 2.

Table 2—Recommended Maximum Air Leakage Rates (NBC, 2005)

Relative Humidity at 21°C Warm Side	Recommended Maximum System Air Leakage Rate L/(s-m^2) at 75 Pa
<27%	0.15
27 to 55%	0.10
>55%	0.05

In addition to the air permeability rate for the air barrier system, NBC also requires "the air barrier system shall be continuous across construction, control and expansion joints, across junctions between different building assemblies and around the penetrations through the building assembly". Furthermore, the structural design of the air barrier system is strictly required by the NBC to be carried out and comply with the corresponding clauses of structural design. The loads acting on the air barrier system are wind loads and air pressure due to stack effect and HVAC fan running. The air barrier system is required to withstand the above loads and be able to transfer them to the building structure without producing excessive displacement and cracking damage.

Air leakage of buildings is caused by the differential air pressure on the two sides of the building envelope; the pressurized air from one side flows through certain air leakage paths. The air leakage in building envelopes can generate substantial problems for the building performance. The air infiltration brings polluted air and dust into living space inside, which imposes a health hazard to the occupants. The air leakage running through wall assembly also generates condensation problem inside the building envelope and potentially increases the likelihood of material deterioration.

Quirouette pointed out that "moisture-laden air passing through an insulated cavity with a vapour barrier may deposit much more moisture than would diffuse through the vapour barrier in the same period of time" (Quirouette, 1985). In addition, there is no doubt that air leakage significantly increases energy consumption due to excessive heating and cooling system burden induced by air exfiltration during winter and infiltration during summer. The increased energy consumption and green house gas emission will impose a negative impact on the environmental and global climate change.

The air barrier system construction can greatly reduce the energy consumption. According to the report (Emmerich et al., 2005) from the National Institute of Standard and Technology, "predicted potential annual heating and energy cost savings ranged from 2% to 36% with the largest savings occurring the heating-dominated climates and the smallest savings occurring in the cooling-dominated climates" (Emmerich et al., 2005).

Air leakage control is one of the important factors which adversely affect the overall performance of building envelopes; nevertheless, Appendix A of NBC also points out that "incidental condensation is not of a concern as long as it is sufficiently rare and in sufficiently limited quantities and dry rapidly enough".

Vapour Diffusion

In addition to air leakage, the vapour diffusion is another process of transferring moisture through a building envelope. Vapour diffusion transports water vapour uniformly through building envelopes due to temperature difference and vapour pressure difference in the air on both sides of the wall. Excessive moisture accumulation in the envelope causes the wall components to deteriorate and increases the possibility of biological growth inside the wall. These effects impose a health hazard on the occupants and may result in potential structural failures of building envelopes. The NBC requires that "a vapour barrier shall be installed to provide the principal resistance to water vapour diffusion"; the appropriate selection of material and proper assembly design are required for controlling vapour diffusion and permitting venting. The material property of measuring the performance of resisting moisture migrating is "water vapour permeance" which is expressed as "the weight of moisture that will diffuse through a given area and thickness of material, over a specified period of time at a unit vapour pressure difference" (Quirouette, 1985). The NBC requires "the vapour barrier shall have sufficiently low permeance and shall be positioned properly in order to minimize and reduce moisture migrating". In practice, "the maximum allowable rates of 15 $ng/s/m^2.Pa$ and 60 $ng/s/m^2.Pa$ are the accepted water vapour permeance standards for type I and type II vapour barrier after aging, respectively"(CAN/CGSB-51.33-M89). In addition to the material property, the water vapour transfer rate also depends on the difference of temperature and vapour pressure on the two sides of the building envelope.

The vapour barrier should be installed on the high vapour pressure side where the temperature is still above the dew-point temperature so that the vapour barrier can block the passage of water vapour transmission into wall assembly and prevent condensation occurring. In Canada, due to its short summer and long winter, the high vapour pressure side is on the interior side during most of a year. Contrary to air barrier, "a vapour barrier needs not be perfectly continuous. Unsealed laps, pin holes and minor cuts, etc., do not increase the overall moisture diffusion rate into a wall or a roof cavity appreciably" (Quirouette, 1985). This is another major difference between a vapour barrier and an air barrier.

Precipitation

Among all the forms of precipitation including rain, snow, hail, and drizzle, etc, it is widely accepted that rain water creates the most serious moisture problem in building envelopes, especially when intense rainfall occurs during hot seasons. Moisture inside a building envelope can generate condensation problems, increase the possibility of fungal growth, and potentially lead to structural failure. Thus, rainwater penetration resistance design is an extremely important aspect of building envelope design.

The National Building Code of Canada stipulates that "a building component or assembly shall minimize ingress of precipitation into the envelope and shall prevent ingress of precipitation into interior space". With regard to the installation of protective material, NBC specifically requires that masonry wall installation shall conform to the requirements of CSA A371 "Masonry Construction for Building". Sealing for joints and junctions exposed to rain water is also required by NBC in order to prevent ingress of precipitation. There is no doubt that rain water ingress can not be completely prevented. Therefore, the methods to drain interior water inside the wall should be provided.

To prevent rainwater penetrating into the wall assembly, blocking the passage of rain water running through the material is the most effective protection from rain water damage. Firstly, cracking should be prevented by performing proper design and construction; for example, install and position movement joints properly, provide bond beam and minimize foundation differential settlement, etc. Secondly, masonry walls shall be constructed to provide sealed joints: mortar needs to be applied densely to head and bed joints; mortar shall be tooled instead of being raked. There are a few exterior wall systems which possess different features to resist rain water penetration, such as, barrier wall systems, drainage wall systems, and rain screen wall systems.

As for the concrete block unit, “the same precautions that make concrete strong and crack resistant also make it watertight” (Beall and Jaffe, 2003), these precautions include: “low water to cement ratio, good cement proportions, entrained air 6% plus or minus 1%, non-porous aggregate, avoiding segregation during placement and good curing (7 to 14 days or longer)” (Beall and Jaffe, 2003).

Sound Transmission

Normal sound is one of the most important means for communication between human and surrounding objectives; but excessive sound (noise) is an annoying disturbance. It is commonly believed that noise with high intensity and long duration can injure human ears and generate physical damages to humans. With regard to sound transmission, NBC stipulates that sound transmission class ratings shall be determined in accordance with “ASTM E 413” (Classification for Rating Sound Insulation), but this standard is not appropriate for building envelope design. Clause 4.1 in ASTM E 413 points out that “a single – number sound transmission rating for building facade elements is given in Classification E 1332”. Therefore, sound transmission class ratings for building envelope design shall be determined in accordance with “ASTM E 1332”. NBC provides an information table A-9.10.3.1.A. which presents the sound transmission class ratings of some widely used building assemblies for design considerations.

NBC requires that the building envelope enclosing dwelling units shall have a sound transmission class rating not less than 50; it should be noted that A-9.11.1.1. (1) in NBC emphasizes that the specified STC rating of 50 is just the minimum acceptable value. More practical value widely accepted by builders is STC 55 or even more if better living comfort is desired according to NBC. NBC recommends using STC 55 or more to account for the condition differences between construction site condition and laboratory condition.

DESIGN PRINCIPLES OF MASONRY BUILDING ENVELOPE

Heat Transfer

The heat flow through a building construction depends on the temperature difference, the conductivity and the thickness of the materials. The temperature difference is an external objective factor. The thickness and the conductivity of the wall system can be decided by the designers to meet the requirements on controlling heat transfer.

The basic equation for governing the rate of heat transfer through one square meter of a material under one-dimensional steady-state condition is (Hatzinikolas, K. and Korany, Y. 2005)

$$q = \frac{1}{R_t}(t_i - t_0) \qquad [1]$$

where, q = Rate of heat flow (W)

R_t =Total thermal resistance of wall ($m^2.^{o}C/W$)

t_i =Indoor air temperature (^{o}C)

t_0 =Outdoor design air temperature (^{o}C)

The above equation accounts for the one-dimension wall component. For a series of parallel components, the total thermal resistance can be expressed by superposing each thermal resistance. Using the above equation, calculation can be done to evaluate the effectiveness of thermal resistance of a wall system.

Numerical Modeling Method

In fact, the rate of heat flow always interacts with air leakage and moisture ingress. The numerical simulation has been developed to model a more complicated condition to indicate the effective thermal resistance of a wall system. Computational Fluid Dynamics (CFD) is a numerical simulation tool that can analyze heat flow problems. CFD can simulate the interaction of air and liquid with surfaces defined by boundary conditions. The thermal behavior of a ventilated cavity wall is shown in Figure 1 (Rodrigues and Aelenei, 2009).

The physical model consists of a double-wall with an internal air space with width b and height H, which can be ventilated through openings located at the extremities. The system separates the environments at different temperatures and the openings face the cooler environment.

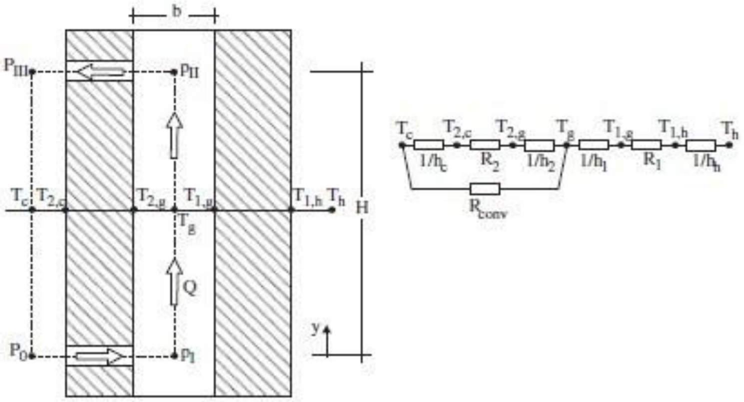

Figure 1—Physical system network (Rodrigues and Aelenei, 2009)

In a theoretical analysis, heat flow simulation follows fluid mechanics principles and the equation from the generalized Bernoulli theory.

The above approach; the CFD approach, provides integral information of the thermal performance of the system in terms of the dimensionless heat flow from the hotter medium to the cooler one (Rodrigues and Aelenei, 2009).

Air Leakage

Air leakage through a building envelope depends on air pressure difference across the building envelope and on the air tightness of the building envelope. The principal reasons that result in air pressure differentials are: wind pressure, mechanical equipment and stack action.

Causes for Pressure Differential in Walls

Wind pressure always interacts with stack action and indoor operation of mechanical equipment (Hatzinikolas, M. and Korany, Y., 2005). However, the extent of how the indoor equipment influences the air flow rate is affected by outdoor environment, such as wind velocity.

Total air infiltration increases with the rising of the wind speed (Khoukhi et al., 2007). The effect of the wind speed on the pressure difference between the stairwell and outside is insignificant for a small value of the wind speed velocity. At high wind speed, the effect is very strong and the pressure difference curves are not linear in shape. Figure 2 shows the research result.

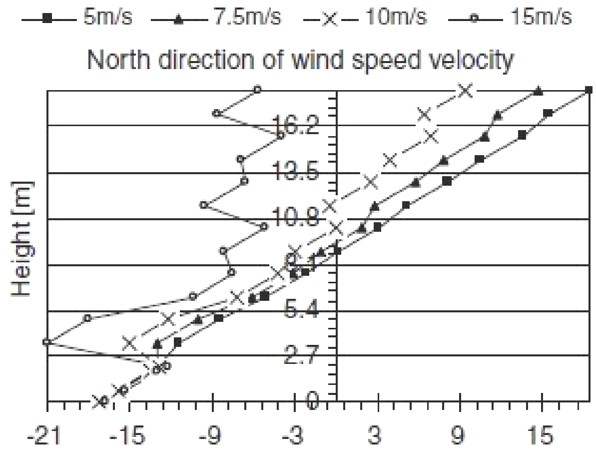

Figure 2—Pressure difference caused by stack effect (Khoukhi et al., 2007)

During a design process, hand calculation is difficult to evaluate the integrated performance. However, software is available to consider the different factors and evaluate the whole system in order for a designer to adjust the design parameters. Hot2000 can provide the evaluation of the integrated performance.

Vapour Diffusion

The effectiveness of a wall assembly in resisting vapour diffusion is defined as its vapour resistance, which is the sum of the individual vapour resistance of its components. The basic equation for governing the rate of vapour diffusion through one square meter of wall under one-dimension is similar with the heat transfer calculation. In vapour diffusion calculation, the air temperature difference and thermal resistance are replaced by vapour pressure difference and vapour resistance respectively.

The basic equations for the design of building envelopes eliminate many of the problems associated with vapour diffusion. However, these equations ignore the amount of moisture that might be absorbed by the wall components. WUFI-ORNL/IBP developed by IBP and ORNL allows realistic calculation of the transient hygrothermal behaviour of multi-layer building components.

Precipitation

One of the most effective methods of protecting a building from rain is the application of a rainscreen, which consists of three elements: an exterior cladding, an interior structure backing and an intervening cavity.

The design is generally based on an assessment of the worst-case scenario for the intensity of rainfall on the site. In addition, to control rain penetration, the principles of a rainscreen must be present in all aspects of the wall system design.

Condensation

Condensation, which results from vapour diffusion and air leakage, is related to air pressure, temperature and humidity. In practice, there are three types of condensation problems on masonry wall systems: condensation on wallboard during warm weather, condensation on gypsum sheathing or within masonry veneer and condensation due to thermal bridge effect during cold weather (Krogstad et al., 2010). The amount and location of condensation are influenced by thermal properties, air tightness and the environment of the whole building envelope. Many studies have been done about the integrated performance of the building envelope through numerical simulation, laboratory experiment and field tests. Hens (2007) indicates that “a healthy mix between modeling, experiment, and field experience in combined heat, air, and moisture work is needed”.

Sound Transmission

The whole STC for a building is affected by various aspects. The IBANA-Calc software is available to calculate the combined acoustic performances of various building envelope components. The IBANA-Calc software is developed by the acoustics laboratory of the Institute at the National Research Council of Canada.

The Process of Building Envelope Design

Building envelope design is a decision-making process to select the appropriate materials and assembly details. To make sure the requirements are met, the design of building envelopes should account for different environments and follow the basic designing process.

As indicated by a research program “the general processes with computer assistance are design context, generation of design alternation, evaluation of design alternation and implementation details” (Fazio et al., 1989). The software tools for evaluating the total performance are available, such as HOT2000. This software is an energy simulation modeling package developed by the Natural Resources Canada. It is used to calculate the heat losses, gains, and estimates the energy consumption (HOT2000 Procedures Manual, 2010).

The major step during the design process is to decide the design on parameters. The parameters are divided into two groups: parameters related to the external environment, and design parameters related to the built environment (Oral et al., 2003). Parameters related to the outdoor environment are: outdoor air temperature, solar radiation, humidity, wind velocity, and sound level. Design parameters related to the expected building are orientation and dimension as well as the properties of the components of the building envelope. These include: thickness, density, and heat conduction coefficient, which play a significant role on the performance of the building envelope.

Design Example of a Single Story House Envelope

Basic design parameters:

- General house characteristics:

  House Type: Single Detached, one storey, and rectangular

  Front Orientation: South, Dimension: 10×10m^2

  Location: Edmonton, Alberta

- House temperature:

  Indoor temperature: 21°C,

  Outdoor temperature: -34°C (January design temperature), 28°C (July design temperature)

- Heating Degree Days (base 18°C [64°F]): 5,589°C
- Cooling Degree Days (base 18°C [64°F]): 28°C

Only the wall system is accounted for. All materials for wall system and calculation are listed in Table 3.

Table 3—Wall Components

No	Component	Thickness(mm)	RSI
1	Outside air film	-	0.030
2	Brick veneer	190	190/100(0.074)=0.141
3	Vented air space	25	0.120
4	Plywood panels	26	26/100(0.87)=0.226
5	Batt insulation (R22)	-	3.9
6	Gypsum board	13	13/100(0.62)=0.081
7	Inside air film	-	0.12
Total			**4.618**

Other parameters selected are listed below:

Roof RSI 9.0, Window RSI 0.36, Door RSI 0.98

The results in Table 4 were obtained using the software HOT2000 to evaluate the whole building performance.

Table 4—Energy Consumption Summary

Estimated Annual Space Heating Energy Consumption	91112.10 MJ = 25308.92 kWh
Ventilator Electrical Consumption: Heating Hours	0.00 MJ = 0.00 kWh
Estimated Annual DHW Heating Energy Consumption	30231.57 MJ = 8397.66 kWh

As estimated by HOT2000, air leakage rate is $0.165 m^3/hr/m^2$ ($0.05 L/s.m^2$), which meets the maximum system air leakage ($0.1 L/s.m^2$).

CONSTRUCTION DETAILS

A successful building envelope stems from appropriate engineering design and appropriate construction practice. To obtain anticipated performance, practical and feasible construction details are equally crucial.

Movement Joints

Due to differential settlement, surrounding temperature changes, shrinkage and creep of materials, slight movements of the components in building envelopes are unavoidable. When concentrated stress due to these movements exceeds material strength, cracks will appear in the building envelope. Bed joint reinforcement to strengthen the wall is a practical option. Another approach is to divide the wall into smaller segments by using movement joints: control joints and expansion joints. The joints shown in the Figure 3 are referred to as movement joints. Expansion joints in the brick veneer allow the horizontal and vertical expansion and contraction; and the vertical control joints allow the horizontal movement of back-up block wall. The joint shall have the same capacity to resist environmental loads as the wall.

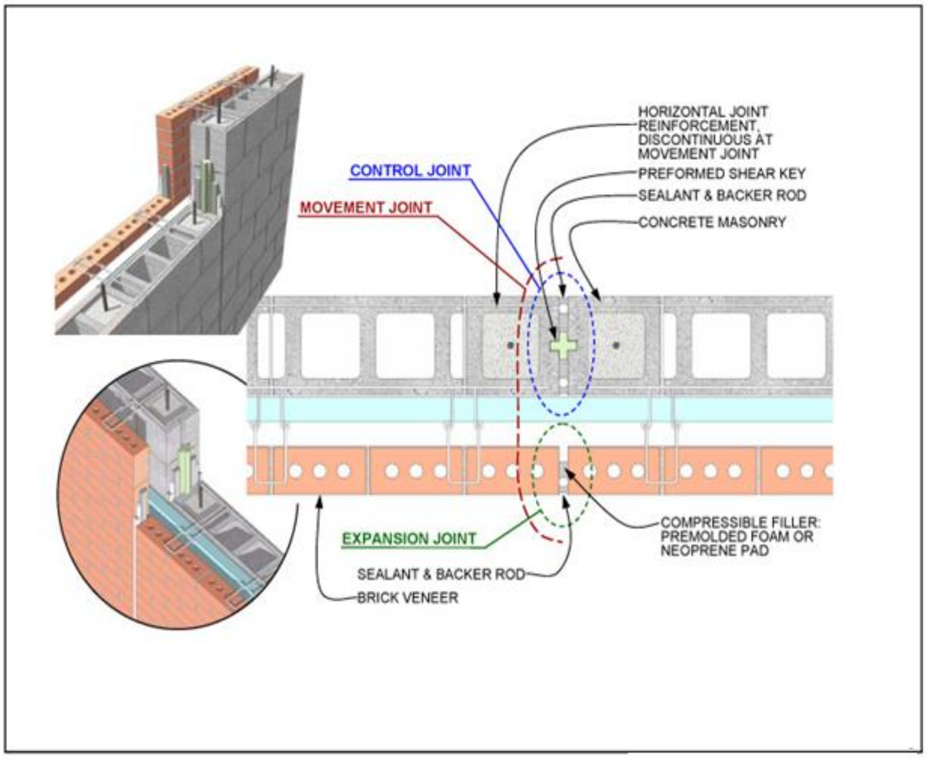

Figure 3—Movement joints in a brick veneer/concrete block wall (IMI, 2008)

Penetration Details

One of the main functions of building envelope is to resist the environmental load and prevent penetration of rain, moisture, air and heat. Figure 4 shows a wall construction detail which presents a reasonable configuration of various elements to resist the moisture penetration. The exterior veneer is the first protection from exterior moisture. Drainage plane constructs another barrier to resist moisture. In order to avoid moisture accumulation inside air space, the flashing is used to collect water and lead the collected water to the outside of wall through the weeping holes. Moreover, the mortar dropping collection devices are able to protect weeping holes from being blocked by the dropping mortar.

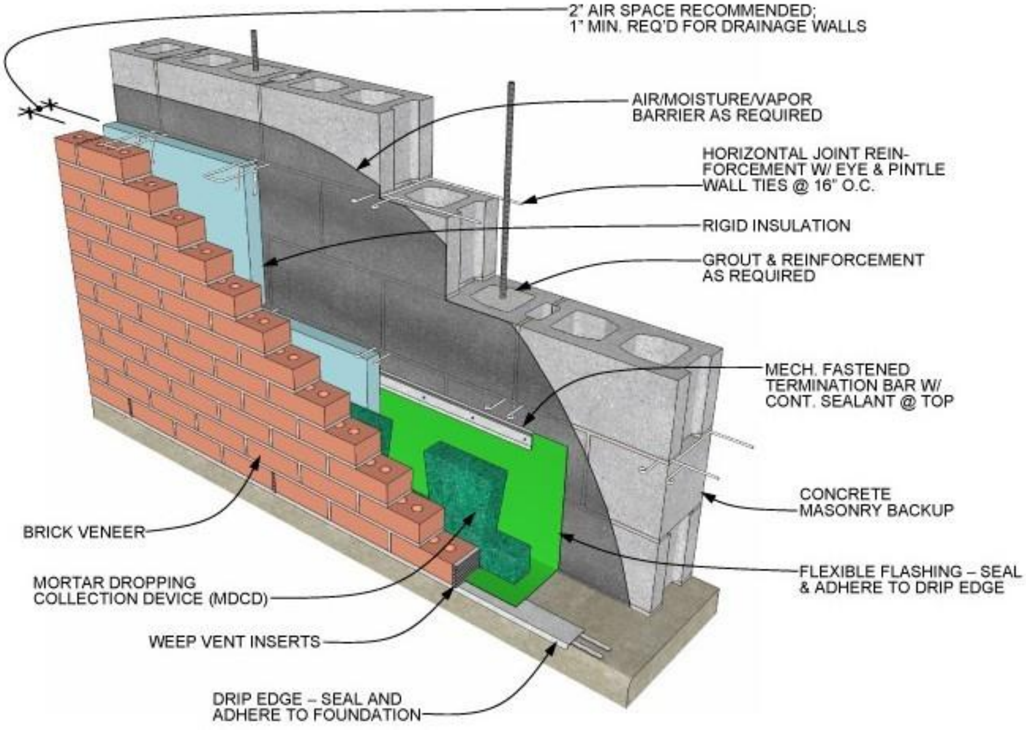

Figure 4—Detail of Wall Section Resistant to Moisture Penetration (IMI, 2008)

COMMISSIONING OF BUILDING ENVELOPES AND TESTS

ASHRAE defines commissioning as "the process of ensuring building systems are designed, installed, functionally tested and capable of being operated and maintained to perform in conformity with the design intent".

The commissioning process regulates the integration of all project expectations during planning, design, construction, and occupancy phases by inspection, functional field test, and oversight of operator training and record documentation (WBDG, 2010). The building commissioning process is interacted with the overall project process, and the basic process includes four steps: planning, design, construction and post-construction (GSA, 2005).

To make sure the building envelope meets the design requirements, in the commissioning process, performance tests demonstrate whether a building envelope is functioning according to the design objectives. Some of the more commonly used test methods are described and formalized by ASTM and CAN/CGSB.

Water Penetration Test

Water penetration through exterior masonry wall systems is a serious problem. As a result, identifying the cause of water penetrations in a wall system is often a critical task. ASTM has developed a standard to test the effectiveness of masonry drainage systems. ASTM E514 formalizes a standard procedure for determining the resistance to water penetration under cyclic static air pressure differences.

According to the ASTM standard, a mounting chamber is installed firmly on the testing wall. The chamber includes an air line with a manometer, a water line with valves, flow meter and water drain pipe. In addition, other equipment such as water tank and devices for measuring time, water quantities and temperature are installed before testing. During the penetration test, water is pumped from a water tank and sprayed at a controlled rate, which is adjusted to 138 L/m^2 per hour. At the same time, the air pressure within the chamber is increased to 500Pa. Water readings are taken every 30 minutes during the first 4 hours of testing under the same specified conditions. The record should include total collected water amount and time of appearance of dampness and first visible water on the back of wall.

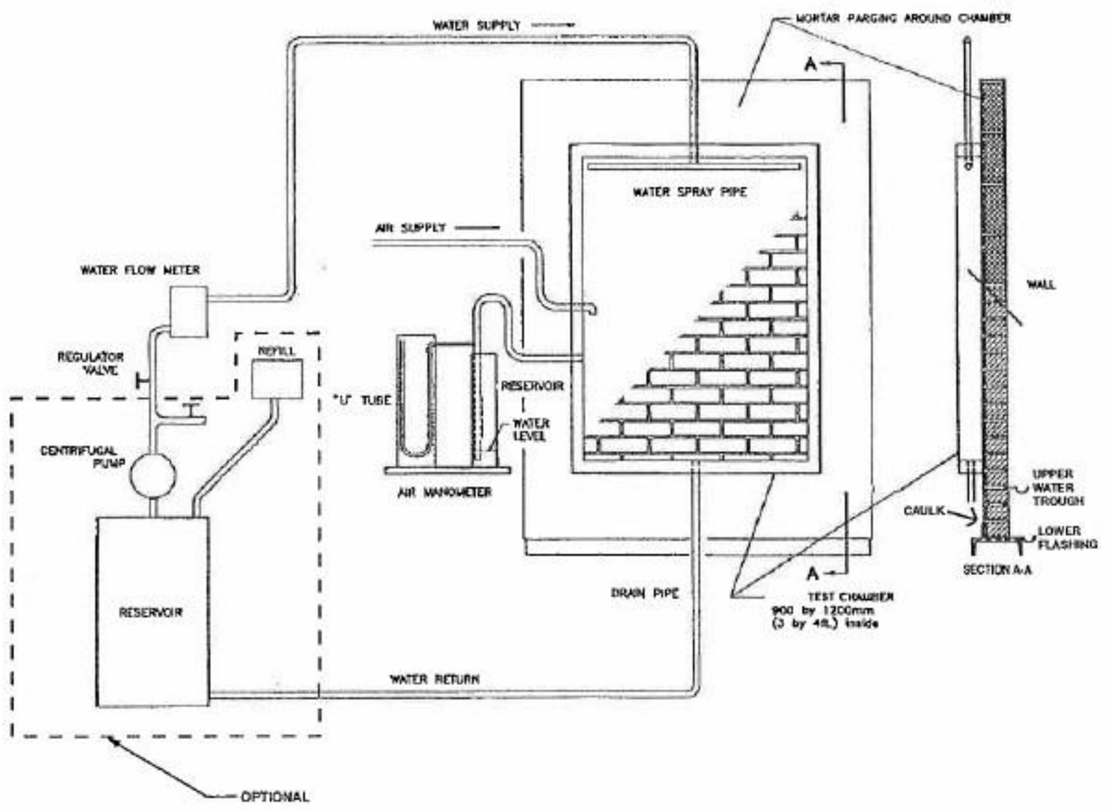

Figure 5—ASTM E514 Masonry Water Penetration Test

Air Leakage Test

An air leakage test is carried out by installing a test chamber to the masonry wall and attaching a fan into the chamber. Flow readings are taken during the testing. While applying a certain fan speed, the air flow rate and the pressure difference across the building envelope are read. Typical pressure differential is in the range of 75 to 150Pa. The test results are affected by site conditions, therefore, all heating, ventilation and air conditioning systems must be turned off during the test. All openings including waste pipes to the outside must be sealed. In addition, when calculating the air leakage rate, a correction should be done with different site conditions. The major standards related to air leakage test are ASTM E 2357, ASTM E 2178, ASTM E 1186, ASTM E783 and ASTM E 779. Figures 6 to 8 are field test photos displaying a typical air leakage test.

Figure 6—Airtightness test conducted by ASTM E 783(Knight and Boyle, 2010)

Figure 7—Airtightness test conducted by ASTM E 1186 (Knight and Boyle, 2010)

Figure 8—Airtightness test conducted per ASTM E 1186(Knight and Boyle, 2010)

CASE STUDY

A two storey masonry building (partial three and four stories) located on the 150 Tunney's Pasture Driveway in Ottawa and has a total of 40,000 m^2 of office space (HOK 2008). This 59 year old building was designated as a heritage building by Federal Heritage Building Review Office in 2005.

An engineering vulnerability assessment of this building was carried out by a joint research project team led by HOK Canada and co-sponsored by the National Association of Engineers and the federal government. The assessment report (HOK 2008) presents some significant findings regarding building envelope as follows:

1) The exterior wall is brick masonry with terracotta backup wall but lacks proper drainage. The trapped water or moisture can generate condensation problems, fungal growth problems, and potentially lead to structural component deterioration and structural failure. This issue is detrimental to the envelope and this design does not meet the requirement of Section 5.6.2.1 of NBC 2005 "Sealing and Drainage," which requires that the assemblies exposed to precipitation shall have a means to drain the trapped water inside walls to the outside of the wall.
2) Wall insulation of 50mm of cork was documented in original design, but was rarely present during the various repairs in the past. The cork insulation with relatively high thermal resistance R value can significantly increase thermal resistance capacity of the building envelope. The lack of insulation can increase the possibility of condensation on

the interior surface; also the absence of insulation can increase the heating cost and reduce comfort level of occupants. This issue does not meet the requirement of section 5.3.1 of NBC "Thermal Resistance of Assemblies".

3) Some cracks were present in the mortar joints, which may have been a potential source for air leakage. This issue does not meet the requirement of Section 5.4 "Air leakage" of the NBC 2005. Crack repair is essential to obtain better overall performance of the building envelope.

CONCLUSIONS AND RECOMMENDATION

The National Building Code of Canada is the guideline of masonry building envelope design and construction as it provides guidance to designers and architects. However, it should be noted that NBC's regulations regarding building envelope design are the minimum requirements. Design engineers and architects should make reasonable adjustments in their design based on the field conditions, client's expectations and local regulations. Meanwhile, site performance tests are an effective way to ensure the quality expected.

Currently the design principle of the masonry building envelope has evolved to reflect the building systems integral performance. However, more lab experiments, site tests and numerical simulation are still needed to verify the design principles. On the other hand, masonry construction methods and details need to be improved as well in an effort to obtain higher efficiency and reduce labour costs.

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Thermal Efficiency of Building Envelope Systems

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ABSTRACT

An investigation into the thermal efficiency of different wall systems is presented. Energy simulations and life cycle cost analyses were conducted on two buildings. The wall system was varied to compare masonry walls with other envelope types. Of the systems investigated, masonry walls were found to provide marginally superior thermal efficiency. However, masonry walls were also found to have higher 50-year life cycle costs than most of the other systems. The findings of the investigation indicate that thermal efficiency is heavily affected by several factors and more research is required to draw a definitive conclusion regarding the superiority of any one system.

Keywords: Masonry, building envelopes, conduction, heat transfer, RSI-value

INTRODUCTION

More than providing a simple separation from the outside world, the building envelope has to control the flow of air, moisture, and heat (Lio 1998). Some of the main design concerns for building envelopes in northern climates are related to the temperature distribution within the wall. The right combination of moisture and heat flow must be achieved in order to prevent condensation from occurring on parts of the wall that could be damaged as a result (Lio 1998). Additionally, the thermal gradient and degree of water infiltration will determine where freezing could occur within the wall. The consequence of freezing occurring in a component not designed to drain water or permit the expansion of ice is freeze-thaw damage. Finally, the thermal efficiency of the building envelope has a direct influence on the building's energy demands and the ability to maintain thermal comfort. A person feels a cold sensation when heat flows away from the body quickly (Young and Freedman 2004). In order to maintain thermal comfort, it is necessary to keep the net rate of heat flow low enough that occupants do not feel perpetually cold.

The background section begins by providing a primer into the theory of heat flow. The mechanisms of heat flow are described, followed by a discussion of some additional considerations in designing for thermal efficiency. The succeeding section describes methods of determining thermal resistance (RSI-value). A section describing and discussing some of the pros and cons of techniques available for estimating heat flow for building envelope design is presented next. The focus is then shifted away from background information to a basic description of some common envelope types, leading into the description of the energy simulations and life cycle cost analyses performed. The results of the analyses are presented and discussed, ending with some general conclusions drawn from the summation of the research and analyses.

BACKGROUND

Heat, Temperature, and Thermodynamics

Heat is a form of energy that can be thought of as "energy in transit" (Young and Freedman 2004). As a form of energy, heat is quantified using joules in the International System of Units (Mills et al. 1993). The flow of heat energy is usually categorized into three different transfer mechanisms: conduction, convection, and radiation (Lienhard and Lienhard 2011, Young and Freedman 2004). Though the different heat transfer mechanisms are often treated as separate entities, they are actually interrelated. Interactions between mechanisms make real heat flow problems more difficult to model accurately.

Heat is typically associated with temperature, and though these two quantities are related, they are not equivalent. Absolute temperature (measured in Kelvin) is directly proportional to the average kinetic energy of molecules in a fluid or solid (Young and Freedman 2004). Molecules in a gas move freely and are sparsely spaced (Petrucci et al. 2002). In a liquid, molecules are densely packed, but still move with relative ease (Petrucci et al. 2002). In a solid, molecules are essentially locked in place, though they still vibrate. The temperature of a solid is a measure of the average vibrant energy of its molecules (Petrucci et al. 2002, Young and Freedman 2004). Though temperature is proportional to kinetic energy, it does not actually quantify heat. To calculate heat, one must look to the laws of thermodynamics. The First Law of Thermodynamics states that the total energy of a system remains constant (Lienhard and Lienhard 2011, Petrucci et al. 2002, Young and Freedman 2004). If no work is done, and internal energy is related to temperature by a constitutive model, the First Law is expressed mathematically by:

$$H = \frac{dU}{dt} = mc \cdot \frac{dT}{dt} \qquad [1]$$

Where U is the internal energy, m is the mass of the system, c is the specific heat capacity of the system (a quantity which is material and temperature dependent), and dT/dt is the rate of change of the temperature. $U(t)$ is rarely known beforehand, so heat transport laws are required in addition to the First Law in order to solve heat flow problems (Lienhard and Lienhard 2011). The three transport laws used by scientists and engineers are: Fourier's Law (conduction), Newton's Law of Cooling (convection), and the Stefan-Boltzmann Law (radiation) (Lienhard and Lienhard 2011). Each of these three transport laws are discussed in the next subsection.

The transport laws arise from the Second Law of Thermodynamics, which states that the entropy of the universe tends to increase (Lienhard and Lienhard 2011, Petrucci et al. 2002). Two important facts arise from the Second Law. First, heat must flow from a region of higher temperature to a region of lower temperature. Second, this heat flow is spontaneous and irreversible (Lienhard and Lienhard 2011, Young and Freedman 2004).

Heat Transfer Mechanisms

Conduction

The flow of heat through a body, or between bodies in contact, is called conduction (Young and Freedman 2004). At the molecular level, conduction of heat through a medium can be thought of as the gradual jostling and excitation of molecules by their warmer neighbours (Young and Freedman 2004). At the warmer end, the molecules have higher average kinetic energy and vibrate with greater vigour than their neighbours. However, they quickly transfer some energy to those neighbours, and those molecules transfer energy further still. Thus, a temperature gradient is achieved. Solids are much better conductors of heat than gases because their denser molecular structure better facilitates the bumping and jostling mechanism of energy transfer. Metals are especially good conductors of heat because they are very dense and because electrons move freely within their structure (Callister 2007, Petrucci et al. 2002, Young and Freedman 2004).

The current mathematical treatment of heat conduction was first published by Joseph Fourier (Fourier 1955, Lienhard and Lienhard 2011). In general form, Fourier's Law of conductive heat flow (for systems with constant volume) is given by:

$$\nabla \cdot \mathrm{k}\nabla \mathrm{T} + \dot{\mathrm{q}} = \rho \mathrm{c}\frac{\partial \mathrm{T}}{\partial \mathrm{t}} \qquad [2]$$

Where ∇ is the gradient operator, k is the thermal conductivity, T is the temperature function, $\dot{q}$ is the volumetric heat release (W/m^3), ρ is the density, and c is the specific heat capacity. In the most general terms, k can vary in space and with temperature, and T can vary both spatially and temporally.

Since homogeneity can be reasonably assumed for many materials, and thermal conductivity is typically not highly sensitive to temperature, $k(x, y, z, T)$ reduces to the constant k for heat flow problems within a moderate temperature range (Callister 2007, Lienhard and Lienhard 2011, Young and Freedman 2004). Heat flow through an ideally insulated wire, or through an infinitely long and wide plate with finite thickness, is a one-dimensional problem (Nagle et al. 2004). If the width and length are finite, but much greater than the thickness, the problem may still be approximated by one-dimensional heat flow. If the problem is assumed to be in a steady-state, and the temperature gradient is assumed to be linear, Fourier's Law and the First Law of Thermodynamics combine to become equation 3:

$$H = kA \cdot \frac{T_H - T_C}{L} = \frac{A(T_H - T_C)}{R} \qquad [3]$$

Where L is the length of the heat flow path, A is the cross-sectional area (perpendicular to the heat flow), R is the thermal resistance, and T_H and T_C are the absolute temperatures on the hotter and colder sides, respectively. Heat transfer through a building envelope is often modeled using equation 3, or a slight variation of it. It is important to be aware of the assumptions implicit to equation 3 in order to judge whether or not the model is applicable.

Convection

Convective heat transfer is divided into two categories: natural (or free) and forced (Young and Freedman 2004). Both types of convective heat transfer are actually a combination of heat conduction and fluid mechanics (Lienhard and Lienhard 2011). When a fluid is warmed, it typically becomes somewhat less dense (Potter and Wiggert 2002), so due to buoyant forces, warmer fluid will rise, taking heat energy with it and sharing heat with its surroundings along the way (Young and Freedman 2004). This is the mechanism of natural convection. Forced convection, as the name suggests, occurs due to fluid moving under the influence of a pump or some other force. Both types of convection are relevant to the building envelope (Arens and Williams 1977, Lio 1998).

Newton conjectured that the rate of change of the temperature of an object was proportional to the difference between the temperatures of the body and its surroundings (Lienhard and Lienhard 2011). If the temperature difference between the body and its surroundings is constant, the problem is steady-state and heat flow can be expressed by:

$$H = \bar{h}A(T_b - T_s) = \bar{h}A\Delta T \qquad [4]$$

Where $\bar{h}$ is the convective heat transfer coefficient and T_b and T_s are the absolute temperatures of the body and its surroundings, respectively. It is important to note that the heat transfer coefficient here is not the same as k for heat conduction. Experiments have proven that convective heat transfer is actually quite complex and Newton's Law of Cooling is often an oversimplification (Lienhard and Lienhard 2011, Young and Freedman 2004). In forced convection, the heat transfer coefficient is essentially independent of ΔT, while in free convection, $\bar{h}$ is typically weakly dependent on ΔT ($\bar{h} \propto \Delta T^{0.25}$ to $\Delta T^{0.33}$) (Lienhard and Lienhard 2011, Young and Freedman 2004). Several other factors also influence the heat transfer coefficient, including the fluid viscosity and velocity, and the surface's geometry and roughness (Arens and Williams 1977, Lienhard and Lienhard 2011).

A dimensionless parameter, called the Biot number ($\mathcal{B}_i$), can be calculated to determine whether a problem is more suitably modeled by conduction or surface convection (Lienhard and Lienhard 2011). The Biot number is given by:

$$\mathcal{B}_i = \frac{\bar{h}L}{k} \tag{5}$$

If $\mathcal{B}_i \ll 1$, the problem is dominated by convection, while if $\mathcal{B}_i \gg 1$, conduction dominates (Lienhard and Lienhard 2011). The Biot number for a single pane of glass is typically less than one, making surface convection significant for old windows. However, multi-pane windows and other typical elements of the building envelope today have a Biot number greater than unity. The overall effect of surface convection can often be ignored without significant error (Arens and Williams 1977). This does not mean that convection can be ignored entirely. Open windows and doors, and poor control of air infiltration, can still lead to significant heat loss by convection through the envelope (Arens and Williams 1977, Lio 1998).

Rather than considering the fluid mechanics and boundary layer theory to calculate $\bar{h}$, surface convection effects are often lumped into the overall RSI-value and considered as part of conduction (Young and Freedman 2004). To account for surface convection and the thermal boundary layer, the thermal resistances of typical air films are simply added to the thermal resistance of the building envelope (Drysdale and Hamid 2005, Hatzinikolas and Korany 2005, Lio 1998).

Radiation

All bodies absorb and radiate heat in the form of electromagnetic radiation (Gray et al. 1970, Young and Freedman 2004). Heat flow by radiation is proportional to the surface area, emissivity, and the 4th power of the surface temperature (as described by the Stefan-Boltzmann Law) (Lienhard and Lienhard 2011, Young and Freedman 2004). If the area of the cooler body is much greater than the area of the warmer one, the net heat transfer is expressed by:

$$H_{net} = A_H \epsilon_H \sigma (T_H^4 - T_C^4) \tag{6}$$

Where A, ϵ, and T are surface area, emissivity, and absolute temperature, respectively, and the subscripts C and H denote the cooler and warmer bodies, respectively. σ is the Stefan-Boltzmann constant and is equal to $5.67 \times 10^{-8}\ \mathrm{W/m^2K^4}$ (Lienhard and Lienhard 2011).

Not all of the electromagnetic radiation reaching a body gets absorbed; some radiation is transmitted or reflected, adding complexity to real heat transfer problems (Lienhard and Lienhard 2011). Problems become even more complicated when considering that emissivity is a function of both wavelength and temperature (Lienhard and Lienhard 2011).

For building envelope design, radiation is generally insignificant except for large areas of glazing, where short wave radiation from the sun is transmitted through the glass and absorbed by the interior. The heat then becomes trapped because the glass is nearly opaque to the long wave radiation emitted by the interior.

Additional Considerations

The Complete Energy Budget

The complete energy budget is complex and difficult to model precisely (Gosink et al. 1983, Gray et al. 1970), though it is useful to know what the components of the budget are in order to make better decisions regarding envelope design. Heat is lost or gained by conduction and forced convection through the envelope, free or forced convection at the exterior surface, evaporation of water, leakage or ventilation of air, incoming precipitation, solar irradiation, and outgoing long wave radiation. In order to model everything, one must have data for air temperature, ground temperature, precipitation, atmospheric pressure, relative humidity, incoming solar radiation, and wind velocity and direction. Solar radiation in particular can be difficult to quantify, since it varies with the amount of cloud cover, time of day, time of year, and latitude (Gosink et al. 1983, Gray et al. 1970). ASHRAE (1993) provides tabulated "clear sky" solar radiation data, as well as the mathematical functions to calculate it, but without a good model to approximate the effects of cloud cover, surface reflectance, and shading offered by the surroundings, using clear sky data can introduce large errors. In order to make use of the climate data, it is necessary to know the thermal resistance, convective heat transfer coefficient, specific heat capacity, emissivity, moisture and air infiltration rates, fluid viscosity, surface roughness, and surface albedo for the building's components and surroundings. The complexity and the amount of necessary data make complete models both impractical to develop and impossible to solve analytically. Computer models certainly account for more factors than hand methods, but no complete model exists. The influences ignored by computer models are typically negligible anyway, so the accuracy is not significantly affected. It is also highly impractical to attempt to include influences in the model that amount to less than 1% of the net energy, especially when you consider that few (if any) of the inputs are known with better than 5% precision.

Thermal Mass

Thermal mass, or more precisely, total heat capacity, will in part determine how long unsteady heat flow will occur (ASHRAE 1993). A sheet of galvanized steel siding has low mass and low specific heat, and thus will rapidly reach steady-state, while a poured concrete foundation wall, which has both greater mass and greater specific heat, will reach steady-state much more slowly. The steady-state represents the upper bound of heat flow for a given temperature difference, so increasing unsteadiness can reduce heating costs. The beneficial effect of thermal mass is more significant in places where temperatures fluctuate greatly, constantly keeping the building in an unsteady state. However, a designer must actually take the time to model the building envelope in order to make good use of thermal mass, since poor placement can actually lead to increased cooling costs (Zhu et al. 2009). In Edmonton, the designer is likely more concerned with heating costs because of the long winter and cool summer. On average, Edmonton experiences a few heating degree days even in July and August. If reducing heating cost is the only concern, thermal mass is most effective when placed on the interior side of the insulation in an area where thermal peaking occurs. For instance, concrete floors or interior walls in an office building can gain a lot of heat during the day, and then release it slowly at night when everyone has left and the thermostat has been lowered. On the other hand, thermal mass inside a storage facility that is empty and windowless would not be well utilized.

Thermal Bridging

Thermal bridging occurs when components of the building envelope with low thermal resistance are allowed to wick heat out of the building (Lio 1998). Thermal bridges like steel studs can become condensation sites and damage finishes because the surface is cooler near these bridges (Lio 1998). Bridging increases heat losses by 5 to 50% in stud walls, depending on stud spacing and stud material (DLR 2011, Kosny 2004, Kosny and Desjerlais 1994). Wood, metals, and concrete can all act as bridges because they conduct heat more readily than insulation materials. However, wood does not cause significant bridging losses because it still provides reasonable thermal resistance. On the other hand, metallic components are so effective at conducting heat that they often cause significant multidimensional effects, resulting in error in one-dimensional models (ASHRAE 1993). To address this, ASHRAE (1993) developed the zone method to empirically account for bridging due to metallic components. Recognizing and mitigating potential thermal bridging problems is an important part of building envelope design. One method of controlling bridging is to place a layer of insulation (often called a thermal break) between the bridging element and the exterior.

EVALUATING RSI

The RSI-value quantifies the thermal resistance to heat transfer per unit cross sectional area. Higher RSI means greater thermal resistance and slower heat loss. When overall thermal resistance for a wall assembly is not known beforehand, RSI-values for individual materials are necessary to calculate this important design parameter (DLR 2011). When highly accurate thermal parameters of a whole wall construction are desired, a few options exist. One method is to construct a wall section and perform an ASTM "hot-box" test. A second method is to perform three-dimensional modeling using the finite difference or finite element method. Finally, for buildings that have already been constructed, careful measurements of pressure, air flow, temperature, and energy consumption can be combined to calibrate thermal parameters for a heat flow model (Said et al. 1999). Hot-box wall tests are used to validate - and sometimes calibrate - multidimensional computer simulations (ORNL 2011). ASTM C1363-05 is the current standard test used for the evaluation of RSI-values using steady-state and dynamic hot-box conditions.

ASTM C1363-05

Also known as the calibrated hot-box method, this test is used for the laboratory measurement of heat transfer through a specimen under controlled air temperature, air velocity, and radiation conditions. It is used extensively for steady state conditions and at temperatures typical of normal buildings (ASTM 2005).

To measure the heat transfer through the specimen, the net heat input into the insulated test box (called the metering chamber) is known, and estimated loss is measured through chamber walls and by flanking the specimen at its perimeter (ASTM 2005). Both estimates are based upon calibrations using a specimen of known thermal properties. The test can be used to determine effective thermal resistance of individual materials or elements like windows and doors, or composite assemblies like a wall with window (ASTM 2005). Hot-box tests have been used to determine published RSI-value equivalents or parallel flow path correction factors to account for thermal bridging in common architectural details.

HEAT LOSS ESTIMATION TECHNIQUES

One-Dimensional Modeling

Hand Calculations

Out of necessity, hand calculations require many simplifying assumptions which have significant impact on accuracy. Heat loss can be calculated quickly and easily using the degree day method, making it a popular modeling technique despite its lack of sophistication. One needs only the number of degree days, thermal resistance, and the area of the heat flow path to use the degree day method. The number of annual heating degree days for various Canadian locations are tabulated in the National Building Code of Canada (NRCC 2005). Heating degree days are calculated by finding the difference between 18°C and the mean temperature of the day (which is assumed to be the average of the highest and lowest temperatures recorded that day). All of the temperature differences on the days that were cooler than 18°C are summed up for the heating period (often taken to be 1 year) (Hatzinikolas and Korany 2005). The mean temperature is more accurately determined by a time-averaging method, but the error is typically small, and over the course of an entire year, the positive and negative errors tend to sum to nearly zero (Valor et al. 2001). The following formula is used to calculate heat losses by the degree day method:

$$Q = 86400\frac{AD}{R_u} \qquad [7]$$

Where Q is the quantity of heat lost during the period (in joules), D is the total number of heating degree days, and R_u is the overall thermal resistance. The constant 86 400 simply converts from days to seconds in the formula.

The degree day method has many drawbacks as a result of the simplifying assumptions implicit to the method.

1. The effect of thermal mass is neglected.
2. Large temperature variations throughout the day are not accounted for. No heat losses will be predicted on cool nights if it was warm enough during the day.
3. The method assumes that heating requirements are linearly proportional to the temperature difference. This has been documented to be only approximately true (Valor et al. 2001)
4. Solar heat gains are neglected. This is probably the most significant source of error in the degree day method.
5. Actual weather conditions are not accounted for. Wind, precipitation, and degree of cloud cover will affect heat loss.
6. Humidity, which will affect the comfort of the occupants, is not accounted for.
7. Infiltration losses are neglected.

The degree day method can be improved by accounting for effects other than one-dimensional conduction when calculating R_u (Arens and Williams 1977, Kosny 2004, Kosny and Desjerlais 1994). Accounting for multidimensional effects and the effective resistances due to convection and radiation will also help minimize error. The method is improved further by accounting for solar heat gain separately, though this may be difficult to do by hand. However, after much initial effort, it is possible to write a spreadsheet with simple input parameters that will automatically update to provide solar heat gain rates. Equations are not presented herein, but the reader is referred to ASHRAE (1993), Gray et al. (1970), and Gosink et al. (1983) for further information. A window heat gain tool is also freely available online (Gronbeck 2010). ASHRAE (1993) and Arens and Williams (1977) also provide guidance on how to account for convection and radiation in R_u.

The envelope's resistance to heat conduction cannot always be modeled with software, and is expensive to obtain experimentally. One simple hand method for determining the thermal resistance is the parallel path method, in which all envelope elements are assumed to be in series and then the overall RSI-value is determined by area weighted average of the conductance of the parallel paths (ColoradoENERGY.org 2010). This method does not appropriately account for thermal bridging and will overestimate resistance. However, it is a popular hand method because the solution algorithm is straightforward and easily input into a spreadsheet. A sample calculation for using the parallel flow path method is presented in Appendix B. ASHRAE (1993) recommends using the isothermal planes method to better account for thermal bridging. The isothermal planes method is expressed mathematically by:

$$R_{series} = \sum R_i \tag{8a}$$

$$R_{parallel} = \left(\sum \frac{A_i}{R_i}\right)^{-1} \tag{8b}$$

$$R_u = R_{series} + R_{parallel} \tag{8c}$$

Where A_i and R_i are the area and thermal resistance of the ith component of the wall, respectively, and A_t is the total area. This is an improvement over the parallel path method, but still assumes that heat cannot flow laterally within the wall (a poor assumption for walls containing metallic elements) (ASHRAE 1993). To account for the multidimensional effects of highly conductive thermal bridges, ASHRAE recommends reducing the resistance using the zone method (ASHRAE 1993). Alternatively, simple tabulated correction factors can be used to reduce the overall RSI-value (CMACN 2006). Another problem is that components in parallel have to be dealt with separately and then added back in. Since the parallel components will change depending on the envelope type and detailing, writing a spreadsheet that can be used for any possible construction is much more difficult. However, designers should not rely on the parallel flow path method because it overestimates thermal resistance by a considerable margin in envelopes with significant thermal bridging. A sample calculation using the isothermal planes method with zone method correction is presented in Appendix B.

Building Energy Analysis Simulations

Several one-dimensional modeling programs exist to simulate heat flow through the building envelope. Examples include eQUEST (based on DOE-2), BLAST 3, EnergyPLUS, SUNCAT 2.4, MOIST 3, and WUFI (Brock 2005, Judkoff et al. 2008). The improvement over the simple degree day method is that these programs account for transience due to thermal mass, and attempt to account for more of the complete energy budget. Since heat flow is largely dependent on the temperature difference, a lumped parameter model can be developed. Using a number of weighting factors, the effects of radiation, conduction, and convection can all be lumped together into an approximate equivalent thermal resistance (York and Cappiello 1982). Performing calculations and updating the model in time steps accounts for transience, and the effects of solar heat gain can be treated separately and then added in. Programs vary slightly because they calculate weight factors differently and they do not account for all of the same elements of the energy budget, but they all work essentially in the manner as outlined above (Judkoff et al. 2008). Inputting all of the data is tedious, but programs today now have databases of construction materials and meteorological data to simplify the task considerably.

The main advantages of these computer programs are that they are inexpensive (many are available for free) and much more accurate than the simple degree day method. According to Haberl and Cho (2004), the program DOE-2 typically predicted heat losses in real buildings to within 10% of that measured empirically. Another advantage is that once the model is developed, the designer can easily make adjustments and observe the effects on annual energy costs. With experience, simplified designs can be input into the program in a few minutes, making the software a useful design tool. After a more detailed design is decided upon, this can also be input into the program for greater accuracy.

Multidimensional Modeling

With the advent of computing technology and numerical solution methods, several programs have been developed and are commercially available for two and three-dimensional heat flow modeling. Some of these programs use the finite element method and can yield highly accurate solutions, but are quite costly. Since many problems in engineering are governed by differential equations, the most sophisticated finite element analysis packages are capable of solving a much wider variety of problems than just heat flow (e.g. ABAQUS, ANSYS, and NASTRAN). Such highly sophisticated programs are much more powerful and expensive than is necessary for building envelope design.

There are many drawbacks to using multidimensional modeling for envelope design. In addition to being expensive to purchase, the programs can be difficult to use. Accurate models can take a long time to draw, mesh, and assemble. Additionally, the memory required to solve a heat flow problem for an accurate model of a whole building could be much more than what is available in a typical desktop computer. Designers using sophisticated finite element analysis software also need to understand the different types of elements and how the finite element method works. Since the whole building is too much for the computer to handle, knowledge of how to employ simplifying assumptions and boundary conditions is essential to getting accurate solutions from an incomplete model.

Nevertheless, some multidimensional heat flow modeling software has been developed specifically for building envelope design. Examples include THERM, HEAT2, HEAT3, and HEATING7.2. THERM and HEAT2 are both two-dimensional modeling software, while HEAT3 and HEATING7.2 model in three-dimensions (Blomberg 1996, 2000, 2001; Carmody et al. 2011; Childs 1993). HEAT2 and HEAT3 use the finite difference method, while THERM uses the finite element method (Blomberg 1996, 2000, 2001; Carmody et al. 2011). The problems of cost and ease of use were addressed by making these specialized programs much less expensive and much easier to use than highly sophisticated finite element analysis packages.

The main advantage of multidimensional modeling is that it can be used to investigate issues like thermal bridging, heat flow through corner or perimeter details, or locating where condensation might be a problem (Blomberg 2000, 2001). Though more accurate than the one-dimensional programs, there are the drawbacks of having to draw and mesh the envelope in the model, and the entire building might still be impossible to model due to memory constraints. However, even if limited computing power precludes analysis of the entire building, multidimensional modeling software can be used to obtain overall RSI-values for architectural details where the one-dimensional approximation is least likely to hold true. This allows designers to improve their hand calculations or one-dimensional program input with RSI-values that account for significant multidimensional effects.

COMPARATIVE ANALYSES

The primary objective of the analyses was to compare wall constructions for use in Edmonton on the basis of estimated annual heating costs. Secondary objectives were twofold. The first was to compare the results of hand methods with those of a building energy analysis simulation. The second was to conduct a life cycle cost analysis to look at the significance of heating costs relative to the costs of construction and general upkeep over the life of the building.

Building Envelope Types

Five common envelope types were chosen for the investigation: masonry veneer, glass curtain wall, exterior insulation and finishing systems (EIFS), precast concrete, and vinyl siding. Excluding glass curtain walls, a specific detail was developed to represent each system. The constructability and insulating value of each system was given consideration in creating each wall detail. In the case of glass curtain walls, different proprietary systems were compared and a representative thermal resistance was chosen. Each envelope type is discussed in the following subsections.

Brick Veneer with Concrete Masonry Unit Backup Wall

Masonry is among civilization's first and most durable building materials (Hatzinikolas and Korany 2005). Masonry does not require formwork, so masonry wall construction can be faster than cast concrete. Masonry has inherent structural capacity, so it offers impact resistance and certain structural and architectural versatility that is simply not available from sheet metal, vinyl siding, or glass. Additionally, masonry does not suffer from problems with corrosion, etching due to acid rain, dirt accumulation due to electrostatic attraction, insect infestation, or dry rot. Masonry is not combustible and has high total heat capacity, making it resistant to fire damage (Buchanan 2001). Colour fading may occur in brick over time, but it is to a far lesser degree than is observed in vinyl siding or painted cladding. However, masonry is not without drawbacks. Bricks can suffer from unsightly efflorescence, though this is something that can be removed with a stiff brush and mild cleaning solution. Masonry also lacks tensile strength, making it susceptible to cracking and difficult to use in some applications. Finally, some climbing vines are capable of attaching themselves to masonry, gradually damaging the wall over time.

The following figure depicts the masonry cavity wall detail used to represent brick veneer systems in the analyses:

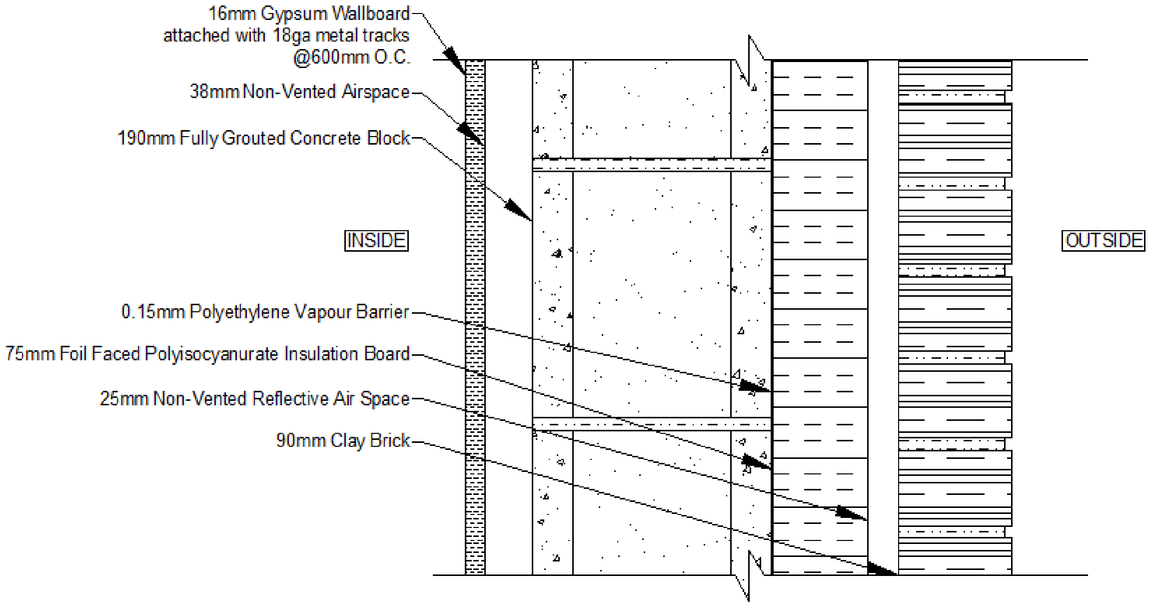

Figure 1 - Brick veneer with grouted concrete block backup wall

Guidance in developing this detail was provided by Malhatora (1997). The guide is published by the CMHC and highlights the superior thermal performance offered by masonry walls in comparison to metal framing systems having the same RSI-value through the insulation path. This was attributed to the less significant thermal bridging losses and the increased thermal mass of masonry (Malhatora 1997). Table 1 (below) shows the RSI-values assumed for the components. The values assumed herein are all within the ranges of values reported in the literature.

Table 1 - Thermal resistances of components of the brick veneer system (Sources: ASHRAE 1993, Hatzinikolas and Korany 2005, Drysdale and Hamid 2005, CPCI 2007, Engineering ToolBox 2008b)

Component	RSI-value (m^{2}K/W)
Interior air film	0.12
16mm gypsum wallboard (attached to concrete block wall using 18ga channel furring at 600mm c/c)	0.10
38mm non-vented non-reflective air space	0.16
190mm concrete block (fully grouted) with ladder joint reinforcement @ 600mm (ties the veneer to the concrete block wall)	0.13
0.15mm polyethylene vapour barrier	-
75mm foil faced polyisocyanurate insulation board	3.35
25mm non-vented reflective air space	0.24
90mm clay brick	0.11
Exterior air film	0.03

The overall RSI-value is 3.944 m^2K/W by the parallel path method and 3.859 m^2K/W by the isothermal planes method with zone method correction for metallic bridges. The small difference between R_u calculated by the two methods indicates that the thermal bridging due to the channel furring and joint reinforcement is not a significant source of heat loss in this wall assembly.

Glass Curtain Walls

A curtain wall is typically designed to simply be suspended in front of a structural frame (Brookes 1983). The dead load from the curtain wall and the wind pressures experienced are transferred to the structural framing through the anchorages (Brookes 1983). A typical curtain wall consists of an orthogonal grid of vertical and horizontal framing (called mullions) with infill panels of glass or some lightweight material. Glass curtain walls were the only type investigated in the analyses. One of the benefits of glass curtain walls is that they can be significant sources of solar heat gains. Additionally, being transparent to visible light, glass allows occupants to benefit from "natural light" and to observe the surroundings. In this regard, glass essentially has no alternative, aside from window panes made of a polymer instead of glass. Glass curtain walls are typically lightweight and can be installed quickly, which can alleviate constructability issues on some projects. However, the drawbacks of glazing are many. Glass is expensive to install and maintain (Means 2007), provides thermal resistance far inferior to typical opaque walls, is susceptible to gradual acid etching in urban areas, and has a significant ecological impact on avian populations (Harden 2002, Klem 1990).

Figure 2 (below) is an example of one proprietary glass curtain wall element:

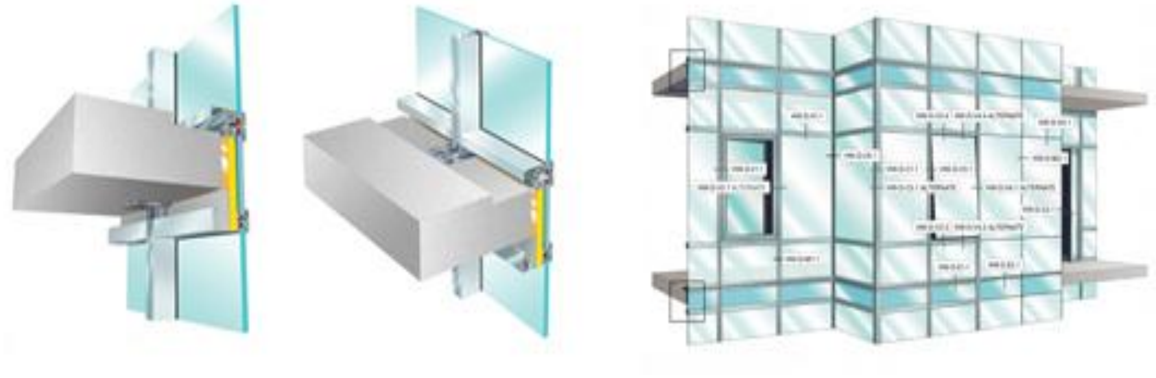

Figure 2 - Hybrid Wall ® by Sota Glazing Inc. (Sota 2011)

Thermal performance of the glass curtain wall is influenced by both the infill and framing (Brookes 1983). Metallic frames will be sources of bridging losses, but the effects can be controlled by using plastic or neoprene thermal breaks (Brookes 1983). Alternatively, framing can be made from vinyl or wood if these materials are capable of resisting the required wind and dead loads. However, wood is susceptible to swelling, dry rot, and insect infestation. Vinyl fades and breaks down when exposed to UV radiation, and both vinyl and wood are combustible.

The RSI-value used for glass curtain walls in these analyses was 0.5 m^2K/W. This is representative of double pane vacuum glass. The solar heat gain coefficient (SHGC) used was 0.65, which is also representative of many clear or lightly tinted double pane glass systems.

Exterior Insulation and Finishing Systems (EIFS)

EIFS consist of rigid insulation (typically polystyrene) substrate with an applied coating of a fibre reinforced polymer (Posey and Vlooswyk 1996). EIFS is similar to stucco, and the two are often considered to be the same. The difference is that stucco is cement based and EIFS is polymer based (Brock 2005). EIFS is sometimes touted as an excellent cladding material because it provides excellent thermal efficiency, ease of installation, and aesthetic versatility (Stucco Works Canada). Lower air infiltration and better thermal insulation than typical stud wall construction with vinyl or wooden siding is certainly achievable with EIFS (Posey and Vlooswyk 1996). Additionally, EIFS is lightweight and can be used in high rise construction (Kayll 2007). However, EIFS is known to suffer from durability issues. In theory, the system is water tight, but failures due to water intrusion have been known to occur within eight years of construction, well within the alleged 25-year design life (CMHC 1996). Some suppliers claim that their system will not suffer from the same problems that plagued EIFS in the past. Unfortunately, such claims take many years to become verifiable.

The detail created to represent EIFS in the analyses is shown in figure 3 (below):

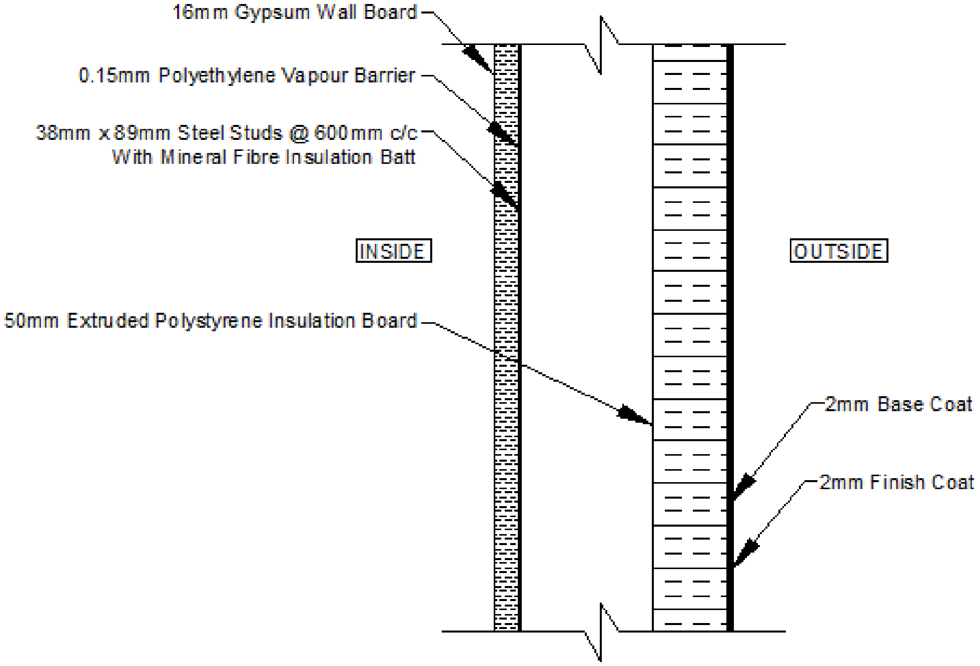

Figure 3 - EIFS supported by steel stud wall

Guidance in developing this design was provided by the CMHC (2004). Table 2 shows the RSI-values of the components of the EIFS detail.

Table 2 - Thermal resistances of components of the EIFS envelope (Sources: ASHRAE 1993, Hatzinikolas and Korany 2005, Drysdale and Hamid 2005, CPCI 2007, Engineering ToolBox 2008b)

Component	RSI-value (m^2K/W)
Interior air film	0.12
16mm gypsum wallboard	0.10
0.15mm polyethylene vapour barrier	-
38mm x 89mm steel studs @ 600mm c/c with mineral fibre insulation batt	2.46
50mm extruded polystyrene insulation board	1.74
2mm base coat & 2mm top coat	0.01
Exterior air film	0.03

The overall RSI-value is 3.699 m^2K/W by the parallel path method and 3.398 m^2K/W by the isothermal planes method with zone method correction for metallic bridges. The difference between R_u calculated by the two methods is not negligible, indicating that thermal bridging a significant source of heat loss in this wall assembly (despite the thermal break provided by the extruded polystyrene).

Precast Concrete

Precast concrete panel systems can be quick and easy to install because they are built in a factory setting and are modular in nature. The panels may be supported by the actual structure through the use of anchors, or comprise the load-resisting system on their own once assembled. From a heat-transfer perspective, the stand-alone panels typically provide poor thermal resistance (unless they are sandwich panels made with an insulation core), necessitating the use of insulation alongside the panels (CMHC 2002). Precast concrete is versatile both structurally and architecturally, is durable, resistant to impact damage from windblown debris, and is not combustible. However, concrete can suffer damage from the intrusion of acids and sulfate ions (Ramachandran 1995). The reinforcing steel will corrode readily in the presence of chlorides, so chloride intrusion indirectly damages the concrete as well (Callister 2007). Like the masonry of the cavity wall system, precast panels add thermal mass to the envelope (CMHC 2002). However, the difference between the two systems is that the masonry cavity wall has thermal mass on both sides of the insulation, while the precast panel's mass is on the outside. On the outside, the precast panel's only significant source of heat gain is solar radiation, so the mass is not well utilized in northern regions. Additionally, concrete panels often reflect more sunlight than brick because of their lighter colour. Although both brick and concrete on the exterior provide little benefit from their thermal mass, brick may be slightly more effective as a result of its lower albedo.

The detail in figure 4 was selected to represent precast concrete panels in the analyses. The system is comprised of a stud wall sheathed with gypsum on the interior side and polystyrene insulation on the exterior side. The precast panel is the outermost component.

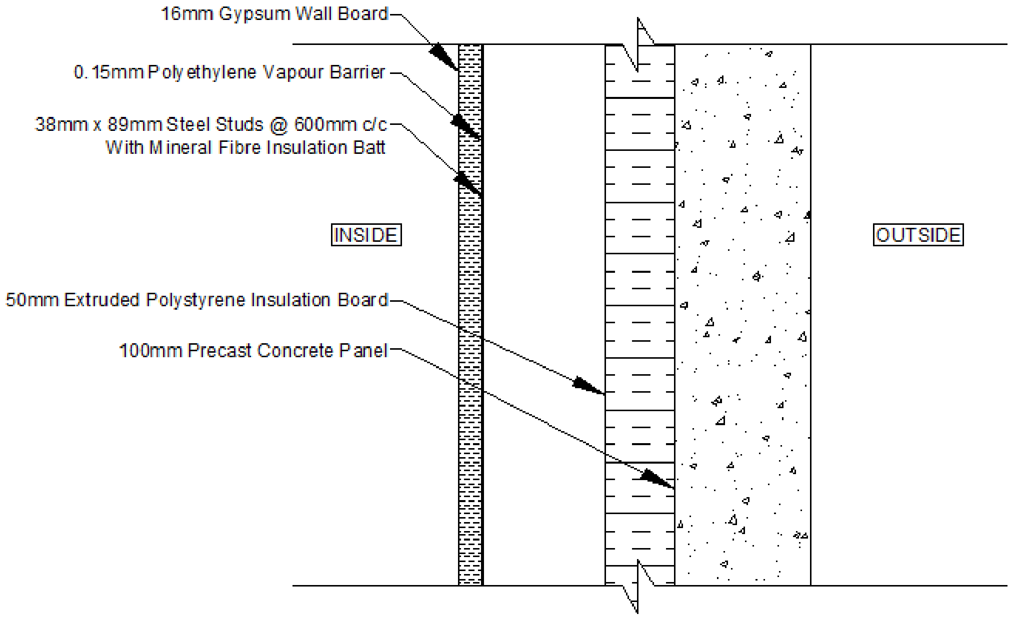

Figure 4 - Precast concrete panel with steel stud wall backup

Guidance for this design was obtained from CMHC (2002). Table 3 gives the thermal resistances of the components.

Table 3 - Thermal resistances of components of the precast concrete panel wall system (Sources: ASHRAE 1993, Hatzinikolas and Korany 2005, Drysdale and Hamid 2005, CPCI 2007, Engineering ToolBox 2008b)

Component	RSI-value (m^2K/W)
Interior air film	0.12
16mm gypsum wallboard	0.10
0.15mm polyethylene vapour barrier	
38mm x 89mm steel studs @ 600mm c/c with mineral fibre insulation batt	2.46
50mm extruded polystyrene insulation board	1.76
100mm concrete	0.05
Exterior air film	0.03

The overall RSI-value is 3.778 m^2K/W by the parallel path method and 3.453 m^2K/W by the isothermal planes method with zone method correction for metallic bridges. Similar to the EIFS, the difference between R_u calculated by the two methods is not negligible, indicating that thermal bridging is a significant source of heat loss in this wall assembly.

Vinyl Siding

Vinyl siding is among the most common cladding systems in Canada. Used almost exclusively in low-rise residential construction, vinyl siding is praised for being inexpensive, versatile, lightweight, and easy to work with and install (VSI 2007). However, there are plenty of drawbacks to consider. While vinyl siding is available in a multitude of colours and styles, most homes seem to be clad using the identical style and only a small range of neutral colours. The touted architectural versatility exists, but is underrepresented in vinyl's actual use. Vinyl is a plastic that is combustible and releases a multitude of toxic chemicals when it burns (Lewis 1996). The Vinyl Siding Institute downplays this fact (VSI 2007). Polymers, including vinyl, are degraded by ultraviolet radiation from the sun (Callister 2007). As a result, vinyl siding fades and eventually is made brittle by exposure to sunlight. Certain admixtures, like titanium dioxide, can improve the resistance, but these are sacrificial only (Callister 2007). High-end siding that is warranted to last decades longer than less expensive products is likely composed of the identical plastic but has more titanium dioxide mixed into it. Eventually, all siding will suffer the same deterioration. Vinyl siding also becomes statically charged and attracts particles of dust. As a result, vinyl siding requires annual cleaning. Finally, vinyl siding is considered brittle at any normal temperature. Since it is so thin, its energy dissipating capabilities are greatly reduced. Though concrete and brick are also considered to be brittle, they are capable of standing up to hail, windblown debris, and stray baseballs and golf balls. The same cannot be said of vinyl siding. Figure 5 shows the detail created to represent vinyl siding. Table 4 lists the RSI-values for each of the components of the vinyl siding envelope.

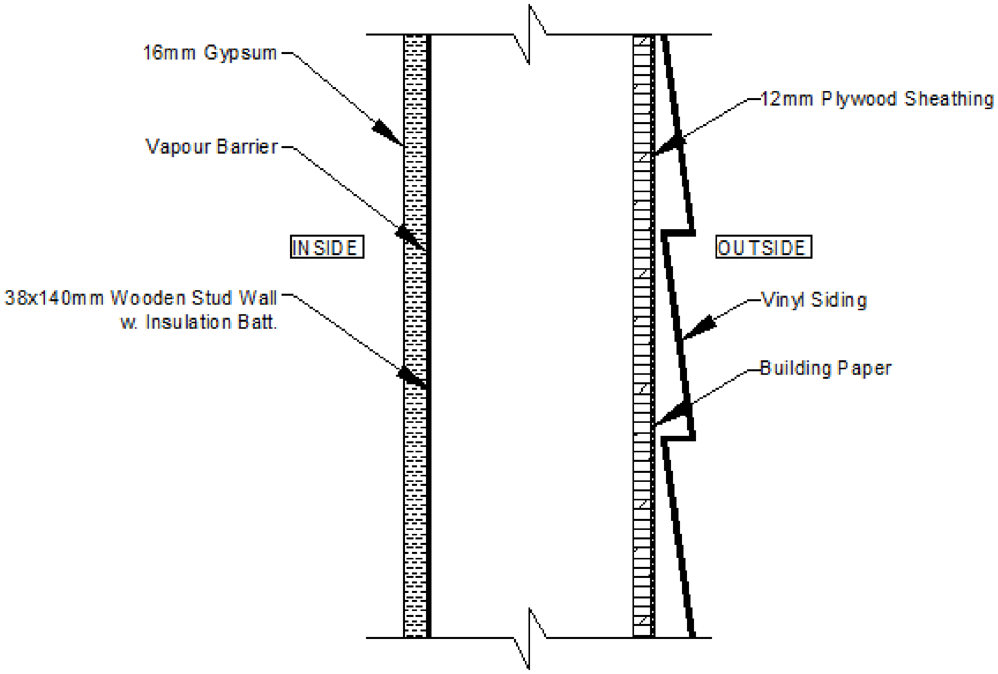

Figure 5 - Vinyl siding on wooden stud wall

Table 4 - Thermal resistances of components of the vinyl siding wall system (Sources: ASHRAE 1993, Hatzinikolas and Korany 2005, Drysdale and Hamid 2005, CPCI 2007, Engineering ToolBox 2008b)

Component	**RSI-value (m^2K/W)**
Interior air film	0.12
16mm gypsum wallboard	0.1
0.15mm polyethylene vapour barrier	-
38mm x 140mm wooden studs @ 600mm c/c with mineral fibre insulation batt	1.08 (stud), 3.67 (insulation)
12mm plywood sheathing	0.11
Building wrap	0.01
Vinyl siding	0.005
Exterior air film	0.03

By the parallel flow path method, the overall RSI-value was 3.126 m^2K/W. By the isothermal planes method, the RSI-value is 3.004 m^2K/W. There is clearly some thermal bridging occurring because of the stud wall, but because wood has much greater thermal resistance than steel, the effect is much less significant than in the systems with steel studs.

Energy Simulations

Energy simulations were performed on two fictional buildings in Edmonton using the software eQuest. The envelope was varied in each building in order to compare different systems using estimated annual heating costs. Estimated energy costs are a more practical parameter to use for comparison than the thermal resistance of the opaque wall. Other parameters were varied to try and qualitatively observe the effects of influencing factors like the orientation of glazing, thermal resistance of horizontal envelope components, and occupancy. Additionally, a complete set of hand analyses were performed on one building in order to compare hand methods with the computer model.

Building 1

Figures 6, 7, and 8 show the plan and elevations of the first fictional building investigated.

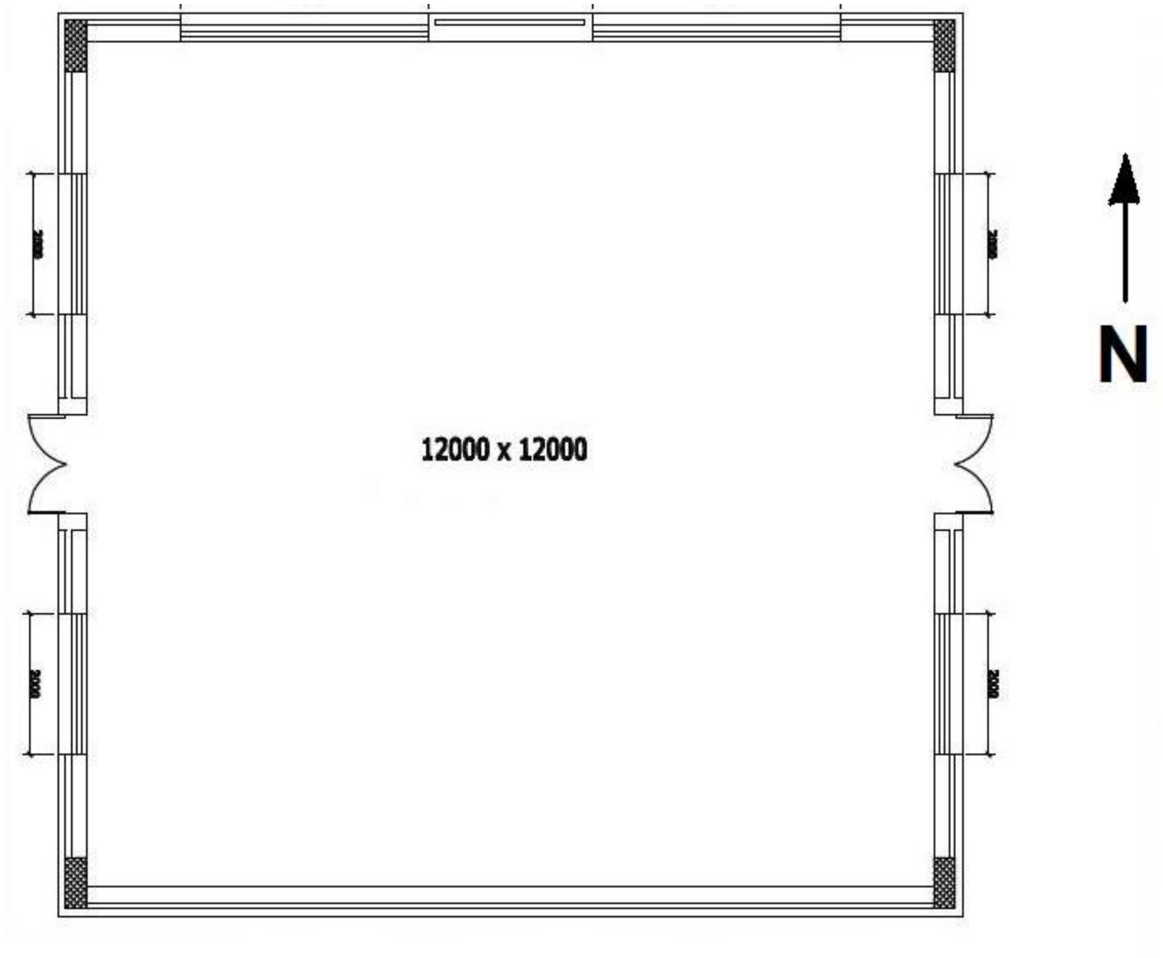

Figure 6 - Plan view of building 1

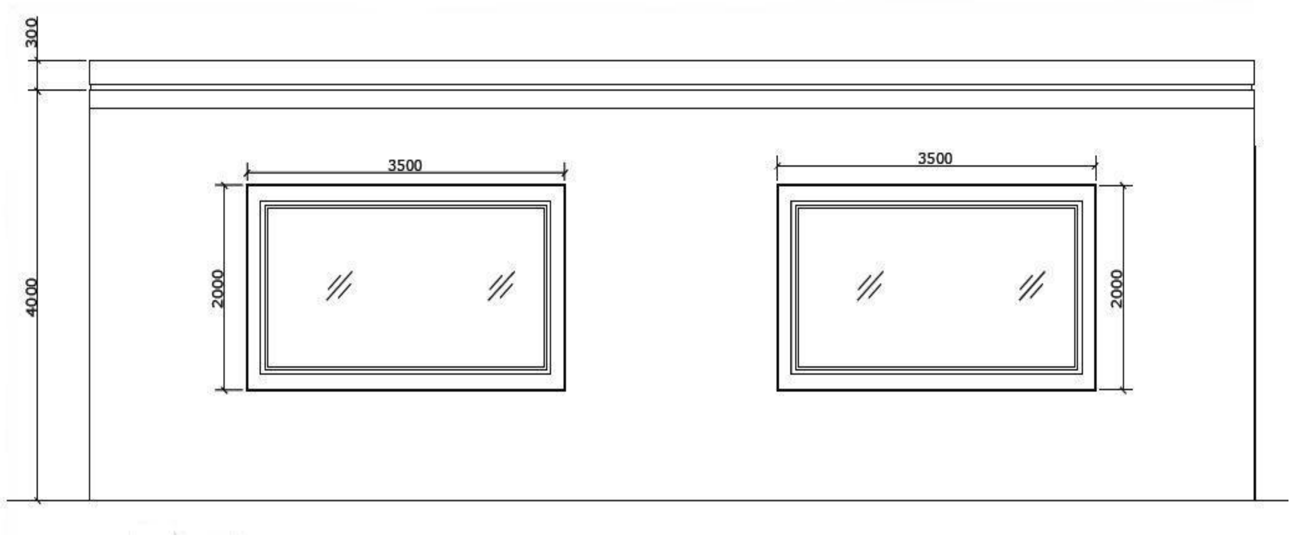

Figure 7 - Elevation view of the north wall of building 1

Figure 8 - Elevation view of the east and west walls of building 1

Building 1 was a relatively small building assumed to have relatively low but consistent usage. The size and assumed occupancy make it comparable (but not equivalent) to a single-family dwelling unit. Being a small building, it was decided that making it into a glass box would be inappropriate, so a glass curtain wall all around was not considered. However, two different options were considered for the south wall. First was to make it entirely opaque, and second was to make it completely glazed using a glass curtain wall. Additionally, the building was analyzed once using an unrealistically well insulated roof and floor, and then once using more reasonable RSI-values. The unrealistic case was modeled to make heat losses through the roof and floor essentially zero. This was to make the effects of differences in wall construction more pronounced.

Heating was assumed to be provided by an 85% efficient natural gas furnace, and the price of gas (including delivery charges and administration fees) was assumed to be $5.04/GJ + $0.77/day + 5% GST (AtcoGas 2011). It was assumed that there were no trees, mountains, buildings, or other major obstructions which would shade the building during part of the day. Loss due to air leakage was assumed to be constant and equal to 0.7 air changes per hour. The room temperature for thermal comfort was taken to be constant at 21.4°C. Cooling the building was not considered, and although heat gains from lights and electrical devices were included in the model, only the natural gas used is considered a heating cost. Running the lights may heat up the building, but the electricity cost is not assumed to be part of the heating costs.

The heat flow analyses of building 1 were performed using three different methods:

1. The degree day method, using the RSI-value obtained by the parallel flow path method and the number of heating degree days specified in the NBCC (NRCC 2005).
2. An improved hand method, using the RSI-value obtained by the isothermal planes method; actual climate data from Environment Canada; and accounting for solar heat gains, infiltration losses, and gains due to occupants. The reader is referred to Appendix B for sample calculations.
3. eQuest building energy simulation.

Method 1 was very easy to implement, but also found to be in poor agreement with the other two methods. Method 1 underestimated heat loss in the envelopes with an opaque south wall and overestimated heat loss in the envelopes with a glazed south wall. Method 2 required much more effort, though yielded good results, consistently predicting heat losses to within 10% of Method 3. However, the window heat gain is an important part of the model which also could not be automated because a separate calculation tool was used. This probably makes the improved hand method more appropriate for ensuring the solution from the computer program is reasonable, rather than Method 2 for actual design work.

Tables 5 and 6 show the results of all variations of the energy simulations performed on building 1.

Table 5 - Annual heating costs assuming floor and roof insulated to RSI-12

Envelope	Method 1	Method 2	Method 3
BV1	$685	$977	$945
BV2	$929	$732	$790
PP1	$690	$991	$961
PP2	$932	$742	$823
EIFS1	$693	$994	$967
EIFS2	$934	$744	$828
VS1	$715	$1,012	$984
VS2	$949	$756	$841

Table 6 - Annual heating costs assuming RSI-7.0 and RSE-1.0 for the roof and slab, respectively

Envelope	Method 1	Method 2	Method 3
BV1	$917	$1,212	$1,146
BV2	$1,161	$967	$971
PP1	$922	$1,226	$1,169
PP2	$1,164	$977	$1,011
EIFS1	$925	$1,228	$1,177
EIFS2	$1,166	$978	$1,017
VS1	$947	$1,247	$1,197
VS2	$1,181	$991	$1,031

Where BV, PP, EIFS, and VS represent brick veneer, precast panel, EIFS, and vinyl siding, respectively. The numeral 1 at the end represents the case of an opaque south wall, while 2 represents a glass curtain wall for the south wall. Several important observations are obtained from tables 5 and 6.

1. Glazing the south wall reduced heating costs by about 15%. This reduction in costs was slightly higher when the roof and slab had high RSI-values.
2. The benefit of glazing was slightly greater in the masonry system. For example, looking at table 6, combining glazing with masonry yielded 15.3% reduction in heating costs compared to masonry alone. The benefit of glazing in the precast

concrete went down to 13.5%. There is some indication here that thermal mass on the interior side of the insulation reduces heating costs even when the only source of thermal peaking is the sunlight coming through the windows.

3. The roof and slab accounted for about 20% of total heat loss.
4. The masonry system was superior, though only by a very small margin. The vinyl siding was inferior. Differences between systems were made only slightly smaller when realistic RSI-values were used for the roof and ground slab.
5. The degree day method provides a rough estimate at best. With the opaque south wall, the degree day method underestimated losses by as much as 28%. With the glazed south wall, losses were overestimated by up to 19%. The *best* agreement on an estimate between the degree day method and the software was 13%.
6. Accounting for significant influences like air infiltration losses, occupants, and solar heat gains greatly improves the usefulness of hand calculations. The *worst* agreement between the improved hand method and the software was just 10%.

Changing the RSI-value of the roof and slab did not have a strong influence on the relative differences in heating costs due to glazing, or differences between envelope types. In other words, the intended effect of highlighting the differences between walls alone was not nearly as pronounced as expected. Thus, it was decided that the walls can still be properly compared when using realistic RSI-values for the roof and slab.

Building 2

Figures 9 and 10 show the elevation views of the second fictional building which was 21m x 30m in plan.

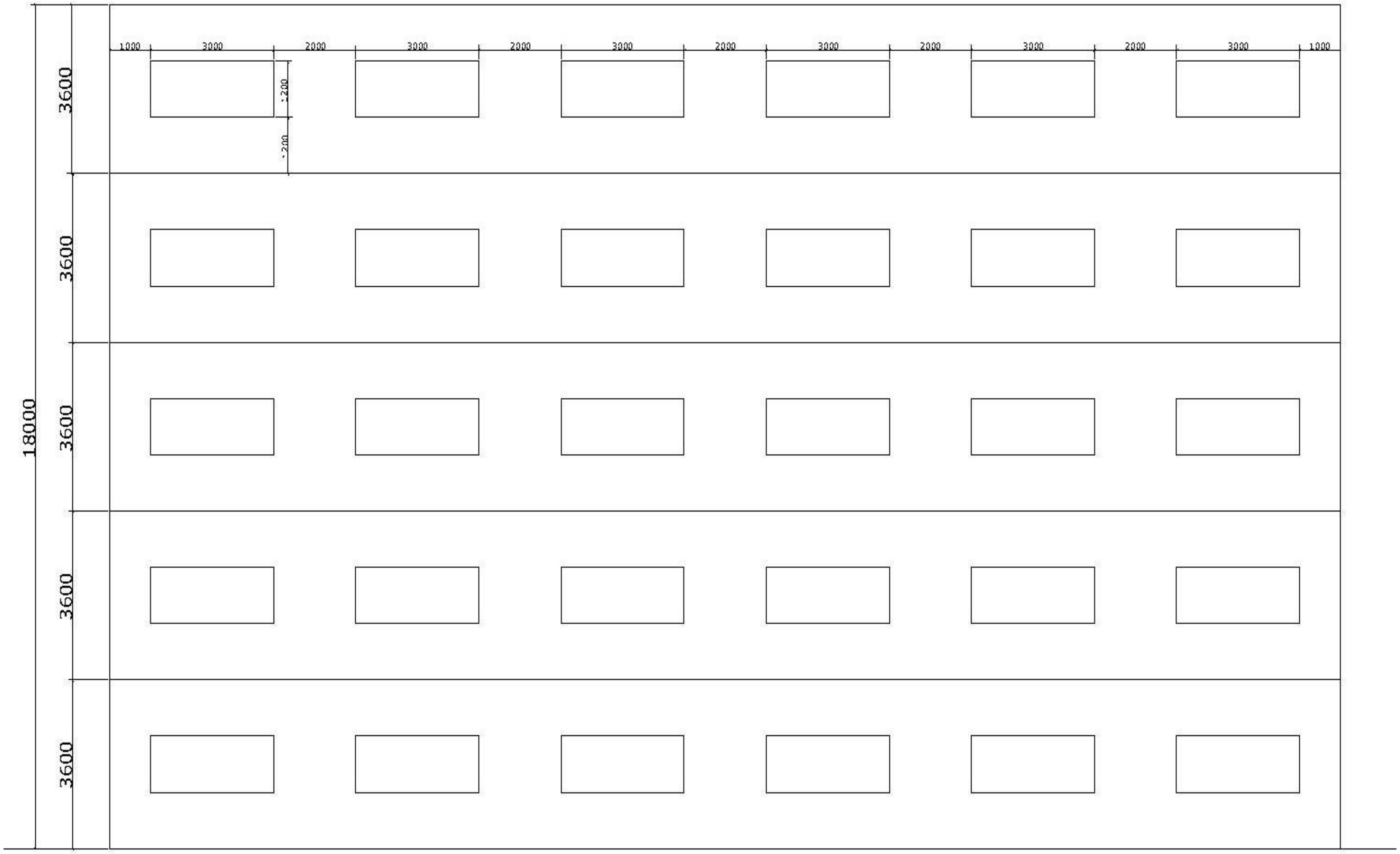

Figure 9 – East and west elevation view of building 2

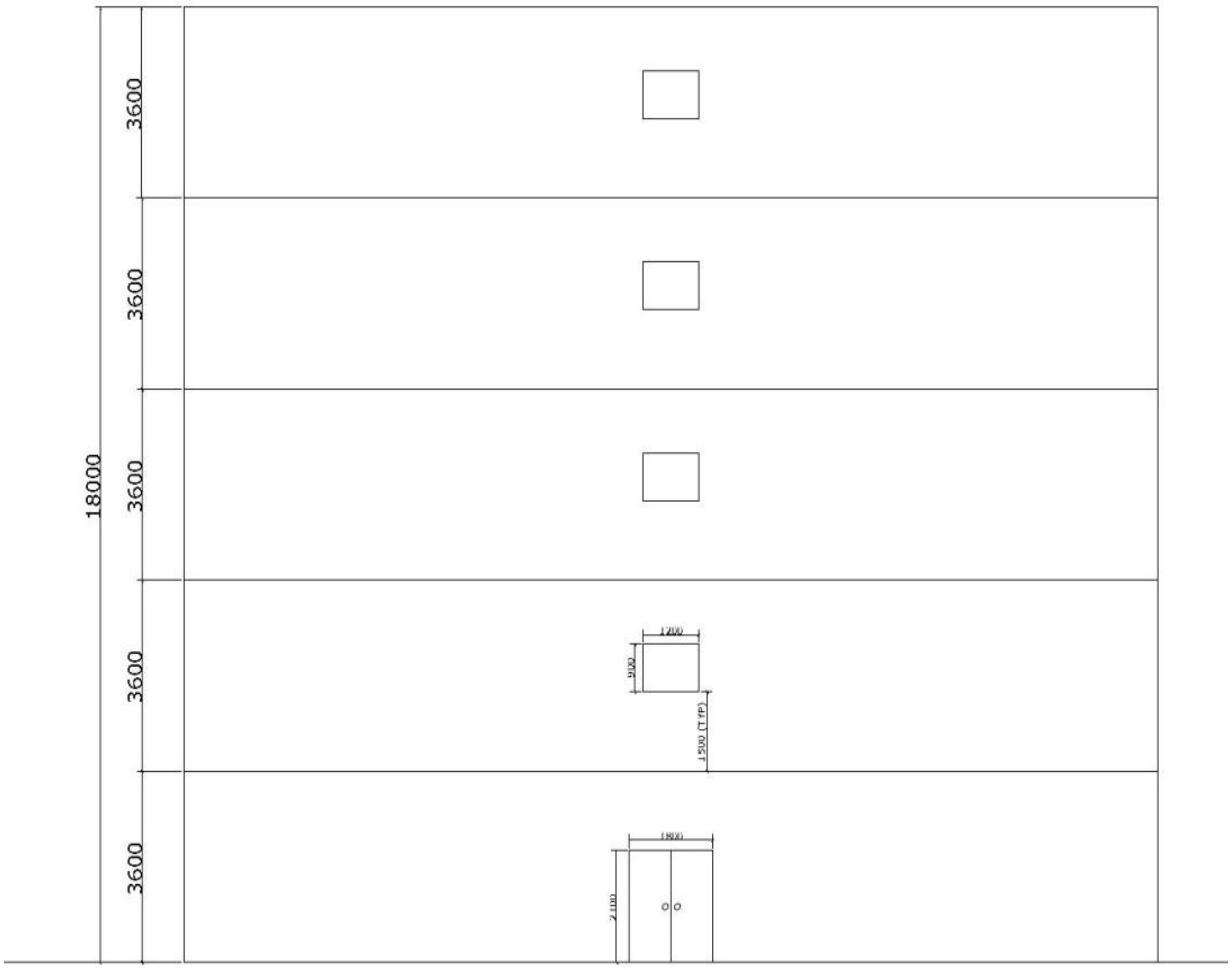

Figure 10 – North and south elevation view of building 2

Building 2 was analyzed assuming two different occupancies. The first case was office occupancy, while the second case was a residential occupancy. In the first case, the building was assumed to have the following zoning:

- 40% open plan offices
- 30% private offices
- 10% corridors
- 5% lobby/reception
- 5% restrooms
- 4% conference room
- 4% mechanical/electrical room
- 2% printing and photocopying

The building was assumed to be at 85% of full capacity from 8am to 5pm, Monday to Friday (excluding holidays). Fifteen percent occupancy was assumed from 9am to 3pm on Saturdays to account for overtime work. While the building was empty, the 10% of corridor lighting and 20% of plug loads were assumed to account for safety lights and the standby power consumption of many electrical devices. The floors were 200mm concrete slabs finished with carpet (no pad). The ceiling used was laid-in acoustic tile, and the RSI-values of the roof and slab were 7.044 and 1.00 m^2K/W, respectively. Loss due to infiltration was assumed to be 0.33 air changes per hour. Office buildings are better sealed and achieve lower losses than residential buildings because they rely on mechanical ventilation (Engineering Toolbox 2008a, University of Liverpool). Heating was assumed to be provided by an 85% efficient natural gas furnace, and the price of gas was assumed the same as in building 1. Once again, shading from trees or nearby buildings was assumed to be negligible. The room temperature for thermal comfort was assumed to be 21.4°C.

For the residential occupancy, a few changes were made to make it more representative of real buildings. First, the RSI-values of the roof and ground slab were reduced to 6.34 and 0.8, respectively. This was done because there seems to be less interest in making residential buildings LEED certified, though this trend is beginning to change (DCN News Service 2006). The losses due to air infiltration were increased to 0.60 air changes per hour to be more representative of residential buildings (Engineering Toolbox 2008a, University of Liverpool). Another difference is that the glass curtain wall was not investigated because it is not a popular cladding system for apartments and condos, though examples do exist. The heating system used in the model was changed to a hot water baseboard heater, with natural gas furnace to heat the water. Zoning of the residential building was as follows:

- 68% dwellings
- 16% corridors
- 7% storage
- 6% laundry
- 3% mechanical

The occupancy schedule assumed reflected the fact the most people would not be at home during business hours. Table 7 summarizes the results of the building energy simulations of building 2.

Table 7 – Estimated annual heating costs of Building 2

Envelope	Office Building	Residential Building
Brick veneer	$2,626	$6,820
Precast concrete	$2,851	$7,261
EIFS	$2,863	$7,302
Glazed curtain wall	$3,262	

Several important observations are obtained from Table 7:

1. The masonry system provided the highest thermal efficiency, though its benefit over precast and EIFS was less than 10%.
2. Glazing the entire building is inefficient. Solar heat gains from the south wall do not offset the significant losses on the north wall. An opaque north wall would have been more appropriate.
3. There was no significant difference between the precast concrete and EIFS. This is because the thermal mass provided by the concrete is not utilized effectively on the exterior side of the insulation.
4. Annual heating costs of the office building were quite low on a per unit area basis. This is attributed to significant gains due to occupants and electricity usage. Recall that electricity costs were not included in heating costs. However, when compared to reported values, it seems that building 2 was unrealistically efficient. E Source (2006) reports that average American office buildings consume 0.346 GJ per m^2 of floor area, which is comparable to the cost estimated for the residential occupancy.
5. Occupancy and usage had much stronger influence on annual heating costs than any of the other parameters that were varied in the analyses.

Life Cycle Costs

To get a sense of how significant thermal efficiency is as a part of the "big picture" when it comes to the cost of a building envelope, 50-year life cycle cost analyses were performed for buildings 1 and 2. The capital costs and maintenance costs were estimated using construction cost data published by RS Means (2007). Where RS Means (2007) did not provide information, costs were estimated using numbers published in Cost Comparisons by Allied Concrete (2005). Costs were scaled up from the published US national averages to expected Edmonton average using the overall city cost index of 1.108 (Means 2007). The values were also scaled up using an estimated historical cost index to convert from 2007 dollars to 2011 dollars. The historical cost index was estimated to be 1.119, based on average annual change in the reported cost index from 1995 to 2007 (Means 2007). In the case of data used from the Allied Concrete (2005) cost comparisons, values were scaled up from 1995 to 2011 and from Minneapolis to Edmonton.

Capital costs were estimated based on each wall detail (as shown in the various figures in the subsection entitled “Building Envelope Types”). Windows and doors were included, as well as miscellaneous items like weather-stripping and kick plates. The units costs used from RS Means (2007) included an allowance for overhead and profit. 5.4% was added to account for architectural fees and building permits. However, the costs of the site preparation, foundation, ground slab, floor finishes, electrical, mechanical, plumbing, roof, interior structural elements, and landscaping were not included.

Maintenance costs were assumed based on schedules that were designed to represent good practice in order to keep the building in good shape over the long term. Guidance in determining maintenance regimes was obtained from CMHC (1996), Farley (1997), Lio (1998), and NIBS (2000). Brick veneer was assumed to require cleaning and repointing every 30 years. Periodic repointing of mortar is necessary to prevent building envelope failure from occurring. Precast concrete was assumed to require cleaning, patching, and recoating every 25 years. Concrete occasionally cracks or spalls, so periodic patching is a necessity. Panels are also coated with some kind of finish to improve the aesthetics. The useful life of the coating will depend on the type and the exposure conditions. EIFS was assumed to require complete replacement every 15 years, with crack repair required 10 years after each new installation. EIFS has known durability issues (CMHC 1996), so a short useful life was assumed. Vinyl siding was assumed to require annual cleaning and complete replacement every 40 years. This long life span is to reflect the fact that most siding today has more UV absorbing additives in it than in the past. All glass was assumed to require annual cleaning. Glass curtain walls were assumed to require gasket replacement and mullion recoating every 20 years. All envelopes have sealants and joint sealants. It was assumed that sealants required replacement every 15 years, except in EIFS, where sealant replacement was assumed to be required at the time of replacement and 10 years after each new installation.

The remaining input parameters for the life cycle cost analyses were the estimated annual heating cost, inflation, and rate of return on investment. Heating costs were determined from the energy simulations described above. Inflation was assumed to be equal to 2% per year. This has been the average in Canada for the past decade and is the rate targeted by the Bank of Canada (Mankiw et al. 2008; Bank of Canada 2009, 2011). A rate of return on investment of 6% was assumed. This should be representative of conservative investing, and is within the common range of values used (Farley 1997, Flynn 2008). For a sample life cycle cost calculation, the reader is referred to Appendix B. Tables 8 and 9 summarize the results of the life cycle cost analyses for the two buildings.

Table 8 – Life cycle costs of building 1

System	50-year life cycle cost	50-year heating cost
BV1	$131,900	$25,000
BV2	$156,700	$21,100
PP1	$129,700	$25,500
PP2	$156,500	$22,000
EIFS1	$106,300	$25,600
EIFS2	$140,500	$22,100
VS1	$78,000	$26,000
VS2	$122,000	$22,500

Table 9 – Life cycle costs of building 2

Occupancy	System	50-year life cycle cost	50-year heating cost
Office	Brick veneer	$1,055,000	$57,100
	Precast concrete	$994,000	$62,100
	EIFS	$952,000	$62,300
	Glass curtain wall	$2,164,000	$71,000
Residential	Brick veneer	$1,147,000	$148,500
	Precast concrete	$1,090,000	$158,100
	EIFS	$1,048,000	$159,000

It is readily seen from the tables that:

1. The glass always cost more money in the long term, despite heat savings in the smaller building.
2. Vinyl siding is inexpensive, despite its underperformance from a thermal perspective.
3. Heating costs become an insignificant component of the building's life cycle costs as the building gets larger. Even in the smaller building, heating accounted for no more than a third of the total life cycle cost. Recall that the life cycle costs do not include the entire building, so relative proportions are actually overestimated here. It is clear that choosing a wall system based on thermal efficiency alone is difficult to justify.

DISCUSSION

Masonry's superiority in thermal efficiency was marginal, largely because none of the opaque systems had significantly different RSI-values. Accuracy of the energy simulations is probably not better than 10%, so the marginal differences in heating costs should be considered insignificant.

The thermal mass of masonry is better utilized than that of precast concrete because it is on the inside of the insulation. However, significant thermal peaking is necessary to benefit from thermal mass. Thermal efficiency of the opaque wall is governed by the insulation thickness and material, and how well thermal bridging is mitigated. Therefore, any cladding system can be designed to have very poor or very high thermal efficiency.

There was a huge increase in heating costs when building 2 was changed from an office building to a residential building. This is because gains due to occupants and electricity usage were quite significant. Much of the heat gained would have been coming from electricity use, so it would have perhaps been more appropriate to consider total energy usage rather than just heating costs.

An attempt was made at qualifying the degree of influence of certain parameters. It was found that the design of the opaque wall might not even be the parameter with the strongest influence on thermal efficiency, and it is certainly inappropriate to neglect all other factors. It is necessary to consider heat gains from the sun, occupants, and usage. It is also necessary to consider losses through the roof, ground slab, glazing, and air infiltration.

Life cycle costs revealed that vinyl siding was very inexpensive for the small building, which is supported by the observation that vinyl siding is the most popular cladding system for homes in Alberta. EIFS was about halfway in between the vinyl siding and the masonry system in terms of life cycle cost. However, it should be noted that building 1 was a little too small for the chosen masonry and precast systems to be practical. The EIFS and vinyl siding were definitely well matched to the size of the building. It should also be noted that EIFS and vinyl siding had to be completely replaced within the 50-year life cycle, while the masonry and precast could easily last another 50 years by following a good maintenance and repair schedule. While replacement was accounted for in terms of actual cost residual values at the end of the life cycle were ignored. There are also the less tangible values of durability, appearance, and environmental impact. Having to replace the cladding system (multiple times in the case of EIFS) might be viewed as an annoyance. The fading and the accumulation of dust suffered by vinyl siding could also be construed as nuisances. Unfortunately, it is difficult to put a dollar value on something as intangible as "annoyance". Someone who wishes to break from the norm, or simply happens to like the appearance of brick, would be more willing to spend a few extra dollars for that intangible value. The same is true of someone who is concerned with his or her environmental impact. Finally, there is a very real cost that was not considered: insurance. Buildings that are made of non-combustible materials are less expensive to insure against fire damage. The vinyl siding detail was the most combustible, so it would be the most expensive to insure.

In the larger building, precast, EIFS, and brick were all within a very narrow margin, making it easy to justify one choice over another using a criterion like appearance, durability, or environmental impact. It should be noted that there is very little confidence in the values obtained from the life cycle cost analyses. These types of analyses are prone to significant error. The observed cost differences of more than 30% may actually be statistically insignificant.

It was found that glass was expensive in all cases. This is because there are high capital and maintenance costs associated with glass. However, the use of glass is justified for many reasons, despite higher cost:

1. To satisfy the owner's desire for a view or natural light. Glass essentially has no alternative. There are variations in coatings, tints, number of panes, etc, but when a transparent material is required, glass (or polymer) windows are the only choice.
2. To satisfy the owner's or architect's vision of the building's appearance.
3. To save weight, thus saving on the costs of the geotechnical preparation, foundation, and structural framing. This was something not considered in the analyses.
4. To match the surrounding architecture.
5. To meet some other constructability constraint (e.g. speed of construction).

CONCLUSIONS

Though it was found that the study was not comprehensive enough to quantify the effects of all influencing factors, some qualitative analysis was possible. Though the masonry system had the lowest annual heating costs, this was only by a small margin. It was impossible to definitively conclude on the superiority of any one system with respect to thermal efficiency. Though the study was very limited in nature, with some critical thinking and a little judgment, it is still possible to draw some useful conclusions.

First, heating costs comprise a small portion of life cycle costs. Even in the small building that was analyzed, heating costs accounted for less than one third of life cycle costs. The choice of envelope system should not be based on thermal efficiency alone.

Second, the degree day method does not adequately estimate heat losses. It is concluded that using the degree day method to make design decisions is inappropriate. By considering several components of the complete energy budget, it is possible to improve estimates from hand calculations dramatically. Estimates from the hand method used herein were in good agreement with computer simulations. This improved hand method is adequate for preliminary design and for verification of the results of computer simulations.

Third, simply adding thermal mass will not necessarily produce the desired effect. It is inappropriate to make the claim that more thermal mass means higher thermal efficiency. To reduce heating costs, it is necessary to place thermal mass on the interior side on the insulation. The effectiveness of thermal mass is improved considerably where there is significant thermal peaking from occupants, solar radiation, electricity use, or any other heat releasing activity occurring inside.

Fourth, adding more insulation to the wall is not necessarily the most cost effective means of reducing annual heating expenses. Consideration should be given to other options, like replacing sealants, replacing old windows and doors, insulating the ground slab, and employing countercurrent heat exchange in the HVAC system. Since the addition of insulation yields decreasing returns to scale, it is necessary to model the effects of various possible changes in order to choose the best solution.

Finally, it was found that many factors have significant influence on the thermal efficiency. These factors include insulation type and thickness, interior thermal mass, thermal bridging, window placement, thermal resistances of the roof and ground slab, losses due to air leakage and ventilation, and occupancy. It seems that cost effective, thermally efficient design solutions come from a combination of design choices, not a “one size fits all” approach. Designers should be aware of the components of the complete energy budget in order to develop an effective, rational, and multi-faceted approach for designing the building envelope.

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APPENDIX A: LIST OF SYMBOLS

∇	gradient operator
$\mathcal{B}_i$	Biot number
$\bar{h}$	convective heat transfer coefficient (watts per kelvin-square metre)
$\dot{q}$	volumetric heat release (watts per cubic metre)
A	area
D	heating degree days
H	heat transfer rate (watts)
H_{net}	net heat transfer rate (watts)
L	length of heat flow path
Q	heat energy (joules)
R	thermal resistance (RSI-value) (square metre-kelvins per watt)
T	absolute temperature (Kelvin)
T_b	absolute temperature of the body (Kelvin)
T_C	absolute temperature of the cooler surface (Kelvin)
T_H	absolute temperature of the warmer surface (Kelvin)
T_s	absolute temperature of the surroundings (Kelvin)
ΔT	temperature difference (Kelvin)
U	internal energy (joules)
c	specific heat capacity (joules per kelvin-kilogram)
k	thermal conductivity (watts per kelvin-metre)
m	mass (kilograms)
t	time (seconds)
x, y, z	spatial coordinates for $\mathbb{R}^3$
ρ	density (kilograms per cubic metre)
σ	Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ \mathrm{W/m^2K^4}$)
ϵ	emissivity

APPENDIX B: SAMPLE CALCULATIONS

RSI by the Parallel Flow Path Method

System: masonry cavity wall

Table 10 – Elements of the parallel paths

Path 1	**Path 2**	**Path 3**	**Path 4**
inside air film	inside air film	inside air film	inside air film
16mm gypsum	16mm gypsum	16mm gypsum	16mm gypsum
38mm air space	38mm air space	metal channel furring	channel furring
190mm grouted CMU wall	10mm of the CMU	CMU wall	10mm of the CMU
vapour barrier	joint reinforcement	vapour barrier	joint reinforcement
75mm polyisocyanurate	40mm of the brick	polyisocyanurate	40mm of the brick
25mm air space	exterior air film	25mm air space	exterior air film
90mm clay brick		clay brick	
exterior air film		exterior air film	

Table 11 – RSI of the parallel paths.

	Path 1	**Path 2**	**Path 3**	**Path 4**
	0.12	0.12	0.12	0.12
	0.099	0.099	0.099	0.099
	0.16	0.16	0.00095	0.00095
	0.1257	0.01059	0.1257	0.01059
	0.00032	0.0078	0.00032	0.0078
	3.346	0.0545	3.346	0.0545
	0.24	0.03	0.24	0.03
	0.1089		0.1089	
	0.03		0.03	
Sum	**4.230**	**0.482**	**4.071**	**0.323**

Assuming 5mm wire ladder type joint reinforcement at 600mm c/c and 38mm wide channel furring at 600mm c/c:

A_1 = 95.95%

A_2 = 0.83%

A_3 = 3.17%

A_4 = 0.05%

$$R_u = \left[\sum \frac{A_i}{A_t R_i}\right]^{-1}$$

$$= \left[\frac{0.9595}{4.230} + \frac{0.0083}{0.428} + \frac{0.0317}{4.071} + \frac{0.0005}{0.323}\right]^{-1}$$

$$= 3.944 \frac{\mathrm{m^2K}}{\mathrm{W}}$$

RSI by the Isothermal Planes Method With Zone Method Correction

System: precast concrete panel with 38mm wide steel studs at 600mm c/c

Width of Zone A:

$$W = m + 2d$$

$$= 38 + 2(100 + 50)$$

$$= 338 \text{ mm}$$

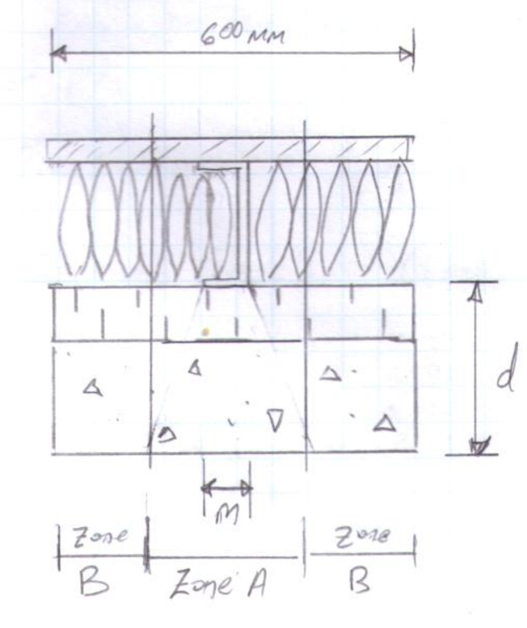

Figure 11 - Wall section showing the parameters used to determine zone widths

Taking a unit height of wall:

$$A_{total} = 0.6\text{m}^2$$

$$A_{ZoneA} = 0.338\text{m}^2$$

$$A_{ZoneB} = 0.6 - 0.338 \ = \ 0.262\text{m}^2$$

Zone A:

Table 12 – Zone A calculations.

Component	**Area (m^2)**	**Conductance (C=1/R) ($W{\cdot}m^{-2}{\cdot}K^{-1}$)**	**A*C ($W{\cdot}K^{-1}$)**	**R/A (=1/AC) ($K{\cdot}W^{-1}$)**
interior air film	0.338	8.333	2.817	0.3550
16mm gypsum	0.338	10.101	3.414	0.2929
vapour barrier	0.338	3,125	1,056	0.0009
stud flange & insulation batt in parallel	0.038 0.300	90,000 36.18	3,420 10.85	=(3420+10.85)$^{-1}$ = 0.0003
stud web & insulation batt in parallel	0.0005 0.3375	511.4 0.411	0.256 0.139	=(0.256+0.139)$^{-1}$ = 2.535
stud flange & insulation batt in parallel	0.038 0.300	90,000 36.18	3,420 10.85	=(3420+10.85)$^{-1}$ = 0.0003
50mm polystyrene	0.338	0.568	0.192	5.207
100mm concrete	0.338	19.23	6.50	0.154
exterior air film	0.338	33.33	11.27	0.089
Sum				**8.634**
Transmittance = $1/\sum\frac{R}{A}$				**0.1158 $W{\cdot}K^{-1}$**

Zone B:

Table 13 – Zone B calculations.

Component	**RSI-value ($m^2 \cdot K \cdot W^{-1}$)**
interior air film	0.12
16mm gypsum	0.099
vapour barrier	0.00032
89mm insulation batt	2.46
50mm polystyrene	1.76
100mm concrete	0.052
exterior air film	0.03
Sum	**4.521**
Conductance = $^{1}/_{\sum \boldsymbol{R}}$	**0.2212 $W \cdot m^{-2} \cdot K^{-1}$**

Overall conductance of the wall is the area-weighted average of the transmittance

$$\frac{1}{R_u} = C_u = \frac{[A_{ZoneB} C_{ZoneB} + T_{ZoneA}]}{A_{total}}$$

$$= \frac{\left[(0.262\text{m}^2)\left(0.2212\,\frac{\text{W}}{\text{m}^2\text{K}}\right) + \left(0.1158\,\frac{\text{W}}{\text{K}}\right)\right]}{0.6\text{m}^2}$$

$$= 0.2896\,\frac{\text{W}}{\text{m}^2\text{K}}$$

$$R_u = 3.453\,\frac{\text{m}^2\text{K}}{\text{W}}$$

Heat Loss by the Degree Day Method

Building 1, brick veneer, opaque south wall

$R_{wall} = 3.944\,\frac{\text{m}^2\text{K}}{\text{W}}$ (By the parallel flow path method)

$R_{glass} = 0.5\,\frac{\text{m}^2\text{K}}{\text{W}}$ (Assuming vacuum glass)

$R_{roof} = 7.044\,\frac{\text{m}^2\text{K}}{\text{W}}$ (Assuming well-insulated roof)

$R_{floor} = 1.0\,\frac{\text{m}^2\text{K}}{\text{W}}$ (Assuming slab on grade with some insulation subflooring)

$A_{wall} = 153.6\ \text{m}^2$

$A_{glass} = 38.4\ \text{m}^2$

$A_{roof} = 144\ \text{m}^2$

$A_{floor} = 144\ \text{m}^2$

Annual degree days: D = 5400 (from NBCC for Edmonton)

Assume ground temperature is constant at 10°C. Therefore:

$$Floor\ degree\ days = (18 - 10)(365.25) = 2922$$

<u>Calculate heat loss:</u>

$Q_{total} = Q_{wall} + Q_{glass} + Q_{roof} + Q_{floor}$

Recall $Q = 86400\frac{AD}{R}$ (in J)

$Q = \frac{AD}{11574R}$ (in GJ)

$$Q_{total} = \frac{(153.6\text{m}^2)(5400\text{K·days})}{\left(11574\frac{\text{days·J}}{\text{s·GJ}}\right)\left(3.944\frac{\text{m}^2\text{·K·s}}{\text{J}}\right)} + \frac{(38.4)(5400)}{(11574)(0.5)} + \frac{(144)(5400)}{(11574)(7.044)} + \frac{(144)(2922)}{(11574)(1.0)}$$

$Q_{total} = 99.9\ \text{GJ}$

Assume 85% efficient gas furnace

$Q_{consumed} = \frac{Q_{total}}{0.85}$

$Q_{consumed} = 117.5\ \text{GJ}$

Based on rates from AtcoGas:

Heating cost = \$5.04 per GJ consumed + \$0.77 per day + 5% GST

$$Cost = \left[\left(5.04\frac{\$}{GJ}\right)(117.5\ GJ) + \left(0.77\frac{\$}{day}\right)\left(365.25\frac{days}{year}\right)\right] \times 1.05$$

$Cost = \$917.24$ per year

Heat Loss by the Improved Hand Method

<u>Calculate gains due to occupancy:</u>

Equivalent occupancy loads assumed for building 1. Real gains due to real occupancy can be calculated in exactly the same way: power multiplied by duration.

- 1 human x 20,000 hrs = 7.2 GJ (this is based on the assumption that humans emit 100W. Almost all of the food metabolized by warm-blooded animals is converted to heat. A 2000 Calorie/day diet converts to 97 J/s = 97W).
- 1 15W fluorescent bulb x 54,000 hrs = 2.92GJ.
- 1 300W electronic device x 6,000 hrs = 6.48 GJ.

Therefore, gains due to occupancy = 16.6 GJ.

Note: these were equivalents only to show how the calculations are performed. Building 1 was assumed to experience constant heat gain at a rate of 525 W due to the combined effects of occupants, lights, and electrical devices. Buildings 2 and 3 on the other hand were given real occupancy with realistic schedules.

Calculate losses due to air leakage:

Assume losses due to leakage, people coming in and out, etc. = 0.7 air changes per hour

Volume of building = 4m x 12m x 12m = 576 m^3

$$\frac{Vol.air}{hour} = (0.7\ \mathrm{hr}^{-1})(576\mathrm{m}^3) = 403.2\,\frac{\mathrm{m}^3}{\mathrm{hr}}$$

Specific heat of air = 1.005 $kJ\cdot kg^{-1}\cdot K^{-1}$

Density of air at 0°C = 1.293 $kg\cdot m^{-3}$

Density of air at 20°C = 1.205 $kg\cdot m^{-3}$

Assume inside temperature kept constant at 21.4°C

$$Q = \frac{\#\,of\ days\ \times 24\,\dfrac{hrs}{day} \times 403.2\,\dfrac{m^3}{hr} \times\ \rho_{outside\ air} \times \Delta T\ \times c_{air}}{1\ 000\ 000}\ \mathrm{GJ}$$

$$\Delta T = 21.4℃ - T_{outside}$$

Assume $T_{outside}$ is the average daily temperature by month from Environment Canada

Sample calculation for January:

$$\Delta T = 21.4℃ - (-13.5℃) =\ 34.9℃$$

$$\rho_{outside\ air} = 1.293\,\frac{\mathrm{kg}}{\mathrm{m}^3}$$

$$Q = \frac{(31)(24)(403.2)(1.293)(34.9)(1.005)}{1\ 000\ 000} = 13.6\ \mathrm{GJ}$$

Table 14 – Losses due to air leakage.

Month	**Average daily temperature (°C)**	ΔT	$\rho_{outside\ air}$	**Q (GJ)**
January	-13.5	34.9	1.293	13.6
February	-10.5	31.9	1.293	11.3
March	-4.5	25.9	1.293	10.1
April	4.3	17.1	1.293	6.45
May	10.4	11.0	1.205	4.00
June	14.1	7.3	1.205	2.57
July	15.9	5.5	1.205	2.00
August	15.1	6.3	1.205	2.29
September	10.1	11.3	1.205	3.97
October	4.3	17.1	1.293	6.67
November	-5.7	27.1	1.293	10.2
December	-11.3	32.7	1.293	12.7
Sum				**85.9**

Calculate gains due to solar heat:

Estimate cloud cover reduction factor. Based on models presented in Gosink et al. (1986) and Gray et al. (1970) and actual solar irradiation data from Alberta meteorological stations, the authors have chosen a linear model to estimate the Cloud Cover Reduction factor:

$$CCRF = 1 - 0.6CC$$

Table 15 – Hours of cloud cover data for Edmonton (from Environment Canada) with estimated CCRF

Month	0 to 2 tenths	3 to 7 tenths	8 to 10 tenths	Average daily cloud cover	CCRF
January	169.2	147.1	427.7	0.639	0.617
February	151.2	139.8	387.2	0.639	0.616
March	165.8	176.2	402.1	0.627	0.624
April	159.9	202.8	357.3	0.610	0.634
May	142.3	214.9	386.9	0.631	0.621
June	124.4	224.0	371.5	0.637	0.618
July	171.6	241.8	330.6	0.585	0.649
August	180.6	237.8	325.6	0.578	0.653
September	177.2	183.1	359.7	0.601	0.639
October	183.6	178.0	382.4	0.607	0.636
November	157.7	148.2	414.2	0.642	0.615
December	167.9	143.8	432.3	0.642	0.615

Sample calculation (January):

Average cloud cover = $\frac{(169.2)(0.1)+(147.1)(0.5)+(427.7)(0.9)}{169.2+147.1+427.7}$ = 0.639

$$CCRF = 1 - 0.6CC = 1 - (0.6)(0.639) = 0.617$$

Input the CCRF into the online window heat gain tool, as well as values for ground reflectance and window solar heat gain coefficient (some representative values are available on the website).

Table 16 – Solar heat gain rates obtained using Window Heat Gain (Gronbeck 2010).

Month	East wall	West wall	North wall	South wall
January	230	230	140	1300
February	460	460	270	1800
March	770	770	460	1900
April	1100	1100	300	1700
May	1300	1300	520	1400
June	1400	1400	650	1200
July	1400	1400	630	1300
August	1200	1200	440	1600
September	920	920	280	1900
October	580	580	150	1900
November	280	280	170	1400
December	170	170	110	1100

Units are in W·hr·m^{-2}·day^{-1}

Sample heat gain calculation (January, east wall):

$$Q = \frac{\#days \times heat\ gain\ rate \times area\ of\ glass \times 0.83 \times 3600\,\frac{\mathrm{s}}{\mathrm{hr}}}{10^9\,\frac{\mathrm{J}}{\mathrm{GJ}}}$$

$$Q = \frac{(31)(230)(12.2)(0.83)(3600)}{10^9} = 0.26\ \mathrm{GJ}$$

Gross area of the opening is used, so the 0.83 factor accounts for the area taken up by framing, plus the shading due to the window being recessed part of the way into the wall.

Table 17 – Estimated solar heat gains through the glass (in GJ).

Month	East wall	West wall	North wall
January	0.259	0.259	0.181
February	0.472	0.472	0.318
March	0.866	0.866	0.594
April	1.198	1.198	0.375
May	1.463	1.463	0.671
June	1.525	1.525	0.812
July	1.575	1.575	0.814
August	1.350	1.350	0.568
September	1.002	1.002	0.350
October	0.653	0.653	0.194
November	0.305	0.305	0.212
December	0.191	0.191	0.142
Sum	**10.9**	**10.9**	**5.2**

Total solar heat gains = 26.9 GJ

<u>Calculate steady-state heat conduction losses through the envelope:</u>

Degrees days: 5708.2 (from Environment Canada)

RSI of BV1: 3.859 $m^2 \cdot K \cdot W^{-1}$ (by the isothermal planes method)

Apart from these two differences, calculation is the same as demonstrated previously for the degree day method.

$$Q_{total} = \frac{(153.6\text{m}^2)(5708.2\text{K}\cdot\text{days})}{\left(11574\frac{\text{days}\cdot\text{J}}{\text{s}\cdot\text{GJ}}\right)\left(3.859\frac{\text{m}^2\cdot\text{K}\cdot\text{s}}{\text{J}}\right)} + \frac{(38.4)(5708.2)}{(11574)(0.5)} + \frac{(144)(5708.2)}{(11574)(7.044)} + \frac{(144)(2922)}{(11574)(1.0)}$$

$Q = 103.9$ GJ

<u>Summary:</u>

Gains: Occupancy: 16.6 GJ

Solar heat: 26.9 GJ

Losses: Conduction: 103.9 GJ

Air leakage: 85.9 GJ

<u>Net heat loss = 146.3 GJ</u>

$$Q_{consumed} = \frac{146.3}{0.85} = 172.1 \text{ GJ}$$

$Cost = [(172.1)(5.04) + (365.25)(0.77)] \times 1.05$

Annual heating cost = $1211.67

Life Cycle Cost

Repointing of mortar on building 2, 30 years in the future

Begin by estimating the cost of repointing today. RS Means (2007) gives the unit cost to be $68.00/m² (including overhead and profit).

A quantity takeoff reveals that there is 1604 m² of brick on building 2, so the 2007 US national average cost to repoint would be:

$$\frac{\$68.00}{m^2} \times 1604m^2 = \$109{,}000$$

Simply multiply by the city and historical cost indices to convert to a 2011 dollar value in Edmonton:

$$\$109{,}000 \times 1.108 \times 1.119 = \$135{,}000$$

We must make the assumption that the intrinsic value of the service does not change in 30 years. This may not be accurate, but it is impossible to predict the effects of improved technology and techniques, or labour surplus (or shortage) in the future. If the value of the service stays constant, the only change from present value to future cost is caused by inflation. Assuming 2% rate of inflation, the future cost of repointing in Edmonton will be:

$$\$135{,}000 \times \left(1 + \frac{2}{100}\right)^{30} = \$245{,}000$$

However, the net present cost of a future expense certainly isn't the amount it will cost in 30 years, because money saved today will accumulate interest. The future expense must be devalued using the rate of return on investment:

$$\$245{,}000 \times \left(1 + \frac{6}{100}\right)^{-30} = \$42{,}600$$

In other words, investing $42,600 today with 6% return on investment will cover the cost of repointing the mortar (including inflation) on building 2 in the year 2041.

Moisture Management Performance of Building Enclosures

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Submitted: 13 April 2011

ABSTRACT

Aesthetic problems, serviceability issues or even health concerns in buildings may be attributed to moisture damage. This paper will discuss the different situations in which moisture problems develop, the mechanisms that cause it, and consider different solutions that may be used to prevent or mitigate any concerns or issues that arise. Moisture in a building envelope is a product of air movement, vapour diffusion, liquid flow or capillary suction. Three general building envelope systems that are widely used to mitigate problems from this moisture sources are the perfect barrier, moisture storage and drained/vented systems. Each of these systems has their own specific advantages and disadvantages depending on how and where they have been used. A better understanding of the mechanisms that cause moisture issues and how each system utilizes different moisture control methods will lead to more effective and durable building envelopes.

Keywords: Building Envelopes, Condensation, Vapour, Capillary, Evaporation, Air Movement, Face-Sealed System, Moisture Storage System, Screened and Drained System

INTRODUCTION

The methods in which building envelopes are designed to handle moisture have always been difficult and challenging. Moisture problems occur in all buildings and climates, therefore no single method may be generalized to be a perfect solution. Aesthetic problems, serviceability issues or even health concerns in buildings may be attributed to moisture damage.

This paper discusses the different situations in which moisture problems develop and the mechanisms that cause it, and consider different solutions that may be used. Moisture in a building envelope is a product of air movement, vapour diffusion, liquid flow or capillary suction. Three general building envelope systems that are widely used to mitigate moisture problems from these sources are face sealed/perfect barrier, moisture storage and drained/vented systems.

Face sealed systems consist of a wall with a layer designed to be impermeable to moisture and penetration. Moisture storage systems or otherwise known as mass storage walls rely on the walls ability to store free water if water drainage is not sufficient. Drained systems are used when water is expected to penetrate the exterior face of the wall, and provide protection for the subsequent layers. There are several forms of drained systems that will be discussed in more detail.

Each of these systems has its own specific advantages and disadvantages depending on how and where it is used. Many parameters can govern the choice of moisture management systems such as location, climate, building use and even building shape and size. A better understanding of the mechanisms that cause moisture issues and how each system utilizes different moisture control methods will lead to more effective and durable building envelopes.

MECHANISMS OF WATER VAPOUR

In order to understand how to adequately design for water vapour, the mechanisms of water vapour transport, wetting, storage and drying process must be reviewed.

Transport Process

Vapour Diffusion

Vapour diffusion is the least powerful water transport process and has only been used in practice since the 1980's, as it was not initially recognized until the 1950's (Straube 2002a). Even though the driving force for vapour diffusion is weak, it is continuously occurring and cannot be ignored.

The process of vapour diffusion is quite complex but can be simplified as the movement of water vapour in air from higher to lower vapour pressures (WUFI 2001). The relative humidity, temperature and moisture content of the air are the controlling factors of vapour pressure (Trechsel 2001). Water vapour will diffuse to where the relative humidity or moisture content is low as it tries to find an equilibrium vapour pressure state as shown in Figure 12.

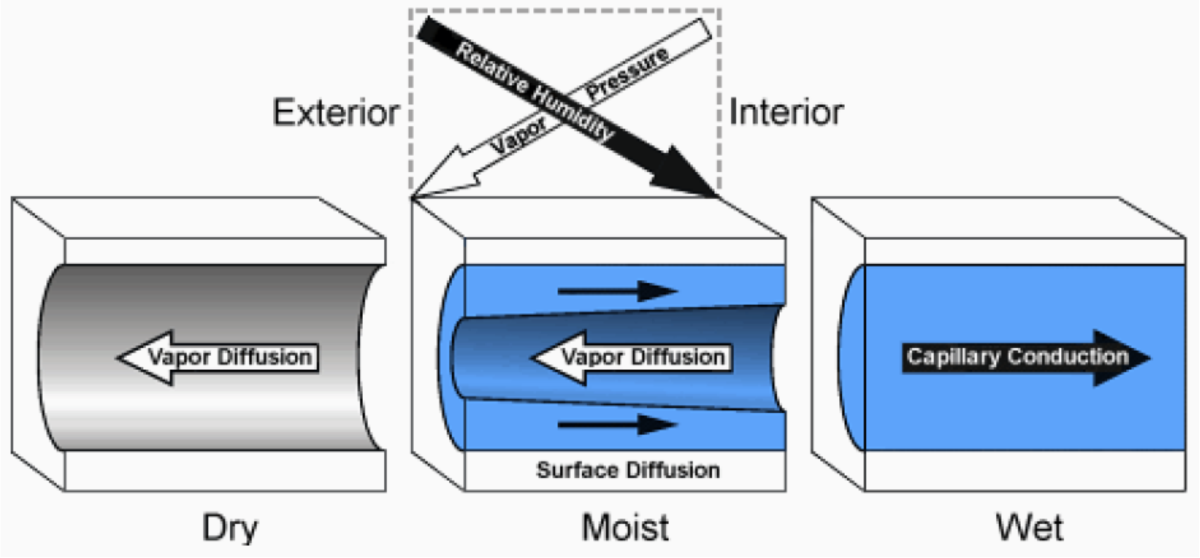

Figure 12: Moisture Transport in Pores for Different Levels of Moisture Content (WUFI 2001)

Vapour diffusion does not consider the transport of air itself, instead it is focused only on the water vapour moving through the air. Therefore, water vapour cannot be transported through nonporous materials by diffusion (Straube 2002a). On the other hand, vapour movement through a porous material by diffusion is possible and is governed by a few parameters. First, a larger vapour pressure differential on either side of the material face will induce a stronger diffusion force. Also, more water vapour will be able to diffuse through a larger exterior surface area. Finally, water vapour will diffuse more easily through a thinner material (Trechsel 2001). Equation 1 quantifies the vapour diffusion flux through a material, m_v (kg/s/m²), based on the material permeability, k_a (kg/Pa/s/m), and the vapour pressure difference, Δp (Pa) (ASHRAE 2009).

$$m_v = - k_a \Delta p \qquad [1]$$

Vapour Convection

Vapour convection is the strongest water vapour transport process but is still the second weakest form of moisture transport. Since it only takes a small convection of air to move much more water vapour than diffusion, vapour convection is considered the primary transport process of water vapour (Straube 2002a).

The process of vapour convection is related to air convection because water vapour is suspended in air and will follow its transport process. Air convection is caused by either a temperature or pressure difference and will transport suspended water vapour in the direction of decreasing pressure or temperature (Straube 2002b). The amount of water vapour, m_v, moved through convection is described by ASHRAE (2009) in Equation 2, which is based on the air flux, m_a (kg/s/m²), the partial water vapour pressure, p, and atmospheric air pressure Pa.

$$m_v = 0.62\, m_a\, p \,/\, Pa \qquad [2]$$

Unlike vapour diffusion, vapour convection does not transport significant moisture through porous materials but instead the majority is transported through openings between materials (Straube 2002a). The air flux through porous materials is based on the gradient in total air pressure and the materials permeability, k_a (kg/Pa/s/m), as described in Equation 3(ASHRAE 2009 and Kumaran et al. 1994). In comparison, the air flux through openings, cracks and vents is based on experimental factors C and n as shown in Equation 4**Error! Reference source not found.** (ASHRAE 2009). Therefore, air movement will drive moisture by vapour convection towards a significantly lower temperature or pressure mostly through openings within a wall.

$$m_a = -k_a\ (\Delta Pa) \qquad [3]$$

$$m_a = C\ (\Delta Pa)^n \qquad [4]$$

Wetting Process

Sorption

Sorption occurs when water vapour contacting a solid surface is captured as water molecules due to a change in relative humidity (WUFI 2001). The degree of sorption of a material depends on the material type, temperature, interior surface area, and vapour pressure (Kumaran et al. 1994). Once the vapour pressure is above a critical value for a certain temperature, sorption of water molecules will continue eventually forming droplets. As long as the vapour pressure and temperature are adequate, sorption can continue until the materials interior surface area is saturated (Kumaran et al. 1994).

Condensation

If the amount of water vapour in the air is above the air's saturation point, the water vapour will leave the air as condensation. The relative humidity indicates how close the air is to being saturated and not being able to hold any more water vapour. The amount of water vapour air can hold decreases with lower temperatures. Hence, if the air is not completely saturated during the day, at night the drop in temperature would increase the relative humidity possibly above 100% causing condensation to form (Wyrwal and Marynowicz 2002). Similarly, if air that is not completely saturated comes in contact with a cold wall, large amounts of condensation can form in the pores of the wall. A simple psychrometric chart shown in Figure 2 is used to determine whether condensation will form. For example, at a room temperature and relative humidity of 25°C and 40%, 100% saturation and condensation will occur at 10°C as illustrated in Figure 2.

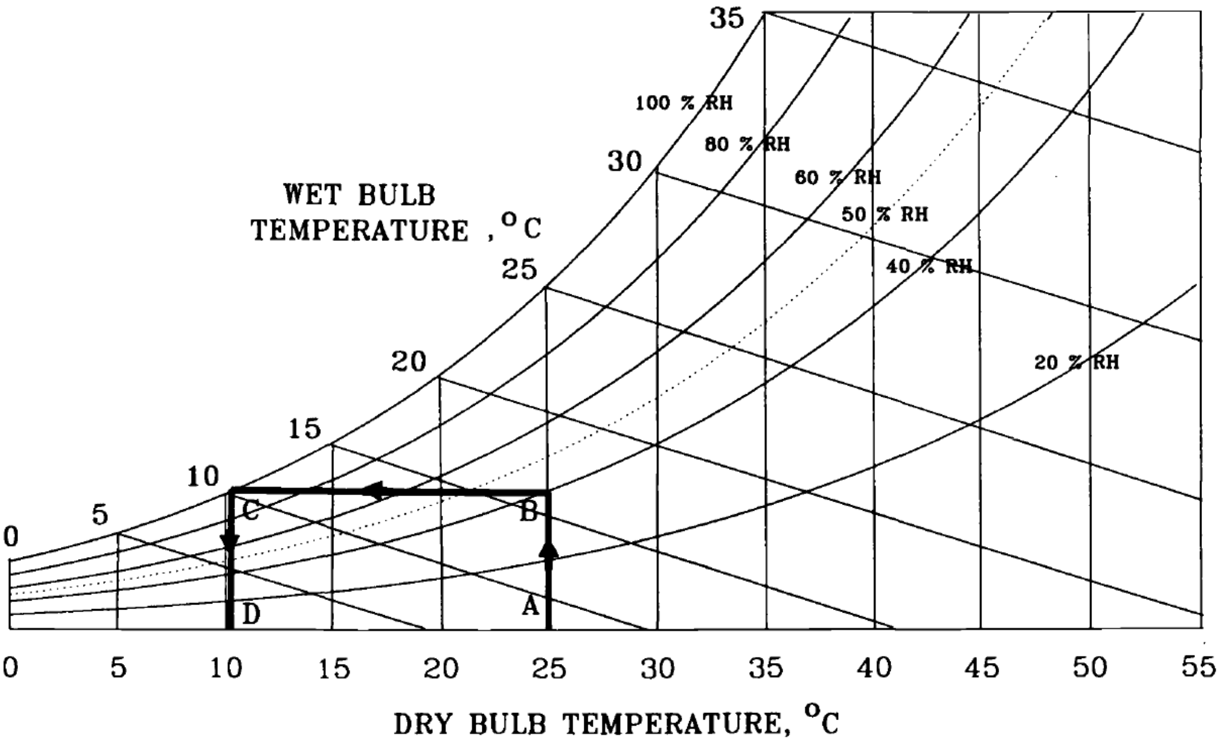

Figure 2: Psychrometric Chart (Kumarane et al. 1994)

Moisture Storage

Adsorbed by Material

The distorted tetrahedral arrangement of a water molecule causes the centroid of the positive charges to be different from the centroid of the negative charges as illustrated in Figure 3. For this reason, a spatially unbalanced distribution of charges exists, causing the water molecules to perform like a magnet (Straube 2002b). Adsorption is caused by the water molecule magnet attaching itself to a hydrophilic surface. Building materials are often hydrophilic, porous, and have a large internal surface area making them extremely susceptible to adsorption of water vapour, often holding several times their dry weight (Straube 2002b).

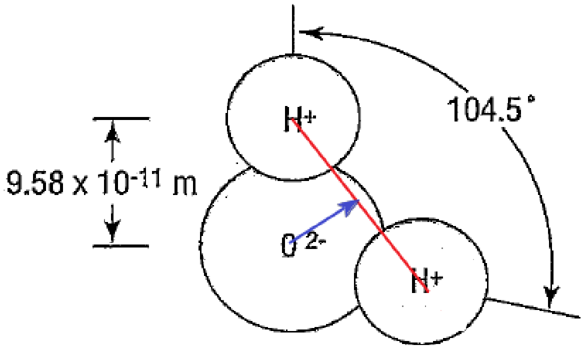

Figure 3: Water Molecule Charge Distance (Straube 2002b)

In Air

Water vapour in its natural state is dispersed in air transferred by diffusion and convection. A relative humidity of 100% indicates that the air is holding as much water vapour as possible at a certain temperature (Wyrwal and Marynowicz 2002). Saturated air inside the pores of a porous material or behind a wall in the cavity could easily change into liquid water and be a concern if the temperature drops.

Drying Process

Desorption

Since most wetting processes either cause water vapour to change phases to liquid, or are already in a liquid phase, there is not a significant amount of water vapour drying. Desorption is the reversal of the sorption process. If the vapour pressure drops below a critical value for a certain temperature, desorption of the water molecules will occur (Kumaran et al. 1994). As desorption process continues, the water molecules will return into the air as water vapour increases the vapour pressure. As the vapour pressure increases from evaporation or desorption, the moisture content in a wall cavity would have to be ventilated out in order to completely remove the moisture (Straube 2002b).

MECHANISMS OF LIQUID WATER

Transport Process

Capillary Suction

Capillary suction is the second strongest of the four moisture transport processes but is the weakest form of liquid water movement. Although capillary suction is the slower liquid water transport process, it can continuously move large amounts of water for many years (Straube 2002a). The mechanism of capillary suction is quite simple to predict since it is due to a single material phenomena, surface tension, as illustrated in Figure 4.

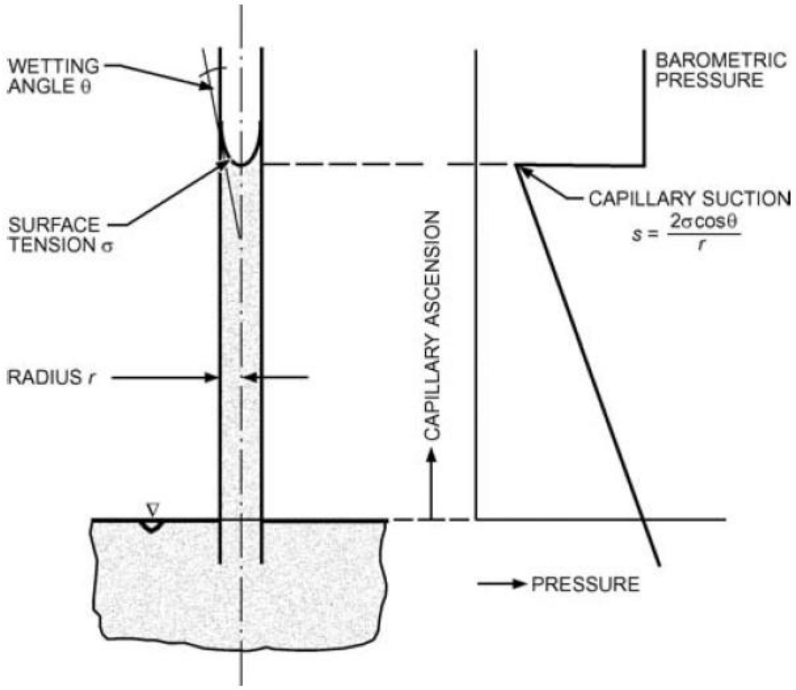

Figure 4: Capillary Rise in Hydrophilic Materials (ASHRAE 2009)

The driving capillary tension force results from the surface tension at the interaction between water and air around the meniscus (WUFI 2001). The pore radius, r (m), the water surface tension, σ (N/m), and the interaction angle of the material, θ (°C), are the controlling factors for capillary suction, s (Pa), quantified by Equation 5(ASHRAE 2009). Similar to vapour flux equations, ASHRAE (2009) and Kumaran et al. (1994) calculated the liquid flux, m_l (kg/s/m^2), as shown in Equation 6 based on the materials permeability, k_a (kg/Pa/s/m), and the gradient in capillary suction, Δs from Equation 5.

$$s = 2\ \sigma \cos\theta / r \qquad [5]$$

$$m_l = -k_m (\Delta s) \qquad [6]$$

The water surface tension strength increases when temperature decreases causing the liquid water to flow towards zones with lower temperature (ASHRAE 2009). Although temperature will affect the surface tension it is negligible compared to the effect of the pore diameter and material interaction angle. A decrease in pore diameter from 0.01mm to 0.001mm will cause an increase in the distance the liquid water can rise from 1.5m to 1500m (Trechsel 2001). Even though larger capillary forces develop for smaller pore radius, larger pores can transport much more liquid, therefore larger pores and water content govern the amount of liquid flow (ASHRAE 2009).

Hydraulic Head Flow

Hydraulic head flow is the most powerful water transport process, moving large volumes of liquid water over short periods of time (Straube 2002a). Buildings have had to prevent pressure flow longer than any other moisture transport process because of its strength and obvious problems.

The process of hydraulic head flow is caused by the hydraulic head forcing liquid water through cracks, openings and macropores (Straube 2002b). The hydraulic head is governed by Bernoulli's equation, which states that the sum of the pressure head, P/γ (m), gravity head, z (m), and velocity head, $v^2/(2\rho)$ (m), must stay constant along a liquids path as illustrated in Equation 7. Hence, if there is a decrease in pressure or height, the velocity of the liquid must increase, initiating liquid flow.

$$P / \gamma + v^2 / (2\rho) + z = \text{constant} = \text{hydraulic head} \qquad [7]$$

Hydraulic head forces will be eliminated by opposing capillary suction forces when the openings are less than one millimeter (Straube 2002a). Therefore, pressure flow will not occur through a typical porous material but will find cracks or openings where it can flow through.

Wetting Process

Wetting Absorption

When liquid water is in contact with porous material absorption can occur. Liquid water will only be able to wet the surface and larger pore holes by absorption (ASHRAE 2009). Capillary effects will pull the moisture into the material allowing more absorption to occur near the surface.

Moisture Storage

Capillary Pores

Capillary suction will store moisture in the cracks and pores of a material after the material has reached adsorption saturation (Straube 2002b). Liquid water will be stored in smaller pores by capillary suction first and then move into the large pores until complete saturation (ASHRAE 2009). After the material is completely saturated, the influence of capillary action will decreases since there is no longer a water and air interaction meniscus surface (Richards 1931). Figure 5 demonstrates that as the moisture content increases towards saturation, the capillary potential is essentially lost. If there is a pressure or temperature differential, the water in the pores will attempt to flow out of the material at which point capillary forces will resist flow at the air interface, holding the stored moisture.

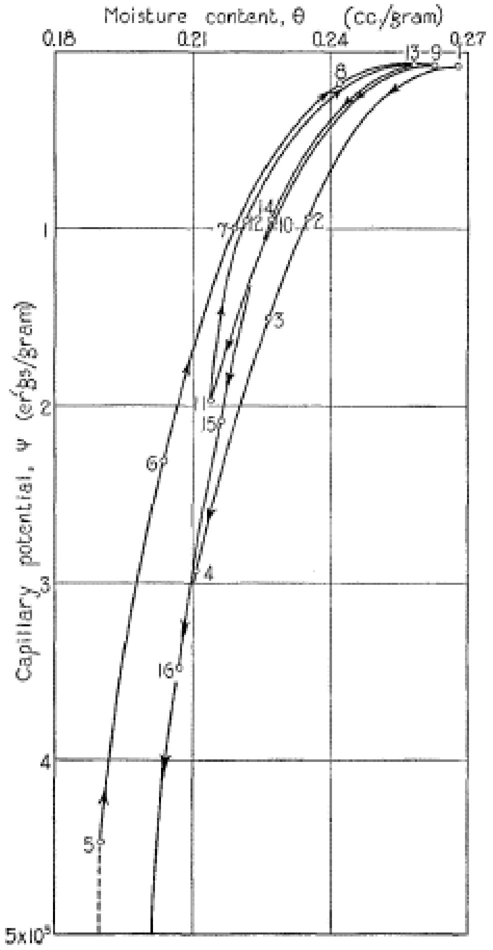

Figure 5: Moisture Content versus Capillary Potential (Richards 1931)

In Pools and Depressions

The simplest form of moisture storage is in pools and depressions within the material or in the joints. The liquid water flows into the depressions by hydraulic head forces where large volumes of water can gather. Since the depressions are the lowest hydraulic head location, moisture will not be able to flow out by hydraulic drainage but must evaporate. The large flow of water by hydraulic head into the depressions and the slower drying process of evaporation ensures that the depressions are the last location where moisture is lost.

Drying Process

Hydraulic Head Drainage

Hydraulic head drainage is the exact same as the transport process, resulting from the hydraulic head force (Straube 2002b). Liquid water will drain in the direction of decreasing pressure or height according to Equation 7. Moisture will not be able to flow out of a saturated porous material by hydraulic head drainage since capillary suction forces will resist the hydraulic head in pores smaller than one millimeter (Straube 2002a).

Evaporation

When the amount of water vapour in the air is below the saturation point, the liquid water will evaporate into the air, which is the reverse of condensation. Hence, if the air was saturated in the morning, during the day the rise in temperature would decrease the relative humidity causing the liquid water to turn into water vapour (Wyrwal and Marynowicz 2002). As mentioned, drainage will not be able to remove the water in a saturated porous material because capillary and adsorbed moisture requires more energy to break the attractive forces than hydraulic head can provide (Straube 2002b). Instead, the water on the surface of the material will evaporate, then capillary forces will bring the water from the interior of the porous material to the surface to be evaporated (Straube 2002b).

CONDENSATION CONTROL STRATEGIES

Temperature changes on moving air in a building envelope may cause condensation on either the exterior surface of the envelope or within it. These problems may be reduced by proper design of joint and connections, as well as use of physical barriers such as vapour and air barriers.

Air Movement

The action in which air travels from the interior to the exterior is called exfiltration, and the opposite direction of air travel is called infiltration. Whether or not the action is exfiltration or infiltration, air movement is dependent on the wind velocity, intensity and its direction. In general, if the condensation occurs on the exterior or interior surface of the wall, several strategies have been developed to control this effect. However, in some building systems the condensation may accumulate within the building envelope itself (Hatzinikolas and Korany, 2005). Condensation trapped inside the walls would be difficult to inspect and would likely only be detected once problems have already developed such as mould, steel corrosion or defects to the aesthetics. In order to control problems with condensation, it is important to understand the circumstances and situations where air is forced to move.

Wind Induced Condensation

Wind is a primary culprit inducing pressure differentials through a building envelope. As the air travels around a structure, it may increase or decrease the relative pressure outside of the building compared to inside. The windward face of a building will typically develop a higher pressure on the exterior and cause infiltration through any joints or defects in the building envelope as illustrated in Figure 6. The opposite effect can occur on the leeward side of the building. In either case, there is the risk that air may condensate if it is cooled enough along its path between the interior and exterior of the structure. If the path for air flow is short, such as a crack through a wall, the air will travel through the wall fairly quickly, and condensation will form just around the crack. If the path between the two climates is not as direct, condensation forms in areas that cannot be inspected or easily repaired.

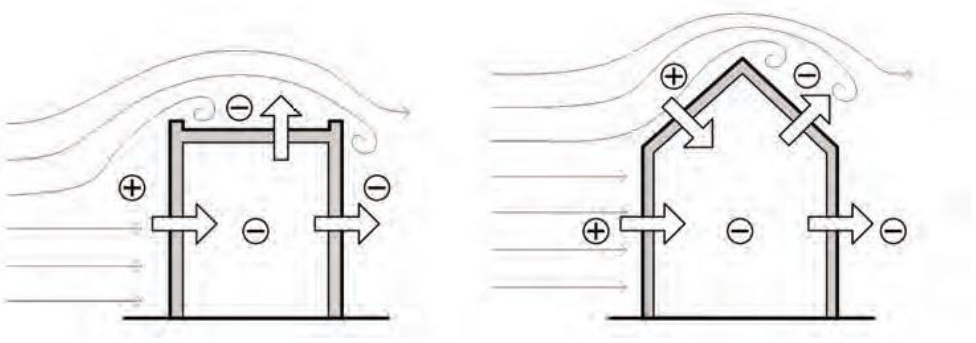

Figure 6: Wind pressure effects on different building shapes (Straube, 2007)

Wind has also been found to have a larger impact on exterior corners of buildings. Exterior corners have poor air circulation, lower insulation practices due to methods used to frame corners, greater surface area, and the potential for wind-washing (Lstiburek and Carmody, 2004). These issues can result in moisture damage occurring on the interior side of the wall for heated buildings. This is not good since heated buildings are often designed to prevent condensation for the exterior and not the interior.

Stack Effect

For taller buildings heated in cold climates, pressure differentials will also form due to temperature and air density changes as warm air rises through the building. This is called the stack effect (Straube, 2007). Figure 7 shows how warmer air at the top of the building will develop a greater tendency to exfiltrate compared to the air near the base of the building. If the building is tall enough, the difference in temperature and pressure may result in infiltration at the bottom. Therefore exfiltration at the top will require careful detailing for controlling condensation at different locations of the building. The stack effect is the main reason why moisture problems are found on the upper areas of heated buildings rather than at the base (Lstiburek and Carmody, 2004).

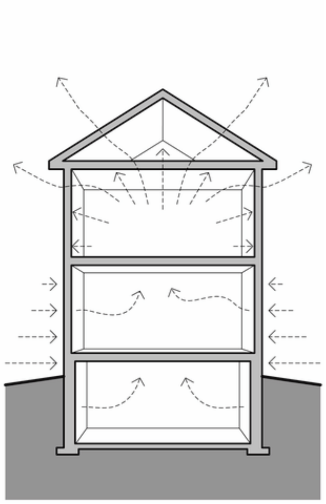

Figure 7: Illustration of air flow for Stack Effect (Straube, 2007)

Controlling Condensation with Air Barriers

It is unreasonable to attempt to design and construct a building envelope that could be considered completely air tight and sealed from the exterior air pressures. Construction joints and connections for windows and doors are always prone to developing cracks and seams where air passage may occur. It is possible though to mitigate the problem to a great extent by using an air barrier throughout a building enclosure. Figure 8 is an example of how air barriers are located in a building envelope.

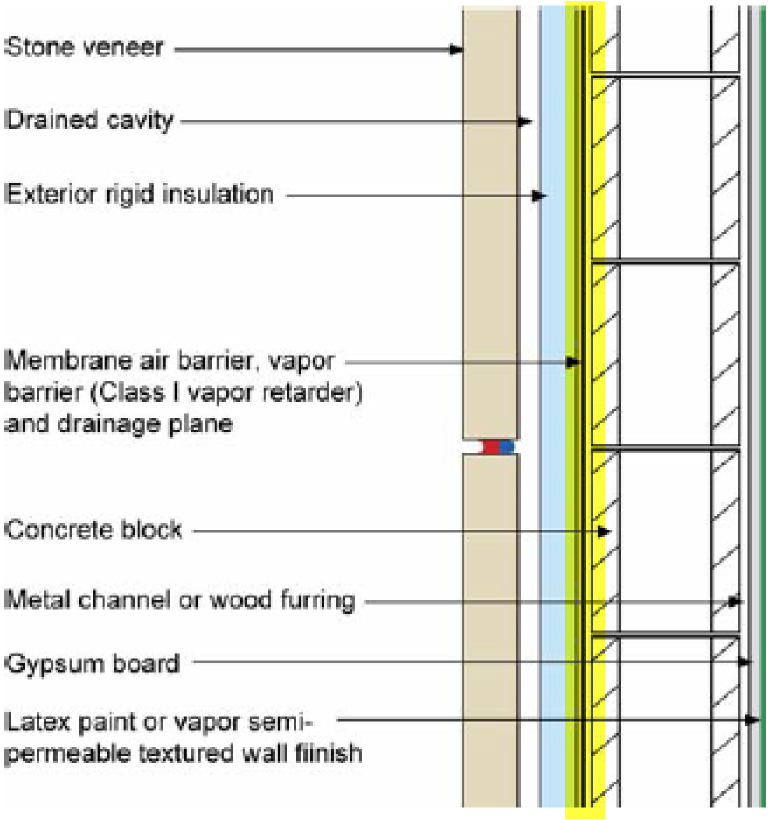

Figure 8: Example of air barrier placement (Lstiburek, 2006a)

Materials that are tested according to the Standard Test Method for Air Permeance of Building Materials, ASTM E 2178, with a result less than 0.02 *l*/s/m^2 at 75 Pa of pressure are considered to be an acceptable air barrier. Air barriers should not be confused with vapour barrier materials. An air barrier will not prevent the movement of physical water nor would it prevent vapour diffusion. Its sole purpose is to act as a resisting membrane against the pressure differentials between the exterior and interior of the building (Lstiburek, 2006b).

The locations of where air barriers should be used are highly dependent on the climate of the building. For example, northern climates have a larger tendency to experience exfiltration, therefore the ideal location would be within the interior of a wall system. The effectiveness of the air barrier will be dependent on the attention to detail during construction as it must be continuous. Any gaps or openings will allow for localized condensation problems and neglect the purpose of using a barrier. If localized condensation is at areas where corrosion may be an issue, the structural integrity of a wall could be compromised.

Vapour Diffusion

Vapour Permeability

Vapour diffusion is often mistaken or confused with condensation due to air movement. The condensation due to vapour compared to the condensation due to air flow differ in their location within the building enclosure. With vapour diffusion, the condensation can occur anywhere on the exterior surface, if air is travelling from interior to exterior of a wall. Some studies showed that a 1 inch square hole under 10Pa differential pressure moved 100 times more water vapour than diffusion through a 32 ft^2 gypsum board (Lstiburek, 2006b).

To determine the permeance of materials, ASTM E-96 is used to find the water vapour permeance of the material also known as perm (Lstiburek, 2006b). Materials are commonly categorized based on whether they are vapour impermeable, vapour semi-impermeable or vapour semi-permeable, as listed in Table 1. To prevent the condensation from occurring vapour barriers are commonly used to mitigate the risk of vapour diffusion.

Table 18: Material permeability ratings (Lstiburek, 2006b)

Vapour Impermeable	≤ 0.1 Perm
Vapour semi-impermeable	≥ 0.1 Perm ≤ 1 Perm
Vapour semi-permeable	> 1 Perm
Vapour permeable	Greater than 10 perms

Vapour Barriers

While air barriers were used to prevent the flow of air, vapour barriers are used to prevent vapour penetration through the exterior materials. In general, it is impossible to stop vapour diffusion so vapour barriers are considered merely as retarders (Lstiburek and Carmody, 2004). In cold climates, vapour barriers are placed on the interior side of the wall, whereas in warm climates the vapour barrier may be on the exterior surface. In general the vapour barrier should be located on the side of the wall that will be exposed to higher vapour pressures and warmer temperatures (ASHRAE, 2009).

A common issue with vapour barriers is that often they are placed in situations where they may be unintentionally trapping water within the building envelope. The National Building Code of Canada defines that only one layer of vapour barrier is permitted as water may get trapped between multiple layers of vapour barriers (Hatzinikolas and Korany, 2005).

RAINWATER PENETRATION CONTROL STRATEGIES

Liquid Flow

The direct impact of water in liquid form has a greater effect on building envelopes than any other mechanism. The three control strategies to lower the risk of liquid flow damage are to deflect, drain and dry. (Straube, 2006) The common goal that all three of these strategies have is to reduce the probability of having the wall becoming oversaturated.

Sloped roofs and overhangs can have a huge impact on reducing the risks of having walls with problems due to rain as shown in Figure 9. Overhangs help shelter portions of the wall from direct impact of the rain.

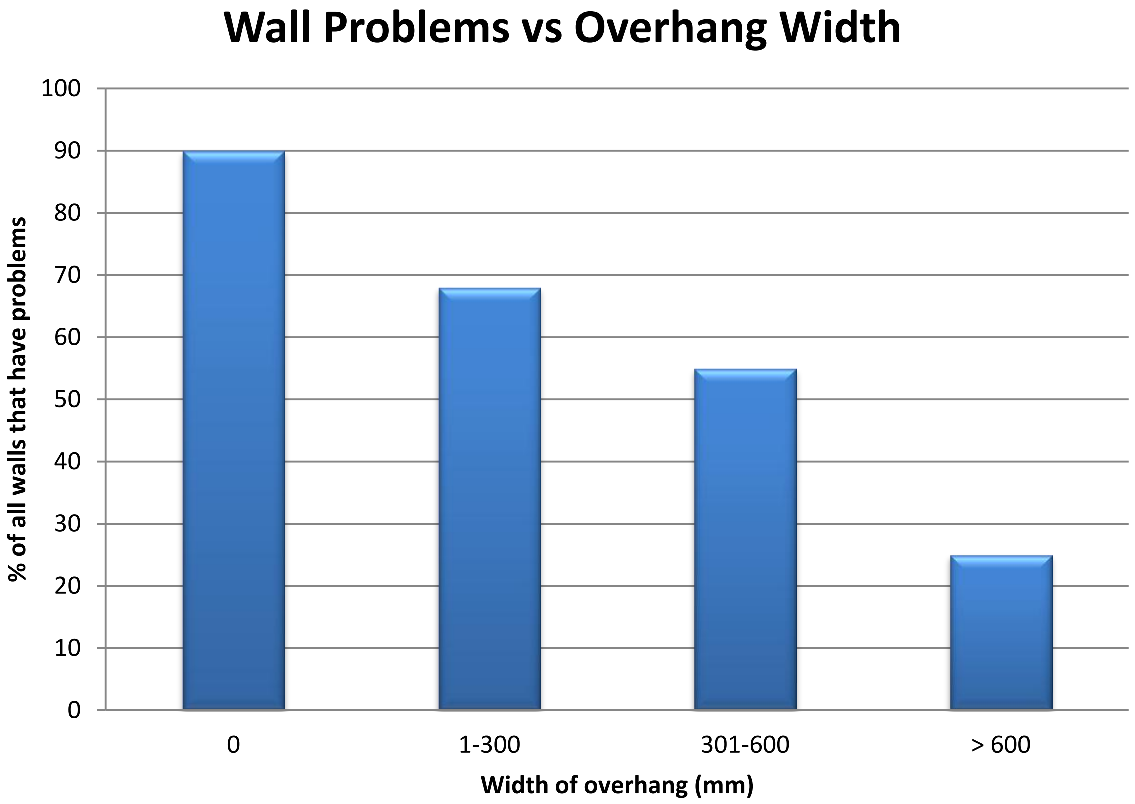

Figure 9: Wall problems with respect to overhang size (Straube, 2006)

Methods to deflect water on the rest of the wall surfaces would be any means of breaking the flow of water. Drip stripes, slopes or trims will help redirect the flow of water or force the water off the wall. Careful attention may be required as a poor design would result in water being redirected to sensitive areas such as doors or windows where there may already be openings for air flow as discussed earlier.

For building envelopes where water is expected to get in, it is strongly recommended that methods of drainage be provided. The sooner the water can exit the wall the better. Providing an air space between the structural wall and the veneer allows water to drain under gravity. Flashing can be placed at the bottom of the cavity to force water to flow out of the building envelope.

Drying of walls may occur from evaporation, vapour transport, drainage or ventilation. Designing the wall to get maximum exposure to sunlight will greatly expedite the drying process on the wall surface. Vapour transport and drainage of the wall may be mitigated by the control strategies mentioned earlier. Ventilation drying of wall surface can be due to wind pressure differences that develop along the surface of the wall or by rising air that has been heated by the sun (Straube, 2006).

Capillary Suction

Capillary suction is a very common issue for walls that are below grade. It may also occur on exterior surfaces where splash back may occur and water gets trapped in porous areas. Capillary suction can be managed by controlling the possibility of capillary action, sealing pores, increase pore size or provide a method in which moisture can be collected (Lstiburek and Carmody, 2004).

Walls Below Ground Level

For walls that are below the ground surface there is only one solution for reducing the risk of capillary suction, sealing the pores. Being buried in the ground makes it difficult to deflect water from the surface of the wall. Buried walls are the foundation of the structure, and increasing the pore sizes of concrete can be detrimental from a structural engineering perspective. Sealing the pores is the most effective method used in current construction methods. Sealant materials will provide a more impervious layer on the surface of the wall reducing the likelihood of capillary suction of the water coming in contact with the wall surface. Dampproofing by using a bituminous type sealant is a typical way of sealing concrete pores in foundations (Lstiburek and Carmody, 2004). For buildings in climates that can vary significantly between hot and cold temperatures, sealing a below ground wall is essential in mitigating the risks of freeze thaw damage which is much harder to repair than in exposed walls.

Exposed Walls

Similar to walls below grade, walls above grade may experience problems with capillary suction if the wall material is porous. Painting or sealing the exterior surface of the wall will help reduce the permeability. Use of siding is also a common method to assist with shedding water off the surface, although, capillary suction often still occurs between the laps of the siding (Lstiburek and Carmody, 2007). To prevent water from being absorbed into the wall behind the siding, it is recommended to provide either an air space between the siding and the wall, or have impermeable sheathing. Ultimately, there are many different combinations that are used but they all have the same goal to remove water from the surface of the wall in order to reduce the opportunity for capillary suction.

DESIGN ENCLOSURES FOR MOISTURE CONTROL

Rain water control design strategies can be categorized in many ways. A particularly common characterization is to define three systems termed the face sealed/perfect barrier, moisture storage and vented/drained. Under this categorization, additional topics which would classify as subjects within the broad definitions will be considered. The aspects of moisture penetration addressed by each of these systems have similarities and differences. In practice, concepts from each may be incorporated into another system which conforms to the description of a different category. In fact, it may not be possible to limit a system strictly to one of these three categories. However, a dominating strategy will exist in most cases and the need to understand the primary mechanism of moisture management each system employs helps to enhance an appreciation for both its strengths and weaknesses. Regardless of the system there are performance requirements that must be met and the penetration of water through the entire assembly will constitute a failure. Other performance requirements may also come into consideration and damaging or durability reducing effects caused by moisture penetrating into sensitive layers must be addressed as these may also amount to a failure of the system (Straube 2005). The ASTM Manual 40 (Trechsel 2001) states that the design process should account for the following three objectives, "(1) Establish appropriate levels of performance for building and components (i.e., the limit states), (2) prescribe performance criteria for materials, components, and assemblies, and (3) confirm acceptability and achievement of performance". This section will try to deal with the achievement of the performance component of the third point. This will be the first step to tackle more complex design issues, but first it is necessary to understand the characteristics of each system.

Face-Sealed/Perfect Barrier System

The face sealed/perfect barrier wall has a layer which is designed to be impermeable to moisture penetration. In the case that the exterior wall serves this purpose the wall is called face sealed, otherwise the term concealed barrier is used (Straube 2005). The moisture deterrence layer and the performance of the system are conditional to repelling all moisture accumulated on the surfaces of the barrier layer. In order to remain functional, impenetrability must be preserved. In practice such a strict requirement may not be achievable as exposure to environmental loads including rain, sunlight and temperature differentials may have the effect of breaking down the systems resistance. Therefore, the successful application of the face sealed system is contentious as it only attempts to eliminate pathways for direct moisture movement instead of other potential driving forces (Straube 1999). In practice, a redundancy in the system is advisable to reduce the impact of a breach in the impenetrable layer. Redundancies can include the strategies used by other systems including methods for allowing moisture storage or having a way to drain the penetrating moisture.

The demands placed on the barrier of the system include not only environmental conditions, but also the aesthetic requirements which may result in an accelerated potential for deterioration (Straube 2005). Due to the variation between interior and exterior temperatures, large stresses may be placed on the cladding connections or on the joints between system components (Chown et al. 1997). The potential for damaging effects of water trapped can be particularly damaging in cold environments where the potential for freeze/thaw cycles exist. In order to mitigate these risks, a maintenance program which addresses the potential of cracks or fissures in the seal, which are capable of transporting moisture inward, is necessary for longevity and durability (Straube 1999).

Moisture Storage System

Moisture storage systems are often referred to as mass storage walls. The moisture storage or mass wall relies initially on its ability to shed a significant portion of the rainfall present on its surface. The water that is not shed is handled by the walls ability to absorb water, therefore this system is limited by its capacity. Water penetrating the face of the system will move inward through capillary actions. Any additional moisture in excess of the amount the system can shed and absorb will result in failure to keep moisture out of the enclosure. The water stored in the walls is dissipated through evaporation between rainfall events. This leaves the wall susceptible to adverse weather because a certain amount of time is required in order to disperse the water held in storage. Therefore, under rainfall events that occur in close proximity to one another, the wall may not have time to dry and the potential of failure is increased. A factor that can help manage these risks is the heat provided from the interior of the building since it can aid in evaporation in cooler climates (Straube 1999). A traditional solid masonry wall is a common example of moisture storage system. The durability of this type of system is dependent on the water content in the wall which is a function of, among other things, the climate conditions of the region, the drying capability of the wall and the duration and frequency of rainfall events (Trechsel 2001). In cooler climates the inability to release moisture from storage can leave this type of system in a similar situation to a perfect barrier wall as both are susceptible to damage from freeze/thaw cycles.

Screened and Drained System

In a drained/vented system the passing of water through the exterior face is expected. The function of the exterior face is to restrict the amount of water moving into the subsequent layers. The water that does penetrate the first layer is drained from the system. This is often accelerated through venting of the drainage cavity. It is necessary with this system to have a highly impermeable layer within the wall as some moisture will accumulate or penetrate the exterior layers and the system must restrict its movement to the interior of the building. Drained and vented systems can be further classified as simple rainscreen, cavity wall, vented rainscreen and pressure equalized rainscreen. Each of the classifications is discussed in more detail below.

Simple Rainscreen and Drained Cavity Wall

The simple rainscreen and drained cavity wall are composed of two principal layers. The first is a cladding or rain resistant layer. In addition to the cladding a water resistive barrier is used as a last line of defence. The water resistive layer is a continuous barrier between moisture and the interior of the building. The distinction between a simple rainscreen and a drained cavity wall is that the moisture barrier serves as the air barrier in the rainscreen wall (Straube 1999). The two systems address the kinetic force of rain which is stopped by the cladding and leave the cavity to address capillarity and gravity (Straube 1999). The major difference is in their ability to handle pressure differences resulting from wind (Kerr 2004). The rainscreen is able to counter the driving force of wind and has the added advantage of being easier to seal and having greater protection from environmental degradation caused by rain and ultraviolet rays (Kerr 2004). However, the ability of rainscreen walls to handle pressure differences is somewhat limited as air within the cavity can flow laterally to areas of low pressure at corners or the tops of buildings which can limit pressure equalization (Straube 1999).

Pressure Equalized Rainscreen

Pressure equalized rainscreens have the added feature of sealed compartments which form a series of chambers which restricts lateral air flow within the cavity (Straube 1999). It is necessary that the compartments be sealed at all corners and at the roofline in order to prevent windward air being drawn into the cavity and getting to areas of negative pressure (Kerr 2004). The area and volume of the compartments are designed to reduce the variation in air pressure across them (Straube 1999). The specifics regarding the number and geometry of vent holes for pressure equalization is based on the passing of adequate air flow into and out of the cavity to react to gusting winds. This will minimize the pressure difference across the compartments and lessen the rain-driving force (Chown et al. 1997).

Additional Rain Prevention

The use of other strategies to limit the amount of moisture which is allowed to reach the building envelope surfaces are also very useful in controlling any resulting damages. The Canada Mortgage and Housing Corporation have a guide (Kerr 2004) which lists a number of other factors to consider when choosing a moisture control strategy. These include the environmental conditions or exposure level, the driving rain wind pressure (DRWP), the annual driving rain index (ADRI) and moisture index (MI). The interested reader is referred to (Kerr 2004) for a more detailed discussion on how these factors may be incorporated into a design strategy. The Moisture Control Handbook (Lstiburek and Carmody 2004) also classifies environments into heating and cooling. A heating climate is a climate in which atmospheric temperatures require that heating of the interior of the building envelope must take place. A cooling climate requires cooling of the interior air due to the extreme heat of the local environment. The distinction helps to clarify what factors are likeliest to require a design consideration based on which environment the building is located.

Design Tools

Once a strategy is chosen, the elements of a system must be analyzed in order to determine if the loadings induced will exceed the resistance of the system. The tools that are available to the engineer or architect fall into two broad categories. Manual design methods allow for the relatively simple calculation of parameters which affect the durability and failure of the building envelope. There are also more sophisticated hygrothermal models which are reliant on proper input data and the use of computing power to run the simulations. These computer methods will not be discussed here as they are beyond the scope of this paper. The interested reader is referred to Chapter 10 of ASTM Manual 18 (Trechsel and Bomberg 2009) or several of the chapters in ASTM Manual 40 (Trechsel 2001) for further discussion and a more comprehensive list of references. The designer also has at their disposal a number of standards, codes and guidelines to help inform their decisions and aid in the use of effective systems being implemented. Table 19 adapted from the information in Chapter 24 of ASTM Manual 18 (Trechsel and Bomberg 2009), lists a number of standards and guidelines along with a brief summary of their applicability.

Table 19: Design Codes, Standards and Guidelines 1

Standard/Guideline	Affiliation	Name	Summary
CSA S478(2001)	Canada	Guideline on Durability in Buildings	Advice for incorporating requirements for durability into design, operation and maint.
EN ISO 13788:2001	European	Hygrothermal performance of building and building elements - Internal surface temperature to avoid critical surface humidity	
EN ISO 15927:2003	European	Hgrothermal performance of buildings calculations and presentation of climatic data	Part 1: specifies procedures for calculating and presenting monthly means of some aspects need to asses moisture performance
CMHC		Best Practice Guides	Guides including recommendations for engineers, many subjects published
EEBA		Builders Guides	Compendia of illustrations and resources on building design and systems which includes their relationship to moisture control

Manual Methods

The manual design methods consist of the dew point method, the Glasser diagram and Kieper diagram. These are steady state tools based on vapour diffusion theory. The use of any of the manual methods must be done with an awareness and care for their appropriateness as they, “impose severe limitation on applicability and interpretation” (ASHRAE 2009). These methods all work by comparing vapour pressures from the interior of the building envelope to saturation pressures (Trechsel and Bomberg 2009). The saturation pressures are those from within the envelope based on interior temperatures. It should be noted that these methods only account for vapour diffusion to the exclusion of all other driving force mechanisms of moisture penetration (Trechsel and Bomberg 2009). In specific, these tools should be used to predict mean conditions over a month or on a seasonal basis rather than a daily or weekly period (ASHRAE 2009). An example of the dew point method and the Kieper diagram will illustrate their use. Example 1, illustrating the use of the dew point method, is taken directly from the 2001 ASHRAE Handbook of Fundamentals (ASHRAE 2001) and is also presented as in an adapted form in ASTM MNL 18 (Trechsel and Bomberg 2009). Example 2, demonstrating the Kieper diagram and its application is taken explicitly from ASTM MNL 18 (Trechsel and Bomberg 2009) and is in reference to the same problem stated in Example 1.

Equation 8**Error! Reference source not found.** for vapour diffusion is an adapted form of Equation 1 and is the basis for the dew point and Kieper methods.

$$w = -\mu \frac{\Delta p}{d} \tag{8}$$

where

w = water vapour flux through a layer of material, ng/s•m^2

μ = water vapour permeability of material, ng/(s•m•Pa)

Δp = vapour pressure difference across the layer (Pa)

d = thickness of the layer, m

If we express the inverse of permeance, μ/d, known as the water vapour resistance, Z then

$$Z = d/\mu$$

and the water vapour flux can be written as

$$w = -\frac{\Delta p}{Z}$$

This equation is the basis of the solution methods presented in the following examples.

Example 1: Dew Point Method

The dew point method is illustrated in reference to the materials described in **Error! Reference source not found.** for frame wall construction. The interior of the building has a temperature of 21°C and relative humidity as 40%. The outdoor temperature is -6.7°C and the relative humidity is 50%.

Table 3: Approximate Vapour Diffusion & Thermal Properties

Air Film or Material	Thermal Resistance R m^2•K/W	Permeance M ng/s•m^2•Pa	Diffusion Resistance Z Pa•m^2•s/ng
Air Film (still)	0.12	9200[a]	0.00011[a]
Gypsum board, painted	0.0079	290	0.0035
Insulation	1.9	1700	0.00058
Plywood sheathing	0.11	29	0.0345
Wood Siding	0.18[b]	2010[b]	0.005[b]
Air Film (Wind)	0.03	57000[a]	0.000017[a]
Total	2.42	NA	0.0391

[a] Approximate values; permeances of surface films are very large compared to those of other materials and do not affect results of calculations

[b] Approximate values; permeance reflects limited ventilation of back siding

Step 1: Calculate the temperature drop across each material

The R-value of the material, which is the ratio of the temperature difference across to the heat flux through a material, is used as the temperature drop is proportional to this value using Equation 9.

$$\frac{\Delta T_{material}}{\Delta T_{wall}} = \frac{R_{material}}{R_{wall}} \tag{9}$$

The temperature drop across the materials and resulting temperatures at the surfaces are presented in Table 20.

Table 20: Calculated Temperature, Surface Temperatures and Saturation Vapour Pressures

	Temperature Drop	Surface Temperature	Saturation Vapour Pressure at Surface
Air Film or Material	**⁰C**	**⁰C**	**kPa**
Indoor air		21	2.496
Surface air Film	1.3		
Interior wall surface		19.7	2.299
Gypsum board	0.9		
Gyp. Board/Insulation		18.8	2.168
Insulation	21.9		
Insulation/Sheathing		-3.1	0.4843
Plywood sheathing	1.2		
Sheathing/Siding		-4.3	0.442
Wood Siding	2.0		
Exterior wall surface		-6.3	0.3796
Surface air film	0.3		
Outdoor air		-6.6	0.3701

Step 2: Find the saturation vapour pressure

These values for saturation vapour pressures at each surface are presented in table X3 and were derived from psychrometric tables and charts, see Figure 2. They may also be located in tables 6a and 6b of ASTM MNL 18 (Trechsel and Bomberg 2009).

Step 3: Obtain the vapour pressure drop across each of the materials

The relationship that governs the drop of vapour pressure is very similar to that of the temperature drop as shown in Equation 10.

$$\frac{\Delta p_{material}}{\Delta p_{wall}} = \frac{Z_{material}}{Z_{wall}} \qquad [10]$$

where

p = vapour pressure, Pa

Z = vapour diffusion resistance, Pa•m²•s/ng

From Table 20 we can calculate the total resistance of the wall as:

Z_{wall} = 1/9200 + 1/290 + 1/1700 + 1/29 + 1/ 2010 + 1/57000 = 0.391 Pa•m²•s/ng

The vapour pressure drop is calculated using the indoor and outdoor saturation vapour pressures (SVP) and relative humidity's (RH) as illustrated in Equation 11.

$$\Delta p = p_{indoor} - p_{outdoor} = RH_{indoor} \bullet SVP_{indoor} - RH_{outdoor} \bullet SVP_{outdoor}$$

$$\Delta p = (0.4)2.496 - (0.5)0.3701 = 0.8314 \text{ kPa} \qquad [11]$$

Table 21 lists the results of similar calculations performed at the surfaces of each material.

Step 4: Determine if condensation is present

We must compare the saturation vapour pressures to the calculated vapour pressures to determine if the calculated values exceed saturation values indicating that condensation is present. If we notice that the initial calculated vapour pressure on the surface of the sheathing (0.9124 kPa) is almost twice the saturation vapour pressure at that location (0.4843 kPa) it is determined that condensation is present.

Table 21: Initial & Final Calculations of Vapour Pressure Drops and Surface Vapour Pressures

	Saturation Vapour Pressure kPa	Initial Calculation Vapour Pressure kPa		Final Calculation Vapour Pressure kPa	
Air Film or Material		**Drop**	**At Surface**	**Drop**	**At Surface**
Indoor air (rh=40%)	2.496		0.9986		0.9986
Surface air Film		0.0024		0.0135	
Interior wall surface	2.299		0.9962		0.9851
Gypsum board		0.0716		0.4292	
Gyp. Board/Insulation	2.168		0.9246		0.5559
Insulation		0.0122		0.0716	
Insulation/Sheathing	0.4843		0.9124		0.4843
Plywood sheathing		0.7169		0.2951	
Sheathing/Siding	0.442		0.1955		0.1892
Wood Siding		0.0101		0.0040	
Exterior wall surface	0.3796		0.1854		0.1852
Surface air film		0.0003		0.00014	
Outdoor air (rh=50%)	0.3701		0.1851		0.1851

Step 5: Select the condensation surface

The interior surface of the plywood sheathing represents the location where the calculated vapour pressure exceeds the saturation vapour pressure by the greatest amount. With saturation occurring at this location we must set the calculated vapour pressure to equal the saturation vapour pressure as seen in Table 21.

Step 6: Recalculate the vapour pressures

Changing the vapour pressures on the sheathing surface changes all the other pressures as well as the vapour flow and they must be recalculated. Vapour pressures will be calculated similar to step 3, the only difference being that the wall will be separated into two parts. The first part is interior to the plane of condensation. The second part is exterior to this plane. The vapour pressure across the part of the wall interior to the condensation plane is

$$\Delta p_1 = 0.9986 - 0.4843 = 0.5143 \text{ kPa}$$

the drop over the exterior part of the wall is

$$\Delta p_2 = 0.4843 - 0.1851 = 0.2992 \text{ kPa}$$

the vapour diffusion resistances of the respective parts of the wall are

$$Z_1 = 1/9200 + 1/290 + 1/1700 = 0.0041 \text{ Pa}\cdot\text{m}^2\cdot\text{s/ng}$$

$$Z_2 = 1/29 + 1/2010 + 1/5700 = 0.035 \text{ Pa}\cdot\text{m}^2\cdot\text{s/ng}$$

the vapour pressure drops across each material are calculated using Equation 12.

$$\frac{\Delta p_{material}}{\Delta p_i} = \frac{Z_{material}}{Z_i} \qquad for\ i = 1,2 \tag{12}$$

The results of the final vapour pressure calculations are presented in Table 21. The condensation plane was chosen correctly as can be seen by the fact that vapour pressure no longer exceeds the saturation pressure. This in turn affects the vapour flow. The vapour flow into the wall from the interior air increases and the vapour flow to the outside from the wall decreases. The difference in the two is the resulting moisture accumulation rate, w_c, given by **Error! Reference source not found.**.

$$w_c = \Delta p_1/Z_1 - \Delta p_2/Z_2$$

$$w_c = 0.5413/0.0041 - 0.2992/0.035 = 117\ \mu\text{g}/(\text{s}\cdot\text{m}^2) \tag{13}$$

The resulting accumulation is approximately 10 g/day•m^2. In this example the surface of the plywood sheathing is below zero and the condensation would likely accumulate as frost resulting in an increased plywood moisture content of 1% in a week.

Example 2: Kieper Diagram

The demonstration of the use of the Kieper diagram is in reference to the problem stated in Example 1. The advantages of using the Kieper diagram are twofold. First it is applicable to different wall configurations under the same temperature conditions and second it is not necessary to recalculate the vapour pressures in the case of condensation occurring. The method uses two parameters, *x* and *y*. The parameter *x* represents the thermal properties of the materials in the wall and parameter *y* the vapour diffusion properties as described in Equation 14and Equation 15 respectively, where R_i is the R value and Z_i is the Z value of the ith material. These values can be between 0 and 1.

$$x_1 = R_1/R_{wall}$$

$$x_2 = x_1 + R_2/R_{wall}$$

$$x_n = x_{n-1} + R_n/R_{wall} \tag{14}$$

$$y_n = y_{n-1} + Z_n/Z_{wall} \tag{15}$$

The temperature in the wall shown in Equation 16 is expressed as a function of x.

$$T(x) = T_i - x(T_i - T_0) \tag{16}$$

where

T_i = indoor temperature, ^{0}C

T_o = outdoor temperature, ^{0}C

The net moisture flow to a point in the wall, according to whether or not condensation or evaporation is present, at that location (x,y) is given by Equation 17.

$$w_c = \frac{1}{Z_{wall}} \frac{p_i - p_s[T(x)] - y(p_i - p_0)}{y(1-y)} \tag{17}$$

where

w_c = moisture accumulation rate, kg/m^2•s

p_i = indoor vapour pressure, Pa

p_o = outdoor vapour pressure, Pa

$p_s[T(x)]$ = saturation vapour pressure, Pa

Condensation is indicated if w_c is positive and evaporation if w_c is negative. This implies that w_c represents the wetting/drying potential at a specified location within the wall. A rearrangement of the terms in the **Error! Reference source not found.** gives us Equation 18.

$$w_c Z_{wall} = \frac{p_i - p_s[T(x)] - y(p_i - p_0)}{y(1-y)} \tag{18}$$

Expressed in this way, a curve in the Kieper diagram where $w_c Z_{wall}$ is constant is an indication of an "equal wetting potential". A curve having a zero wetting potential is referred to as the condensation barrier. Using the values in Table 3, Figure 10 was determined and it is shown that the curve (dashed line) penetrates the condensation region. The deepest penetration point in the condensation region, corresponding to the plywood sheathing layer, is the point of greatest wetting potential. This point is located between curves *d* ($w_c Z$ = 3386 Pa) and *e* ($w_c Z$ = 5080 Pa). Using linear interpolation the wetting potential value is $w_c Z$ = 4740 Pa. Given that Z = 39.7 10^9 m/s the estimated rate of accumulation is w_c = 4740/[39.7 10^9] = 120 10^{-9} kg/m^2•s = 120 μg/m^2•s.

This value is very close to the value of 120 μg/m^2•s calculated for w_c in Example 1.

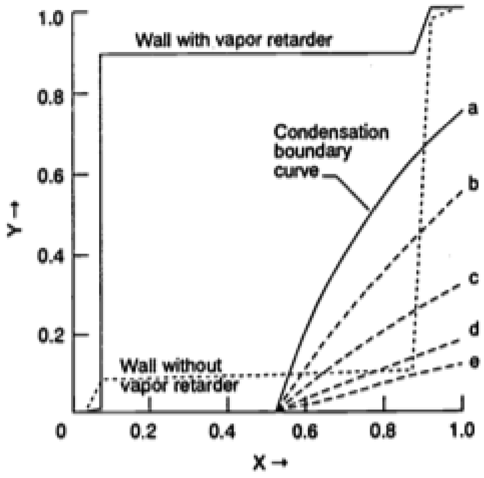

Figure 10: Kieper Diagram. W,Z values for the curves are (a) 0 Pa, (b) 677 Pa, (c) 1693 Pa, (d) 3386 Pa, (e) 5080 Pa (Trechsel 2001)

SUMMARY OF DESIGN CONSIDERATIONS

The issues that have been presented as most relevant to design include environmental conditions and driving forces. Lstiburek and Carmody (2004) classify the moisture management solutions based on the environment for which the building is located which are presented in Table 6. This allows for easier consideration as to what factors may govern potential failures of the moisture management system. In attempting to choose the most appropriate moisture management systems this table will list issues to gauge what design parameters will help to mitigate the most severe concerns you will face. From there it can be determined whether a face sealed, moisture storage or a screened/drained system is most suitable and how you can incorporate the elements listed in the table into your design. The manual methods presented can aid in determining whether condensation will occur within the chosen system, but must be used with care and proper application. More detailed methods of evaluation are available and references to their use and applications are Trechsel (2001) and Trechsel and Bomberg (2009). Moreover, there also exist guidelines, standards and codes to aid in the design process. A few of them are listed in Table 2.

Table 6: Design Recommendations

Environment	Relevant Moisture Penetration Consideration
Heating	(1)Reduce moisture in the interior air (2)Install vapour diffusion retarder on interior (warm) side (3)Eliminate air inlet/outlet openings (4) Control air pressure differentials
Cooling	(1) Control rain via rain screen or barrier wall (2)Provide a capillary break (3)Install vapour diffusion retarder on exterior (warm) side (4) Eliminate air openings (5) Control air pressure differentials

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Review of Building Envelope Failure Mechanisms, Diagnostic Tools, and Repair Strategies

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ABSTRACT

A review of various building envelope failures, including moisture, wind, and structure related failures. Deterioration mechanisms, including chemical, mechanical, and biological attacks and the consequences of envelope failure are investigated. Inspection and diagnosis tools, including drawing reviews, visual inspections, smoke testing, thermo-graphic imaging, water spray testing, and selective demolitions, as well as recommendations for a diagnosis procedure. Recommendations for repair processes focusing on the use of masonry, and a case study of a building envelope failure, and repair, of a masonry structure in a cold climate.

Keywords: building envelope, failure, diagnosis, repair strategy

INTRODUCTION

The intent of the building envelope is to act as the physical barrier between the internal and external environments. Failures of the building envelope can cause a multitude of issues ranging from superficial blemishes, structural deterioration (wood rot, corrosion) and biological issues like mould. Building envelope failure typically falls under three different categories: moisture related failures, wind related failures, and structure related failures. Although all building envelope malfunctions can cause serious issues, the most severe issues typically arise from moisture related failures as building envelopes that suffer from wind or structure related failures inevitably experience moisture related failures if left unrepaired.

A structure's building envelope can often appear intact to an outside observer; however, there can be various deterioration mechanisms present that suggest a building envelope is not performing as intended. These deterioration mechanisms are chemical, mechanical and biological (Trovato, 2011); the underlying cause of most of these degradation issues is moisture. When symptoms of these deterioration mechanisms are present within a building, it is indicative that the building envelope is not performing as intended. When this occurs there are several inspection and diagnosis tests that can be performed. Many of these are non-destructive diagnostic techniques such as a drawing review, visual inspection, smoke testing, thermo-graphic imaging, and water spray testing; although, in many cases selective demolition is inevitable to determine the exact cause of the problem.

The diagnosis and repair of a failed building envelope can be costly and time consuming. An example of this can be seen in the case study of Building X in this report. The investigation and subsequent repair required considerable resources to undertake. For this reason, it is critical to properly design and construct the building envelope initially in order to prevent failure. Consequently, it is important that critical thinking be employed at all times by designers, contractors, and construction workers.

Failure of a building envelope system will be defined for this paper as any condition whereby the envelope no longer performs the intended function. This can include moisture ingress, thermal leakage, air leakage, excessive staining or damage to finishes, mould, rot, or excessive deformation. It is noted that the serviceability of the structure does not necessarily need to be impacted for the envelope to be considered failed. For example, buildings that experience thermal leakage will often still perform the required function, but utility costs will increase substantially. Building envelope failures and defects will be considered together in this paper.

GENERAL PRINCIPLES

To understand building envelope failures, it is necessary to have a basic understanding of the general principles behind building envelopes. Three things are required for moisture to infiltrate the building envelope: the presence of water, an opening, and a force to drive moisture through the opening. The elimination of any of these factors will reduce the potential of water penetration (Ricketts, 1999). The existence of water can be from outdoor moisture (rain, snow, etc.), moisture from construction, or internal humidity. The pathway for water can result from an intentional opening (vents, drainage holes), porous materials, at the interface of materials and building components, or unintentional openings (failed sealants, shrinkage cracks, etc.). Finally, the driving force can be from kinetic energy, capillary action, surface tension, gravity, air pressure differentials or any combination of the aforementioned. To design for these factors, there are 3 wall design approaches that are typically employed:

- Face seal
- Concealed barrier
- Rain screen/PERSIST

The face seal wall design illustrated in Figure 1 is designed such that there is only one line of defence against the elements. The barrier is directly on the outer side of the wall assembly. In theory this type of wall construction is good; however, since there is no air space or second line of defence, the face seal wall is very vulnerable to workmanship and sealants must be frequently maintained. A substantial issue that arises within this system is due to the fact that a watertight and airtight outer skin makes for a moisture trap if water enters the system. This system is only effective in locations that are subject to low wind and rain loads (DuPont Tyvek, 2006).

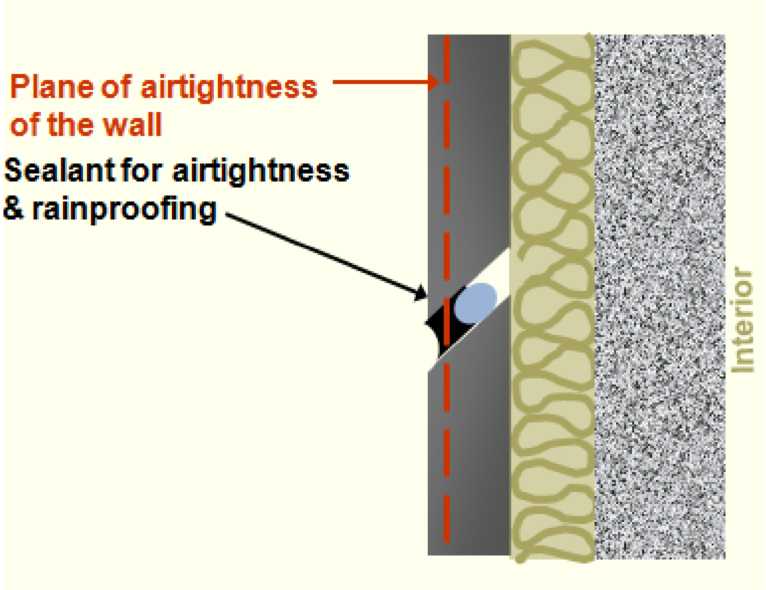

Figure 13 - Face Seal Wall System (image courtesy of Read Jones Christoffersen)

The concealed barrier system is similar to the face seal system but relies on an additional layer (typically water resistive barrier membrane) behind the face seal for moisture penetration control (DuPont Tyvek, 2006). This type of wall system is cost effective, hence, commonly seen in house construction (stucco system) and is effective in locations that are subject to moderate wind and rain exposure.

The rain screen system and pressure equalized rain screen insulated structure technique (PERSIST) are wall envelope systems that are commonly seen in modern construction. The rain screen wall assembly assumes that some moisture will enter into the assembly and is designed to facilitate drainage and drying. This is done by constructing a wall system that has a rain screen, to prevent the majority of moisture from entering the system, as well as an air chamber/air barrier system to keep the pressure equalized on either side of the exterior cladding and to allow for drainage (Rousseau et al., 1998). Flashing is also commonly present to aid in the drainage of water from the system. The PERSIST wall system, seen in Figure 2, is a variation of the rain screen system wherein the structure is insulated on the exterior resulting in a structure that is kept at a constant temperature (Trovato, 2005). This design method is highly effective but also much more expensive to design and build.

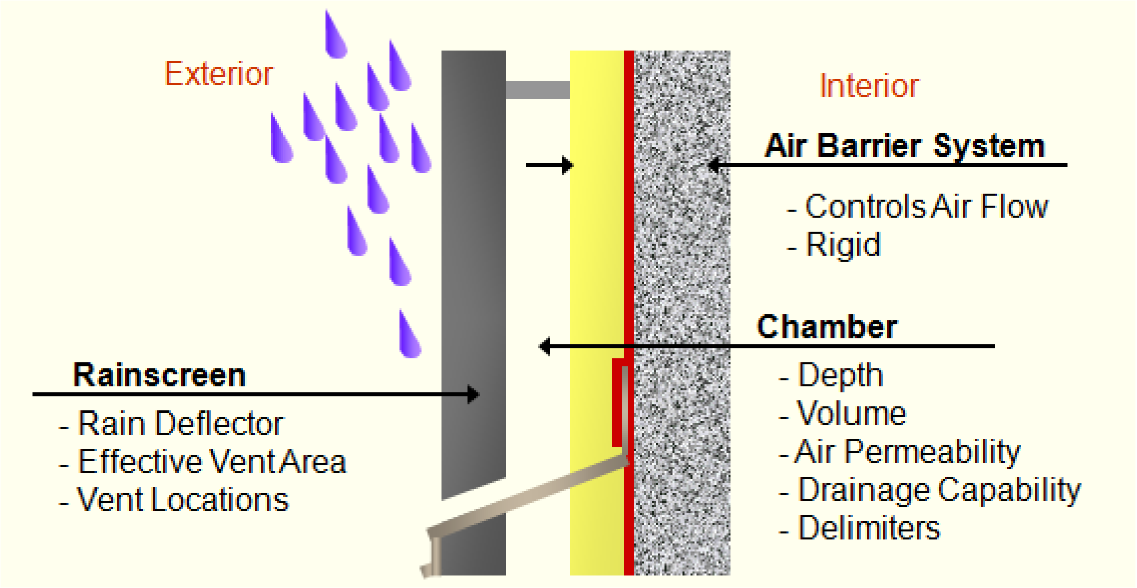

Figure 14 - PERSIST Wall System (image courtesy of Read Jones Christoffersen)

FAILURE MODES OF BUILDING ENVELOPES

Building envelopes are designed to separate the interior function space of a structure from the outside elements. According to Hatzinikolas and Korany (2005), the main environmental considerations of a building envelope are: heat transfer, moisture flow, air leakage, condensation, rain penetration, and sound transmission.

According to Donnan (2010) there are a number of causes of building envelope defects such as poor quality (design and construction), lack of knowledge about building envelopes, poor workmanship, and hiding errors during construction. The lack of understanding of building envelope systems can lead to errors in decision making regarding the construction process.

Poor workmanship is often the cause of construction defects in general. This also holds true for defects in the building envelope. High quality products will not perform in the manner that they are intended to if they are not properly installed. Similarly, details will not perform as expected if not built properly. Unfortunately poor workmanship is an ongoing problem, but there is a solution. This problem can be solved with more on-site inspection and supervision, as well as more education. Poor product choice and poor detailing are typically the results of lack of knowledge or poor planning. When designing a building envelope, critical thinking is essential. A designer must be intimately familiar with the products available and details must be well thought out.

As a building ages, the chances of failure increase due to the building being subjected to more physical damage. In addition to this, older products will deteriorate over time so it is important to properly maintain the building and its components throughout its life. Roofing assemblies, windows, and doors are just a few of the building envelope components that will deteriorate over time. All facets of the building envelope should be inspected and maintained regularly, particularly when damage occurs. Overall, a lack of understanding is typically the main cause of building envelope failure.

Moisture problems, cited as the most common envelope failures by Donnan (2010), wind related failures, and structural inadequacy leading to envelope failures, will all be discussed in the following sections.

Moisture Related Failures

Moisture problems can be the result of moisture inherent in the building materials we use, the penetration of rainwater into the building envelope, or through condensation as warm air cools as it moves through the envelope system. These different sources of moisture all require careful consideration and detailing to prevent moisture related failures.

According to Busque (2010), concrete construction, simply as a result of the cement hydration process, incorporates water into the wall structure. The water not consumed in hydration can be released into the building and a typical 200mm concrete wall can release up to 9 L/m^2 to the interior of the building in the first few years. If not detailed properly the wall system will not be able to shed the moisture released. It is imperative that the water in the wall system have an outlet. For example, let the concrete breathe to the interior. Also, these systems should be designed, according to Busque (2010), to readily show moisture related distress as these types of distresses can lead to large scale failure. In the case of a cast-in-place wall, acting to carry load as well as enclose the structure, this could mean total collapse of the structure.

Designers of envelope systems must realize that moisture ingress is more probable than not and measures must be taken to dissipate excess moisture. One method of controlling rain ingress is the use of a double wythe wall that acts as a rain screen (Straube, 2001). The double wythe wall permits the inclusion of an air space between the masonry veneer wythe and the inner wythe. Weep holes serve to drain the air space and allow any moisture that penetrates through the outer veneer wythe to be drained to the exterior. In this fashion, water does not progress through the envelope into the interior of the structure.

Condensation is also a source of moisture within an envelope system. As warm humid air from the interior of the structure moves toward the exterior, through the envelope, condensation of excess moisture will occur where the temperature of the air drops below the dew point. Condensation should not occur. It should be stopped by providing a proper vapour retarder on the ‘warm side’ of the insulation so that the humid air cannot condense. The secondary step is to allow the cavity to vent. Proper detailing of moisture barriers, ventilation, and controlling air movements can be used to minimize moisture issues resulting from condensation, (Trovato, 2011).

Wind Related Failures

The failure of a building envelope, due to wind, can precipitate complete loss of functionality of the structure. Once the building envelope is compromised rain can enter the structure to cause moisture damage and internal pressures are developed by the wind that can result in structural damage. According to Minor (2005), the increase in internal pressures can cause roof uplift, roof sheathing removal, and start the progressive collapse of the structure. Wind related failures of building envelopes typically result in moisture and structural issues that are both discussed in other sections and will not be elaborated on in this section.

The compromise of a building envelope can quickly increase damage to a structure and increase the cost of losses dramatically. For this reason Sparks et al. (1994) recommends that the building envelope be designed for the same ultimate limit state as the structure itself. This would require that all envelope systems, walls, windows, doors, shingles, etc. be designed to resist higher wind loads to prevent the failure of the envelope.

Structure Related Failures

The movement of the structure relative to the envelope can have effect if not considered by the designer. In a case study, Donnan (2010), discusses the impact that the movement of a structure can have on an envelope system if it has not been designed to accommodate the movement. The movement of the structure under service loads caused deflections in the supporting slabs that the glazing system was unable to accommodate. This resulted in a joint opening due to movements and allowed moisture ingress.

Busque (2010) discusses a similar type of distress in which the supporting slab is extended past the glazing system for architectural reasons, see Figure 15. This extension, called an eyebrow, can provide a path for water ingress below the glazing system. The eyebrow is often coated with some form of sealant; however, if not properly designed and applied, it may not be able to span large concrete cracks in the eyebrow providing an ingress point. Again, this is another case where better understanding of structure performance is required to provide the 'best' envelope design for a given location.

Figure 15 - Slab Projection past Glazing System showing loss of coating from the concrete (Busque, 2010)

DETERIORATION MECHANISMS

The deterioration mechanism of building envelope components occurs when the building envelope has failed and external elements penetrate the building envelope. From this there are three major types of deterioration mechanisms (Trovato, 2011):

- chemical
- biological
- mechanical

These mechanisms are discussed below and the remediation of these issues is discussed in Section 6.

Chemical

Chemical deterioration is the degradation of a substrate due to chemical interactions. It often is present in the form of corrosion, subflorescence and efflorescence, as well as chemical incompatibility.

Corrosion refers to any process by which metal deteriorates or degrades (Sereda, 1961). Most commonly, corrosion is electrochemical in nature. The most common by product of corrosion is red rust, see Figure 16. Oxygen is integral for corrosion to occur; however, moisture, time, the presence of chlorides and acids, as well as temperature are significant contributing factors that affect the corrosion of metals.

Moisture is a critical factor in corrosion because in the absence of moisture, corrosion would have little to no effect. This is because the moisture will act as an electrolyte in the presence of oxygen causing an electrolytic reaction, and in turn, corrosion occurs. The more time that a metal is exposed to moisture, the more severe the corrosion will be (Straube and Burnett, 2005).

Chlorides increase the rate of corrosion and enhance its initiation. Chlorides are most commonly present from sea water, de-icing salts and soils. Acids reduce the relative humidity at which corrosion can begin. It also accelerates corrosion.

Temperature is also a factor that affects corrosion because at lower temperatures, corrosion occurs at a slower rate. The Arrhenius relation predicts doubling in corrosion rate for every 10°C increase in temperature (Straube and Burnett, 2005).

Figure 16 – Corrosion of a metal roof deck caused by water ingress. If left unrepaired, corrosion can cause structural failure in structural metal components such as the roof deck (O'Reilly, 2006)

Subflorescence is the accumulation of soluble salts deposited within the surface of cementitious materials as moisture in the wall evaporates; whereas with efflorescence, the salt accumulates on the surface (as opposed to under) (Straube and Burnett, 2005). Efflorescence is most commonly observed as a defacement of the cementitious materials as it appears to be blemished with a white film, see Figure 17. This can be an indication that there is a possibility of real damage to the cementitious material caused by subflorescence behind the surface. Subflorescence and efflorescence can not only be unattractive, but can cause failure from the large stresses that may accumulate within the material from the salt deposits. Another problem arising from this is the welcoming of more moisture into the system, causing other moisture related issues such as the aggravation of freeze-thaw damage.

Figure 17 – Efflorescence staining on a building's brick façade indicates moisture issues within the wall cavity (photo courtesy of Read Jones Christoffersen)

Mechanical

Mechanical building envelope deterioration is the degradation that is caused by physical weathering. Examples of these mechanisms are freeze-thaw, shrinkage-expansion stresses, fatigue, and impact. Not all of these deterioration mechanisms originate from moisture; however, the damage caused is almost always further aggravated by the introduction of moisture into the system.

The phenomenon of freeze-thaw damage only occurs in the presence of moisture. When moisture is allowed to penetrate a porous material, such as concrete or masonry, and there is a decline in temperature below freezing, the moisture will freeze and in turn expand causing stresses on the material. As this cycle repeats itself, the material is weakened and visible damage can occur, see Figure 6.

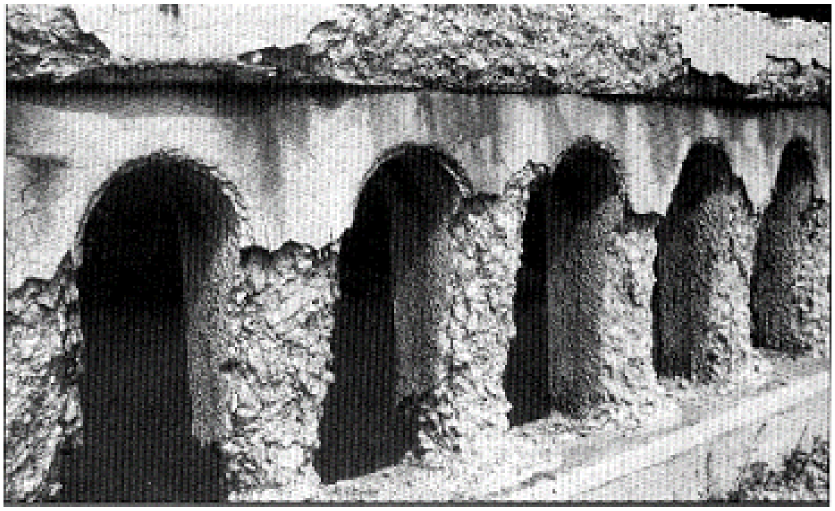

Figure 18 – The effects of freeze-thaw on an older structure (Portland Cement Association, 1998)

The rate of cooling and the temperature has a significant affect (Straube and Burnett, 2005). If allowed to continue, freeze-thaw cycles can lead to significant deterioration of a structure.

Shrinkage and expansion are reactions wherein the material contracts and expands respectively. For some materials, such as polymers, this movement is often reversible; however, in concrete or other rigid materials, this reaction is not reversible. This can result in large cracks in the material which can provide a path for air and water leakage to occur (see Figure 19).

Figure 19 – Horizontal shrinkage cracks of a concrete foundation wall allow for water to seep through the crack (photo courtesy of Read Jones Christoffersen)

Both fatigue and impact are caused by external loads. Fatigue is caused by repeated stress on a structure over a period of time. This is most common in steel, especially in bridges, and can often cause "fatigue cracks" (Straube and Burnett, 2005). In building envelopes, cyclical loads from wind and temperature changes can overstress the components.

Damage caused by impact is simply deterioration of the building envelope caused by external forces such as vandalism, storm damage, etc. This can lead to leakage.

Biological

Biological deterioration mechanisms are primarily caused by moisture; however there are some modes of degradation that can be caused by insects (termites, beetles, carpenter ants, etc.). The most common non insect-related biological deterioration mechanisms are rot, mould, fungus, and mildew. Moisture is essential for all living organisms and temperature is important for the growth of these organisms. The ideal temperature for mould is in the range of 20 to 30°C; although mould will grow, albeit more slowly, between the temperatures of 5 to 20°C and 30 to 50°C (Straube and Burnett, 2005). The growth of any type of mould, fungus or mildew can have mild to extreme adverse health effects on the occupants. In addition to this, rot and mould can cause decay of both architectural building materials (such as drywall, baseboards, etc.) as well as structural components (such as wood studs, glulams, etc.).

Figure 20- Mouldy insulation in a wood stud wall caused by water entering the wall cavity (photo courtesy of Read Jones Christoffersen)

INSPECTION AND DIAGNOSIS PROCEDURES

The inspection and diagnosis of building envelope failures is complex, and should vary from project to project depending on the severity of the failure and the type of failure. However, the general process should be similar for all failure inspections. The first step is general information gathering including interviews with tenants and owners, review of construction and as-built drawings, as well as a cursory visual inspection. This should be followed by a more detailed study of the suspected causes of the failure including in-depth visual surveys, spray and smoke testing, and any other useful tests depending on the situation. Finally, if the cause cannot be identified, selective demolition in the form of boreholes or cutting out selective areas to determine the cause should be used.

Initial Information Gathering

The initial information gathering is very useful in determining potential causes of failure and narrowing the investigation process. The first step in this process should be interviews with tenants and owners to determine the effects of the failure. As Rodrigues et al. (2011) noted the inhabitants of the building can often provide useful clues to the failure mode by detailing envelope problems such as moisture damage, heat loss, or poor acoustic insulation. They are also helpful in detailing past repair work that has occurred. This information can help investigators focus on particular areas of the structure, and look for specific failure mechanisms.

Visual Inspection

A visual survey of the building is crucial to the investigation process. Vital clues to the failure mode can be identified and sometimes the cause of failure will be immediately evident. As Peraza (2009) noted, an inward leaning parapet, see Figure 9, of a building with clay brick veneer is generally a sign of poor detailing in regards to the expansion of clay bricks. This problem often causes cracking, and decreases the façade's ability to repel moisture as well as reducing its strength.

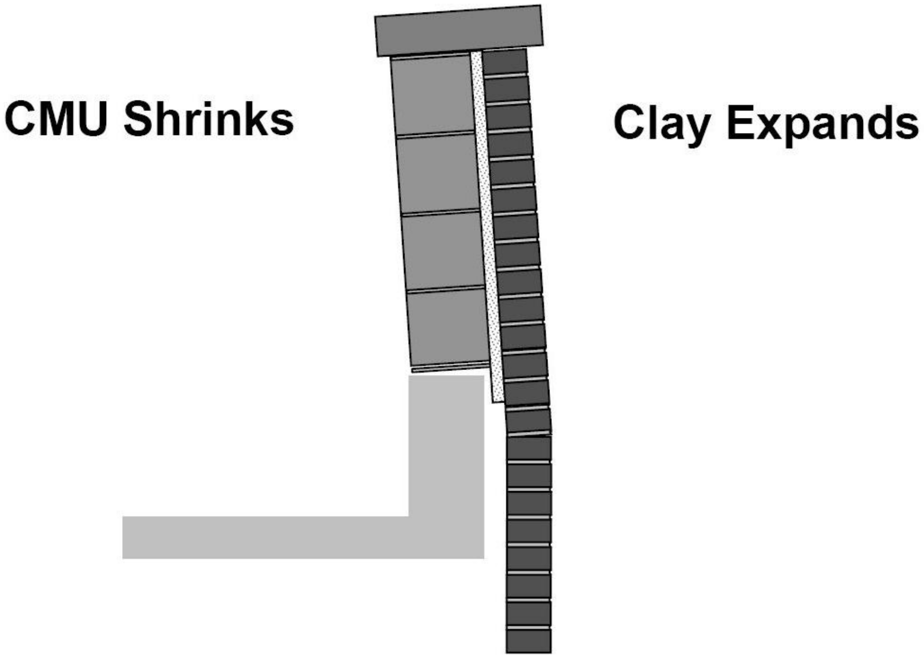

Figure 21 - Leaning parapet caused by volumetric changes in clay brick and concrete masonry units, and by lack of relieving angles (Peraza, 2009)

A visual inspection of the site can identify many problems caused by building envelope failures. For example water penetration of the envelope can generally be identified by a range of damp materials on the interior to the extreme of mould growth or rotten interior materials. While a visual inspection usually cannot identify the failure mechanism, it is very useful in identifying the type of envelope failure (Peraza, 2009). Certain visual clues suggest various failure types; corrosion can identify a moisture intrusion, and efflorescence of masonry can be indicative of air or water leakage.

A visual inspection can also be useful in identifying poor workmanship which is a very common cause of envelope failure (Ratay, 2010). For example, an inspection during construction could identify improperly installed moisture barriers. In the case of masonry buildings visual inspections are incredibly useful in identifying improper joints, and mortar finishing. This type of poor workmanship can have huge effects on moisture and temperature control within the envelope.

Drawing Review

A review of the documents associated with the building can help in identifying areas of insufficient design and poor workmanship. As Beasley (2009) noted, building envelope science has been poorly understood in the past, and is often still poorly designed due to the shared design responsibility between many parties and poor coordination between them. Often times the causes of envelope failure can be identified in the original design drawings as was the case in the Litton Reaves facility at Virginia Tech. Peterson and Shelton (2009) noted that in several areas throughout the building no account was taken to prevent air moving from the interior of the building to the exterior through the roof causing heat loss and moisture problems due to heat gradients. While this is an extreme case, there are often minor detailing problems that can be found in a thorough document review.

A drawing review is very useful in identifying the designing intent of the building envelope and bringing to light many deficiencies in the design itself. According to Ratay (2010) approximately 25% of all envelope failures are due to detailing errors. A well trained building envelope specialist will be able to identify these errors through careful inspection of all building drawings and documents.

Detailed Examination

There are many options available to investigators in determining whether identified potential problems from the initial building survey are the causes of envelope failures. Depending on the suspected cause of the failure, there are many different solutions.

Water Spray Testing

If moisture transportation is the suspected cause of failure, there are many different accepted tests that range from simple spray testing to destructive sampling including laboratory testing. However, Rens and Royston (2009) noted that the cheapest, and often most effective, test involves simply spraying the suspected area with water, and monitoring both the interior and exterior surface for moisture transportation. While this method of testing often requires removing interior cladding, it is significantly less destructive than the standard laboratory test for water penetration that requires removal of portions of the exterior façade. It also provides more substantial results as it can be used to detect cracks in the façade, not simply excess permeability.

There are many different water tests that are used to evaluate the effectiveness of a building envelope in keeping moisture from entering the building. The most commonly used tests are "spray tests conducted at measured pressure with a calibrated nozzle to detect leaks at seams and boundaries in curtain walls and glazings as quality control during installation. This simple procedure is also useful for diagnosing sources of leaks in doors, windows, and flashings in all types of walls" (Ratay, 2010). This test can be done in the field, with some modifications, to obtain fairly reliable results. In laboratory conditions it can be used to accurately measure both the quantity and rate of water penetration of the structure. Spray testing is most effective when used on areas where capillary action or other indirect moisture transportation methods are suspected.

Smoke Testing

If cracks or air leaks are the suspected failure mechanism, smoke testing is the most effective method for analysis as noted by Rens and Royston (2009). This is because the test not only determines if leaks are present, it can also illustrate the severity. Some small leaks are to be expected, especially around door and window openings, as it is extremely difficult to completely seal the façade. However, large leaks can indicate serious problems with the façade that can cause heat loss and moisture build-up due to rapid heat loss at the exterior wall.

Smoke testing is useful for identifying both the size and location of air leaks in a building envelope. Rens and Royston (2009) identified that by pressurizing the envelope with coloured smoke, any air leaks can be identified by escaping smoke. By selectively testing areas with smoke it is often possible to indentify—in a non-destructive manner—possible locations of breaches in the building envelope. Smoke testing is most effective when cracks or other potential air leaks are the suspected cause of envelope failure.

Thermo-Graphic Imaging

Thermo-graphic imaging is useful in determining heat gradients within structures. This imaging shows the temperature of various elements of the structure and can be used to identify areas where heat loss or air leakage may be occurring. Ratay (2010) suggests that this information can be used to determine locations of insulation, as well as masonry grouting. This information is critical in building envelope analysis to determine where potential heat loss problems occur. It is a very useful, non-destructive test, to determine areas where insulation is inadequate, or areas where moisture could be present inside of walls due to rapid temperature changes. The data can be used to assess moisture content problems due to heat gradients; however, specialized interpretation is required. It is recommended that experienced personnel be used to obtain and evaluate this data. The test cannot identify the cause of temperature gradients, and is only helpful in illuminating the area that requires further study.

Other Methods

Other tests are available for more difficult to diagnose cases however these methods often involve selective demolition, large costs, and interpretation. Borescopes are useful in determining whether there are any problems with the interior of the wall, (Beasley, 2009). However, they can only be used to inspect small patches of wall, and require holes to be punched through the façade in areas to be checked.

There are a number of other tests that can be used to determine the integrity of the façade such as metal detectors to check for correct rebar and support placement, and pulse velocity tests to check for voids in the material, (Kesner and Brown, 2009). While these tests are useful for specific problems, they are not practical for most envelope failure investigations.

Selective Demolition

Some selected demolition is often required to determine exact causes of envelope failures. This is because the cause is often poor workmanship that occurs between the exterior and interior walls (Donnan, 2010). While demolition is never a desired inspection technique, it is often unavoidable. However, the scope of demolition can be limited by proper use of other testing techniques. The destructive testing generally includes removal of cladding to inspect for poor workmanship or damage to interior envelope systems such as insulation and vapour barriers, (Rens and Royston, 2009). This destruction is not necessarily detrimental to the building as it is often required to affect repairs to the envelope.

Removing some interior or exterior cladding, vapour barriers, insulation, and other building envelope elements can be very useful in assessing damage, discovering flaws, and determining if the building was built to design. Generally this can be done by cutting small sections in the interior or exterior facade to expose areas of interest (Rens and Royston, 2009). This should only be used in cases where non-destructive tests yielded inconclusive results. However, one major advantage to this method is that the faulty system is already exposed, and in some cases can be replaced without other demolition being required.

REHABILITATION WORK

Rehabilitation work, to deal with a failed building envelope, will vary on a case by case basis and should be approached with care and a pre-defined plan.

The first step in assessing the proper course of action for rehabilitation of any failure is to determine the root cause of the failure. Without information to understand the reason for the failure it is difficult to repair the existing failure and prevent future failures. It is important to fully understand the wall construction as the failure may be caused by poor workmanship or a poor detail (Trovato, 2011).

Once the reason for the failure has been assessed it is necessary to determine the extent of the issues to properly understand the scope of the problem. The long term expectations of the building are important in determining the appropriate rehabilitation (Drysdale and Hamid, 2005). For example, if the building is to be sold or demolished in the near future an extensive repair to eliminate heat loss may be far more expensive than the higher utility costs in the short term. Alternatively, even if the building will be in service for an extended period of time it still may be more cost effective to utilize patch repairs instead of a full replacement. Consultation with the owner and understanding of his or her specific needs is very important in developing the correct rehabilitation plan for the owner.

In general, it is best to replace like with like to maintain the original building system (Trovato, 2011). Mixing of different envelope systems can lead to unexpected issues during the service life of the structure that cannot be accurately assessed at the time of the rehabilitation. Masonry can be used in the rehabilitation of an existing masonry wall, or in some situations, a non-masonry wall. Masonry's main advantage is that no formwork is required to provide a structural system.

The most effective uses of masonry in non-masonry rehabilitations is to use masonry to construct the outer wythe in a two wythe wall to prevent rain penetration or using an outer masonry wall in a high wind zone to protect against impact damage.

CASE STUDY – BUILDING X

Building History

Building X is a structure used primarily for classroom and laboratory space in Edmonton, Alberta. It consists of three above-grade levels, a single storey basement, and is connected to an existing building via pedway. Building X implemented the Pressure Equalized Rain Screen Insulated Structure Technique (PERSIST) as the method of building envelope design along with brick cladding with inset precast concrete sections at the 2nd floor level and corners, and high-performance glazing systems. The typical wall section is shown in Figure 10. The construction of the building was completed in August of 2000; however, just before the construction concluded, a fire occurred on a portion of the main floor of the building. Due to this setback, a section of the exterior wall between the main and 2nd floor was replaced prior to construction completion.

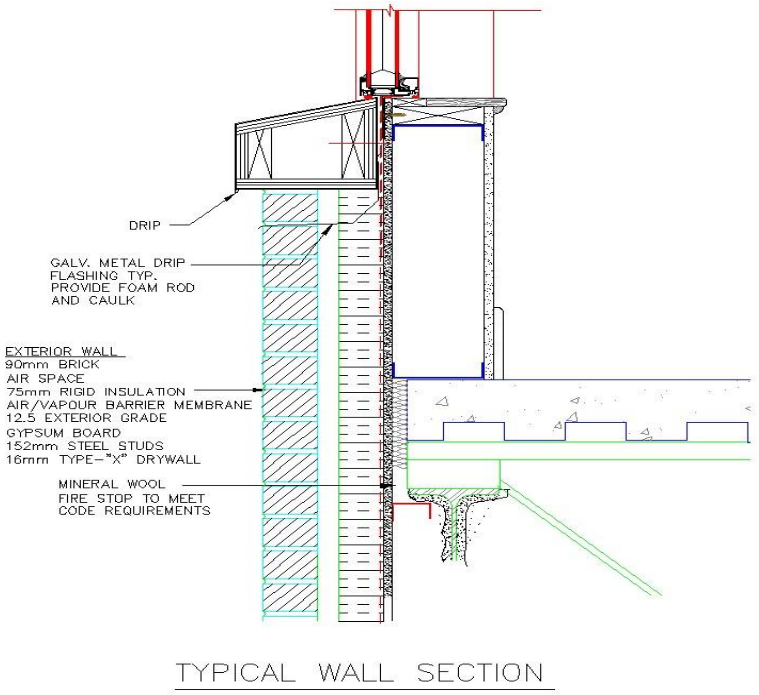

Figure 22 - The typical wall section for Building X was well detailed, implementing PERSIST

Initial Building Envelope Issues

The first building envelope issues noticed were condensation problems. These were first observed in November of 2000. Condensation was observed on the interior surfaces of many windows and water leakage and staining became evident at locations on the exterior walls. Due to these issues, the Contractor performed selected repairs in the fall of the following year. These repairs entailed sealing certain wall penetrations with air barrier foam at the interior (seen in Figure 11), repair of discontinuities of the air vapour barrier AVB at the entrance canopies, skylight, roof parapet and brick curtain wall joints as well as repair of the curtain wall itself. A short two weeks after these repairs were completed; leakage was still present throughout the building including the areas that were repaired. Humidity in the building was lowered in the hopes that the condensation related problems would cease; however, they did not. Thermo-graphic scans showed that there was air leaking in a number of locations throughout the building. In 2003 a full investigation of Building X's building envelope was carried out.

Figure 23 - Wall penetration repair had been completed after building envelope failure was first expected in hopes of solving the building envelope issues

Investigation

The investigation used many of the diagnosis methods discussed in the inspection and diagnosis section. A combination of visual inspection, review of the drawings, thermo-graphic scanning, smoke testing, and selective demolition was carried out.

Through the visual inspection, efflorescence was noticed on the building's exterior as seen in Figure 12. This was indicative of condensation and air leakage issues occurring behind the brick façade. Condensation and ice formation was also noted by building occupants on the windows during the winters and water stains were visible on the inside of the window glass at many locations. In addition to this, water stains were observed on the inside of the curtainwall glass directly below the roof caused by condensation forming in the ceiling below the roof parapet. Although these issues were present, there were no signs of interior water damage and overall the building seemed to be in relatively good condition. These initial visual issues implied that further testing was necessary.

Figure 24 - Efflorescence stained brick façade on the exterior of Building X. This indicated condensation issues occurring behind the façade

The drawing review consisted of an inspection of the architectural drawings and specific structural drawings to determine the design intent of the building envelope function, as well as to check if there were any details omitted. Additionally, the details were reviewed for any errors as well as examined for constructability. It was found that overall the drawings were well detailed with a few isolated details missing. There were also a few areas noted where ease of construction could have been improved, particularly the knife edge brick angle support.

Thermographic scanning was used to locate areas of air leakage and heat loss. Substantial air leakage was found at the joint between the existing building and the new building. The thermographic scans also indicated that there was substantial heat loss at the vertical joints between the brick and curtain wall but that overall, the curtainwall itself did not exhibit any areas of significant heat loss.

Smoke testing was employed to further locate the areas of air leakage. This was carried out under both positive and negative pressure. From the smoke testing it was found that air leakage occurred around the steel brick support brackets penetrating the exterior wall, through the penetrations that were previously sealed from the interior in 2001, through the punched window assembly, at the roof parapet locations, and at the 2nd floor.

The results of the non-destructive investigative techniques were then used to determine the areas that would require selective demolition.

The finishes around the joint between existing building and new building were removed because of the excessive air leakage noted in this area. This demolition determined that there was no continuity of the air barrier between the two buildings and so air was flowing through this joint.

Heat loss at the vertical joints between the brick and curtain wall was obvious through both thermography and smoke testing and so a selective demolition was carried out in this area and confirmed that the AVB membrane was discontinuous and in turn allowing heat loss.

The locations of the knife edge at the brick support angles appeared to be an issue from the drawings, so a selective removal of brick around this area was carried out. It was determined that the membrane was often not intact and was applied in bits and pieces in an attempt to seal around the brackets completely as shown in Figure 13.

Figure 25 - Knife edge support at brick angle location where heat loss was present. Membrane appeared to be haphazardly applied

The punched window assembly, if constructed properly, should have had the entire perimeter of the glass sealed to the frame with a caulking joint on the interior prior to installing the stops. The air leakage indicated that there was a failure of the perimeter caulked seal and selective removal of the stops determined that the sealant was only intermittently applied which in turn allowed for a large path for air leakage.

Roof parapet locations had been previously disassembled and discontinuities between the air barrier and the wall were observed and repaired; however, since the smoke testing indicated that these areas were still an issue, selective removal of flashings was carried out and it was evident that this barrier was still discontinuous.

Since air leakage was noted at the 2nd Floor, brick between the 2nd and 3rd floor was removed and it was found that the membrane was melted (see Figure 14) in three locations and was sagging from overheating in the wall from the fire during construction. The insulation was melted in areas and was overall quite smoke stained. However, heat loss was not detected by the thermographic scan most likely due to the air movement in the gap behind the brick in addition to the close proximity to an exhaust duct.

Figure 26 - Melted membrane caused by the fire during initial construction

Recommendations

Continuity of the AVB was the major problem with this building's building envelope. The areas in need of repair were:

- the roof parapets and curbs
- joints between walls and punched windows
- joints between the frame members for the punched windows
- joints between the wall and curtainwall
- penetrations through the wall assembly
- joints between the existing building and new building

In order to effectively deal with these issues the precast, brick, and insulation would have to be removed, since the brick and precast covers the AVB membrane. After removal, the area would have to be examined and repaired/replaced as necessary. This would be a very costly and disruptive solution. Alternatively, further non-destructive testing could be employed and selective areas could be repaired; however, this would likely miss many of the minor air leaks and the problems could persist for a great deal of time. During this time it would be possible that interior damage could appear in the wall assembly. Due to cost and practicality reasons, the latter solution was employed.

Preventative Techniques

Although the architectural drawings were fairly adequate and the intent of the building envelope system was generally clear, there were some serious issues when detailing the AVB between the existing building and the new building. Membrane termination details at the aforementioned location would have been helpful in showing how the contractor was to provide more continuity. In general, the method of achieving the seal was mainly left to the contractor to detail. If the designers were to have shown details that clarified the method of construction, it is likely that some details with constructability issues would have been replaced with more constructible details.

Workmanship was the primary cause of the air leakage in the building. Debonded, poorly applied, or discontinuous membrane was the most prevalent cause of air leakage. This air leakage caused efflorescence and condensation issues. Workmanship is a vital factor in building envelope performance and if the Contractor and workers had a better comprehension of the design intent many of the issues arising from both the original construction and the later repairs could have been avoided. Mock-up installation and testing is an excellent way to achieve this knowledge. A higher standard of care when performing the work as well as increased inspection can go a long way. On-site testing, such as thermography and smoke testing can also be used during construction to determine if certain areas will pose problems before the building façade is in place. This allows for less costly repairs while the building is still under construction.

CONCLUSIONS

The building envelope is a complex system with many facets. In order to determine the mechanism and cause of failure it is important to understand the envelope system. Each building has a unique building envelope with different requirements, and must be approached as such. There is no single solution for the diagnosis or repair of envelope failures; however, general steps can be taken. The cause of failure and type of failure must be identified through inspections, document reviews, testing, and sometimes selective demolition. Envelope failures can be classified into three broad categories, moisture, wind, and structure related failures. Each failure type will present unique signs and be investigated differently. There are a variety of failure mechanisms including biological, chemical, and mechanical, that will lead to different types of failures and require different types of repairs. Once the cause and type of failure is identified, a repair strategy should be developed to work with the original envelope to meet the needs of the owners. It is critical that any envelope failure be thoroughly understood and the original intent of the envelope system recognized before any repair attempt is made, as improper repair attempts can often prove detrimental to the envelope. While these strategies can reduce the costs of envelope repairs, a good design, with correct construction and proper maintenance is always the best strategy in dealing with building envelope systems.

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