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Multi-criteria assessment of new residential building envelope typologies, that meet 2012 Ontario Building code requirements

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Multi-Criteria Assessment of New Residential Building Envelope Typologies, That Meet 2012 Ontario Building Code Requirements

by

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A thesis

presented to Ryerson University

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Multi-Criteria Assessment of New Residential Building Envelope Typologies, That Meet 2012 Ontario Building Code Requirements

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Abstract

In keeping with Canada's climate change mitigation goals, the 2012 Ontario Building Code will demand higher levels of insulation than in current practice. Rapid changes to higher RSI levels will force light frame home builders to employ building envelope designs that are hitherto untried, and therefore present risks in terms of durability and efficiency. To address the disparate issues in choosing design options with respect to OBC 2012 requirements and beyond, seventeen wall assembly configurations were analyzed in terms of heat transfer, moisture safety, environmental impact and costs, for new residential housing in Ontario. ASHRAE Standard 160P was used to determine the moisture safety of the wall assemblies. Furthermore, a new technique for analyzing hygrothermal performance was developed where the maximum number of consecutive daily average relative humidity levels that exceeded 80% were quantified and analyzed. An overall normalized score was awarded to each wall to assist stakeholder decision-making processes.

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Abbreviated Terms

Short form terms used in this document are:

- ACH Air Changes Per Hour
- CO_2 Carbon Dioxide
- EIFS Exterior Insulation and Finish System
- EPS Expanded Polystyrene
- GWP Global Warming Potential
- ICF Insulated Concrete Form
- OBC Ontario Building Code
- OSB Oriented Strand Board
- O/C On Centre (referring to frame stud spacing)
- NBC National Building Code of Canada
- RH Relative Humidity
- SPF Sprayed Polyurethane Foam
- XPS Expanded Polystyrene

1 Introduction

1.1 Research Topic

Driven by regulatory practices shifting toward reductions in energy use, important building code changes facing the residential construction market are prompting the use of untried wall assemblies, assuming risks that can negatively affect the performance of the buildings.

The 2012 Ontario Building Code will require higher levels of insulation than the previous release, ranging from nominal RSI3.87 (R22) to RSI4.75 (R27) for external walls. Although nominal insulation levels are defined in the OBC, the building code has not been explicit about the deleterious effects of thermal bridging within the wall assemblies. The significance of thermal bridging cannot be overstated, as the thermal resistance of a wall can be reduced by as much as 50% from the nominal insulation levels (Kosny, 2001)

Although conserving energy is essential, unfortunate consequences from improper use of insulating materials and their locations within wall assemblies can have disastrous results due to moisture damage. The advent of insulated sheathings present new challenges in designing resilient wall assemblies that are able to dry out in the event of bulk water leaks or condensation. Despite best intentions, the OBC only considers vapour control in wintertime conditions, whereas inward vapour drive during the cooling season can be equally dangerous to the durability of a building enclosure.

Building materials also account for a large environmental impact through resource extraction, manufacturing, transportation, construction, maintenance and eventual demolition. Design decisions have a multitude of upstream environmental consequences, affecting health concerns and climate change contributions. Selecting materials with lowest environmental impact is a necessary consideration for the ongoing pursuit of a sustainable built environment.

Despite the pressing issues of environmental impact, moisture safety and thermal efficiency, a governing influence on wall design is cost. Builders invest heavily into the construction of the houses they build and are acutely aware of consumer demand in a highly competitive market. The costing analysis supporting this thesis research was conducted by David Twiddy from George Brown College (Twiddy, D., 2011). Quantity surveying analyses were conducted through RS Means database calculations.

The balance of multi-criteria priorities in residential building wall assembly design requires a holistic view of the competing interests of thermal efficiency, moisture safety, environmental impact, and cost on the ultimate goal of creating a wall assembly that will perform exceedingly well, have minimal impact on the planet, and is affordable.

This research attempts to answer the question:

What are the consequences of the wall assemblies used by production builders in Ontario in terms of moisture safety, global warming impact, heat transfer and cost, and which walls perform best in the context of the 2012 OBC?

1.2 Goals

This research aims to provide the Ontario home building industry, consumers and regulators, with a means of making holistic decisions that balance the competing concerns regarding costs, environmental impact, heat transfer considerations and moisture safety. With a focus on above grade walls, a series of residential wall assemblies that will meet the 2012 Ontario Building Code requirements, and are being proposed or used by builders are considered. Wall assembly options are analyzed and subsequent design improvement recommendations are provided where necessary.

1.3 Scope

Although this research focused on above grade wall assemblies in general, importance was primarily placed on the moisture safety aspects of the wall assemblies because moisture safety is the only criterion under consideration that can affect the health of the occupants and durability of the construction. Five separate analysis methodologies were used to ascertain the resilience of the constructions to vapour diffusion, drying potential after bulk water wetting events, mould growth minimization criteria, summertime inward moisture drive and likelihood of condensation occurrences in exfiltration conditions within the wall assemblies. The analyses focused on wall systems and were carried out using climatic and other relevant data for Toronto, Ontario, but the analysis methodology could be extended to other parts of the province.

Effects of thermal bridging on the overall heat transfer performance of wall types were analyzed through a two-dimensional heat transfer simulation program. The whole-wall thermal resistance was approximated including RSI calculations of clear wall, wall/rim joist connection, and top plate segments.

The environmental impact of the chosen wall assemblies were analyzed from the viewpoint of global warming impact of the manufacturing, construction, maintenance and end-of-life phases of its lifecycle using life cycle assessment methods. Comparative analyses between each wall sample was made on a per square meter basis.

The cost related analysis was performed by David Twiddy from George Brown College.

A decision-making matrix was created based on weighting criteria provided by the builders. The matrix is structured to incorporate the results from the hygrothermal, heat transfer, environmental impact and costs assessments.

2 Literature Review

2.1 Thermal Performance

Wasteful energy misuse is an important consequence of wall assembly designs that ignore highly conductive materials that separate the interior and exterior environments. Although energy efficiency is a high priority, walls with elevated levels of insulation have additional design challenges. The introduction of thermal insulation in wall cavities has played a role in reducing the outside sheathing temperature, causing elevated relative humidity levels and even condensation issues that enable biological growth and building material degradation (Bomberg & Onysko, 2002).

The new home construction industry in Ontario is steadily moving toward higher R-value envelope designs. Although regulated nominally higher R-values are demanded, envelope designs must simultaneously limit thermal bridging that significantly reduces the effectiveness of insulation, if high performance is expected.

In current practice, envelope design strategies to reduce the effects of thermal bridging and achieve high R-values are variations of double stud framing, insulated sheathing and specialty construction techniques such as structural insulated panels, Insulated Concrete Forms and straw bale construction (Pierquet, Bowyer, & Huelman, 1998; Straube & Smegal, 2009.).

For low R-value designs, thermal bridging is not a great concern. However, as wall assemblies are designed with more emphasis on energy saving, thermal bridging accounts for ever-increasing portion of heat loss through building envelopes (Trethowen, 1997).

A major contributor to envelope heat losses is the structural framing. These are approximated according to the area that they occupy in the wall assembly. These relationships are characterized by framing factors. Research conducted on behalf of the California Energy Commission has reported as high as 27% framing factors for wood framed residential buildings (McGowan & Desjarlais, 1997). A similar study by Enermodal reports a slightly more conservative US national average of 25% framing factor for wood stud construction on16" centres (Carpenter & Schumacher, 2003).

Framing factors are defined as follows:

"Wall Framing Factor: *ratio of the framing area in the insulated walls to the wall area (either gross or net). Framing includes headers, sill plates, studs, framing around doors and windows, corners, blocking and where floor joists penetrate the wall insulation layer. Framing that does not bridge the insulation (e.g., exterior or interior strapping, let-in bracing, rim joist) is excluded." (*Carpenter & Schumacher, 2003*).*

An 11% framing factor is considered appropriate for light-weight steel framing due to the use of single top and bottom tracks while spaced at 600mm (Steel Framing Alliance, 2008). Thermal conductivities of softwoods and steel are approximately three and one thousand times higher than low density fiberglass insulation respectively. The presences of structural materials within wall assemblies that bypass the functionality of the cavity insulation contribute to large quantities of thermal inefficiencies. By minimizing the amount of structural materials within the walls, represents a significant opportunity for energy efficiency improvement in housing.

There exists a significant difference between the centre of cavity thermal resistance of a wall assembly and the actual overall resistance to heat flow that it has in reality. Nominal insulation refers to the RSI value of a given material as printed on the material packaging. The disparity is cause by materials within the wall assemblies that conduct heat better than the insulation. Structural materials that separate the interior finishing materials from the sheathing, act as thermal bridges, allowing for a path of least resistance for the flow of thermal energy. Whole-wall RSI values are determined by means of calculating the effect of thermal bridging in wall to floor junctions, top and bottom plates as well as the framing factors within wall assemblies themselves. If not designed to minimize this phenomenon, the framing materials create a short circuit, effectively bypassing the functionality of the cavity insulation.

Sponsored by ASHRAE, McGowan and Desjarlais compared nine methods for calculating thermal bridging effects. Their research involved testing wall samples in a rotating climate simulator facility, finite volume computer simulation and then comparing the results to the calculation methods. The R-value calculation procedures that were analyzed were ASHRAE parallel-path, isothermal planes and zone methods; the European standard ISO/DIS-6946-1; the ORNL modified zone method; the methods suggested in ASHRAE Standard 90.1 and the model national energy code of Canada; and two dimensional finite-volume computer simulation (McGowan & Desjarlais, Undated).

In comparing the methods for calculating the losses produced by thermal bridging, they concluded that if physical testing is not possible, computer simulation was preferred. In the absence of computer simulation expertise, the preferred methods in order were ASHRAE 90.1 Tables, ISO/DIS-6946-1 and modified zone method (McGowan & Desjarlais, Undated).

Analysis techniques have been developed to calculate effective thermal resistances of wall assemblies, which indicate more realistic overall thermal resistances. Research supported by Building America involved two dimensional finite element analysis software, developed by Lawrence Berkeley Laboratories, to determine the whole-wall thermal resistances of several advanced wall assemblies (Straube & Smegal, 2009).

Wall sections were modeled with stud spacing arranged to reflect the thermal bridging effect determined by the framing factor as shown in Figure 2-1.

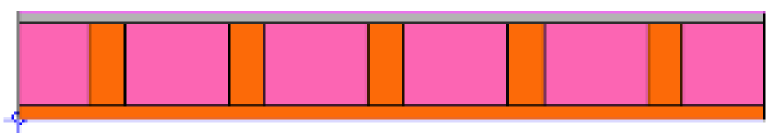


Figure 2-1 Simulated Stud Distance in Plan View of Wall Section Accounting for Framing Factor (Source: Straube & Smegal, 2009)

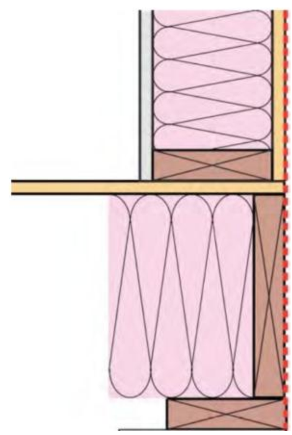


Figure 2-2 Simulated Rim-Joist Section (Source: Straube & Smegal, 2009)

The rim-joist section was modeled as shown in Figure 2-3, as well as double top plate for wood framing as shown in Figure 2-4, and single top track for steel. Significant disparities were found in the wall designs that were studied. Differences between nominal and whole-wall RSI values were found to be over 30% due to thermal bridging (Straube & Smegal, 2009).

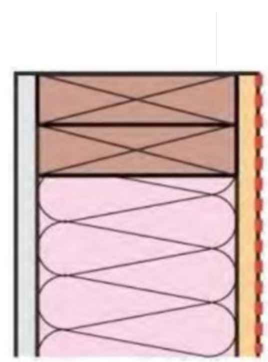


Figure 2-3 Simulated Top Plate Section (Source: Straube & Smegal, 2009)

There is some concern however, that Straube and Smegal's approach to modeling whole-wall thermal resistance values accounts for the effects of the top and bottom plates twice. Since the bottom plate is accounted for as shown in Figure 2-3 and the double top plate is accounted for as shown in Figure 2-4, the question of what spacing is to be used for the plan view of the wall section, that excludes top and bottom plates as shown in Figure 2-1, is raised. The framing factor values determined by Carpenter and Schumacher include top and bottom plates in the framing factor values for walls and as such, a framing factor value for wall section is needed that excludes the effects of top and bottom plates.

Carpenter and Schumacher's field research determined that there is an average framing factor of 24.2% for detached homes in the U.S., although there were regional variations ranging from 19.1% in the Western part of the country to 29.4% in the Midwest. In the absence of Canadian studies, little is known about the framing factor values in this country. Ontario, as a region distinct from those in the U.S., could involve framing factor values as high, or higher than the data obtained by Carpenter and Schumacher.

Calculating the wall area occupied by the bottom plate and double top plates results in a 4.7% value and assuming that the Canadian new home construction industry could be using framing factors as high or higher than Midwestern U.S. values, their 29.4% framing factor without the 4.7% contribution of the bottom and top plates yields a framing factor of 24.7%. It is therefore concluded that the 25% framing factor used by Straube and Smegal is appropriate and the simulated distance between studs can be set to a distance appropriate for 25% of the wall.

Moreover, research undertaken by Lstiburek for the U.S. Department of Energy's Building America program, framing contractors were determined to think in terms of structure at the expense of insulation, at times installing framing members five pieces in a row in some cases (Lstiburek, 2005).

Dividing the image in Figure 2-4 into eight foot sections, the calculated area occupied by the framing members, excluding top plates, bottom plates and openings, ranged from 48% to 12%. Although the he average framing factor of the example given was determined to be 30%, this may be an atypically framing intensive example, but still, a 25% framing factor is determined to be acceptable.

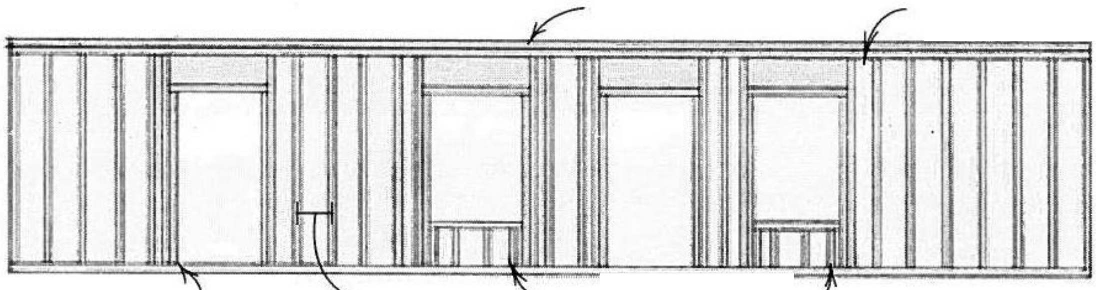


Figure 2-4Standard Framing (Source: Lstiburek, 2005)

Steel framing, with high thermal conductivity, can lead to significantly higher levels of thermal bridging than wood stud framing. Researchers at ORNL however, have shown through experimental laboratory tests and computer modeling, that it is possible for steel framed walls to have similar performance or even exceed that of some wood framing configurations , although without due attention to design, thermal bridging in steel framed construction can reduce the centre of cavity insulation values 50% or more. Although this is not a wall assembly used by the construction industry, the best results (least thermal bridging) were obtained from a wall that had 51mm of EPS to the exterior, with no cavity insulation (Kosny, Jeffrey, & Desjarlais, 1997).

Timber has a much lower thermal conductivity than steel. Despite this material property, as nominal cavity insulation levels increase, the thermal bridging effect of timber is also significant. Guarded hot box test have shown 27 to 29% reductions from center of cavity or nominal RSI values for 38x92mm framing and low density fiberglass insulation (Kosny, Yarbrough, & Childs, 2001). For 38x140mm framing these are likely to be worse.

Calibrating the heat transfer modeling software (Heating 7.3 finite difference), to the hotbox test results, Kosny et al., predicted the effects of various framing configurations. The research effort concluded that steel framed samples with 19mm of XPS sheathing outperformed wood framed samples without insulated sheathing, and that small gaps between the junction interfaces of wood framing members reduced their performance to that of steel studs (Kosny et al., 2001).

The design of wall sections with higher RSI values have moisture related challenges as well. Testing research conducted by the National Research Council has shown that due to wintertime sheathing temperature drops, the cavity temperatures can be reduced to the dew point temperature of exfiltrating interior air potentially causing condensation within the wall assembly. Although insulated sheathing can help to reduce this condensation effect, the advent of low permeance insulated sheathing has raised additional concerns about the drying potential of wall assemblies by vapour diffusion (Maref, Armstrong, Rousseau, Nicholls, & Lei, 2010). These considerations must be well understood for durable wall assembly design.

2.2 Moisture Safety

Assessing the moisture risks inside the wall cavity is not as simple as accounting for occasions where condensation will occur. Although methodologies are not specified, the Ontario Building Code states that no condensation shall be permitted within wall assemblies. But although this is a prudent approach, it is an oversimplification of moisture physics as hygric buffer materials can readily accommodate some moisture without causing harm as is shown graphically in Figure 2-5. It is critical to determine the threshold of 'excessive' moisture that can lead to deterioration (Bomberg & Onysko, 2002).

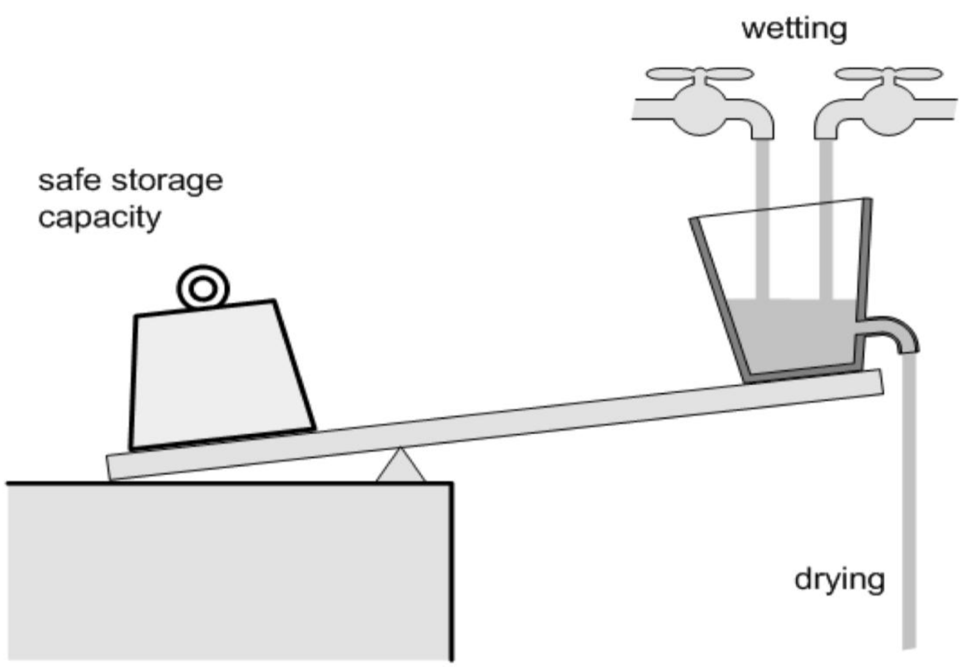


Figure 2-5 Moisture Balance (Source: Straube & Burnett, 2005)

There are four emergent factors that threaten residential building envelope durability: increased levels of insulation, reduced permeability of envelope components, materials' sensitivity to biological growth and reduced ability for materials to absorb moisture. Numerous field investigations conducted by Lstiburek have indicated that engineered materials such as OSB, Gypsum board, particleboard, and engineered I-joists, which are ubiquitous in modern construction, are highly susceptible to mould and do not have the hygric buffer capacity to safely store water (Lstiburek, 2009). The permeability of enclosure linings such as vapour retarders and insulated sheathings have been reduced to the point that drying periods are greatly extended (Lstiburek, 2009).

Karagiozis and Kumaran's 1993 numerical simulation findings suggest that in Vancouver's climatic conditions, a vapour retarder may not be necessary to prevent dangerous moisture levels due to vapour diffusion. In Winnipeg only a type II vapour retarder may be required and in Ottawa, only vapour retarding paint (Karagiozis & Kumaran, 1993).
Toronto's climatic conditions may require vapour retarders with lower permeance than polyethylene by extension. Although these findings are preliminary, and did not consider solar radiation and wind driven rain, they suggest the need for a better understanding of how walls perform in relationship to winter and summertime vapour drive. Despite this knowledge, the community of building inspectors still considers polyethylene to be a firm requirement (Bomberg & Onysko, 2002).

A vapour retarder's function is to manage the amount of moisture entering the assembly through diffusion. Low permeance vapour retarders such as polyethylene have the unfortunate side-effect of preventing the assembly from drying when moisture accumulates from other sources such as air leakage or bulk water wetting. Research done by the Canadian Mortgage and Housing Corporation on Canadian houses have shown that low permeance vapour retarders can be problematic during warm weather periods where spaces are air-conditioned, below grade. Their field investigations have shown that inward vapour drive in summertime conditions, especially when absorptive claddings are used in outside air conditioned spaces, experience longer periods of elevated relative humidity, as well as condensation and mould (Canadian Mortgage and Housing Corporation, 2007).

In Canada, already in the 1950s it was clear that in conjunction with mandated vapour retarders, the exterior weather barrier was required to have a permeance of 3-5 perms as dictated by the National Building Code. By providing these numbers, which were effectively rules of thumb, it gave architects and building engineers a false sense of security that the moisture issues were fully addressed (Bomberg & Onysko, 2002).

This is a basis for concern over growing numbers of low-permeance products being installed on the exterior of residential buildings. Experimental work conducted by Timusk and Doshi has shown that low-permeance insulated sheathing can indeed accumulate condensation particularly in cold conditions. Wall sections were placed in a climate simulator with wintertime conditions with warm, moist air introduced into the assemblies to simulate interior air exfiltrating through the wall assemblies. Improper installation of batt insulation and back-vented sheathing was shown not to provide improved drying potential when faced with wintertime outward air leakage (Timusk & Doshi, 1986).

The National Building Code recognizes the increased risk of elevated relative humidity levels as well as the increased possibility of condensation in wall assemblies that include low permeance insulated sheathing. To address this, the NBC has developed a prescriptive approach to this in the form of a ‘Ratio of Outboard to Inboard Thermal Resistance’ (Brown, Roppel, & Lawton, 2007).

Table 2-1 Ratio of outboard to inboard insulation (Source: Brown et al., 2007)

Heating degree days of building location, Celsius degree-days	Minimum ratio, total thermal resistance outboard of material’s inner surface to total thermal resistance inboard of material’s inner surface
Up to 4999	0.20
5000 to 5999	0.30
6000 to 6999	0.35
7000 to 7999	0.40
8000 to 8999	0.50
9000 to 9999	0.55
10000 to 10999	0.60
11000 to 11999	0.65
12000 or higher	0.75

These prescriptive ratios, as shown in Table 2-1, apply to small buildings with planned interior relative humidity levels below 35% in the heating season, but for large buildings, the NBC defines performance-based stipulations. For occasions where indoor relative humidity levels are at risk of being above 35%, wall systems need to be designed in accordance with National Building Code’s methodology for reducing the risk of condensation large buildings (Brown et al., 2007).

Computer modeling research performed by Brown et al. from Morrison Hershfield, a consulting engineering firm has shown the need for a higher ratio of insulated sheathing to wall stud cavity insulation. For various regions across Canada, hygrothermal simulations indicated that a ratio of insulated sheathing to cavity insulation of 0.31 to 0.53was needed to avoid condensation issues during the heating season, when indoor relative humidity levels were less or equal to 50%as seen in Table 2-2 (Brown et al, 2007).

Table 2-2 Suggested outboard to inboard insulation ratios for RH levels at 50% (Source: Brown et al, 2007)

Location	DD Below 18ºC	Minimum Outboard/Inboard Thermal Resistance Ratio	Minimum Exterior Insulation	
			2x4 Stud w/RSI-2.5 [R14] Batt	2x6 Stud w/RSI-3.9 [R22] Batt
Toronto, ON	3650	0.31	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Yarmouth, NS	4100	0.34	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Halifax, NS	4100	0.34	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Montreal, QC	4250	0.36	RSI-0.9 [R5]	RSI-1.4 [R7.5]
Ottawa, ON	4600	0.38	RSI-0.9 [R5]	RSI-1.8 [R10]
Moncton, NB	4750	0.39	RSI-0.9 [R5]	RSI-1.8 [R10]
St. John's, NL	4800	0.40	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Quebec City, QC	5200	0.43	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Sudbury, ON	5400	0.44	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Edmonton, AB	5400	0.44	RSI-1.4 [R7.5]	RSI-1.8 [R10]
Winnipeg, MB	5900	0.48	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Saskatoon, SK	5950	0.49	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Prince Albert, SK	6450	0.52	RSI-1.4 [R7.5]	>RSI-1.8 [R10]
Fort McMurray, AB	6550	0.53	RSI-1.4 [R7.5]	>RSI-1.8 [R10]

This is significantly higher than the 0.2 ratio defined in the NBC. The dotted lines in Figure 2-6 represent a fitted curve through the 'pass' configurations for outboard to inboard insulation, the stepped curve indicates the ratio defined by the National Building Code, whereas the solid lines indicate the minimum ratios recommended by Morrison Hershfield for indoor relative humidities above 50% and 60% during the heating season (Brown et al., 2007).

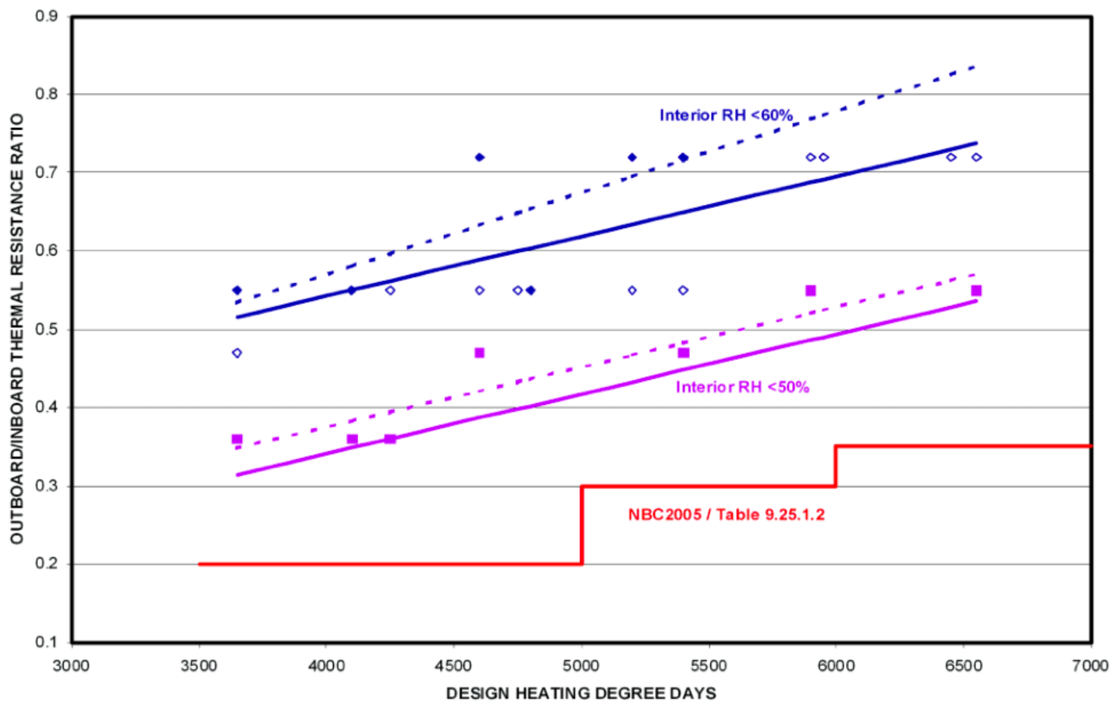


Figure 2-6 Suggested Ratio of Insulated Sheathing to Cavity Insulation (Source: Brown et al., 2007)

Wall assemblies with varying degrees of moisture-absorptive materials have various tolerances for moisture loads. The tipping point for moisture balance can be caused by numerous factors including outward vapour drive in winter conditions, inward vapour drive in summer conditions and unforeseen wetting events such as bulk water leaks through wall penetrations. Low permeance insulated sheathing present additional concerns due to reduced outward drying potential. Safe amounts of low permeance sheathing can be determined according to indoor relative humidity during the heating season.

2.3 Mould

Water exists in wood in two forms: as bound water, which is water contained within the cells, and 'free' water, which is stored within cavities between cells. When free water is gone, the wood is at the saturation point, which ranges from 25% to 30% moisture content, depending on the species. Research conducted by Wang and Morris conclude that the optimal temperatures for mould growth is between 21°C and 30°C, but relative humidity and moisture content are the dominant driver of growth (Wang & Morris, 2010). OSB, plywood and hemlock sheathings did not lose structural integrity over 3.5 years despite intentional fungal inoculation at moisture content of 25% (Wang & Morris, 2010). Zabel and Morrell found that mould was unable to propagate in wood with moisture content below 28%; however the majority of the literature such as research performed by Black, Doll and Hukka, suggests that if all conditions are favourable for mould growth, moisture content of 26% is the critical level for decay initiation. Experimental work conducted by Doll showed that mould growth was possible within five weeks after a wetting event (Black, 2006). The use of 20% moisture content for the upper limit of safe moisture levels in wood, as is often quoted in literature, accommodates a significant margin of safety and tolerance for fungal growth and deterioration (Wang & Morris, 2010).

Relative humidity is also a critical phenomenon in the creating conditions that support mould growth. Experimental work undertaken by Hukka and Viitanen involved a dose-response model for anticipating the onset of mould growth finding that risks exist in the range of 75 to 100% relative humidity levels. Their findings also show that the accuracy of mould onset prediction is tied to the location of analysis (Hukka & Viitanen, 1999). Mould growth in attic spaces was in good agreement with expectations whereas crawl spaces and locations closer to the ground were not as easy to predict (Isaksson, Thelandersson, Ekstrand-Tobin, & Johansson, 2010). Relative humidity and moisture content Figures may indeed be extended if other fungal growth conditions such as temperature are unfavourable, or materials are chemically treated to resists biological growth (Wang & Morris, 2010).

The experimental research at University of Waterloo on Canadian test wall and samples achieved excellent agreement of moisture content with predictions from WUFI software models. Any differences are accredited to errors in instrumentation placement of uncorrected moisture content data or inappropriate product property assumptions (Black, 2006).

ASHRAE Standard 160P – Criteria for Moisture Control in Buildings, an approved ANSI Standard, is based on extensive literature review and public review. The public review process is open to everyone, with responses made to all queries and comments from ASHRAE personnel. The standard sets out three criteria that must be met to minimize the risk of mould growth. The criteria outline critical relative humidity levels and durations for each exposure level. All three criteria must be met (ASHRAE, 2008). Standard 160P's conservative approach allows for a substantial margin of safety.

2.4 Hygrothermal Modeling

The function of hygrothermal modeling is to evaluate the temperature and moisture conditions that occur within a building envelope over time. Conducting parametric analyses, where relatively accurate results are generated, may be more useful than in-situ measurements for a specific situation, because of the influence of multitudes of variations and flaws (Straube & Burnett, 2001).

WUFI v4.2 software uses a full moisture retention function, derived from the sorption isotherm and suction curve. Moisture sources from air leakage, wind driven rain and the behaviour of ventilated cavities can be specified as well (Karagiozis, Hartwig, & Andreas, Undated). Extensive validation of the WUFI model has been done with good agreement. Buxbaum and Heiduk compared measured in-situ data from the test house at Lake Weissensee showing minimal variation between measured and simulated results (Buxbaum & Heiduk, 2008).

2.5 Air infiltration

Interior exfiltrating air that enters the wall cavities brings with it a large quantity of heat and moisture. Furthermore, the exothermal process of condensation releases thermal energy. As the amount of leakage increases, so does the amount of heat, whereby a point is reached where the heating dominates the wetting and condensation is reduced (Bomberg & Onysko, 2002). For this reason, very leaky enclosures are not as susceptible to moisture damage and their continued presence is evidence of durable constructions.

Dangerous conditions can occur in moderately air-tight buildings that experience air leakage. Computer simulation research done by Ojnanen and Kumaran shows that with high and low leakage rates, moisture accumulation is not of great concern, as is shown in Figure 2-7 (Ojnanen & Kumaran, 1996). Air leakage rates of 1 to 8 L/m^2S 75Pa is shown to have the greatest amounts of moisture deposition.

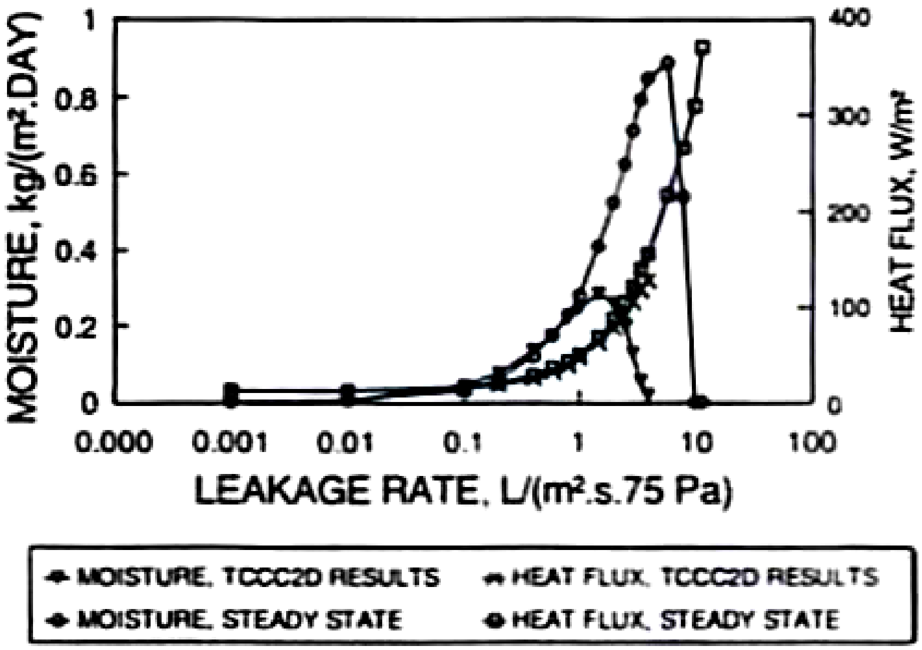


Figure 2-7 Inter-relation between air leakage rate, heat transfer and moisture accumulation (Source: Ojnanen & Kumaran, 1996)

Already since the 1960s, Wilson and Nowak demonstrated that depending on the location of the neutral pressure plane, the amount of moisture introduced through exfiltration could be 10 times that of diffusion (Wilson & Nowak, 1959). Their seminal experimental work involved the transfer of water vapour to and from the panes of non-factory sealed glazing identified the relationship between vapour diffusion and moisture introduced from air movement.

The complex inter-relationships between air leakage mechanisms are shown in Figure 2-8.

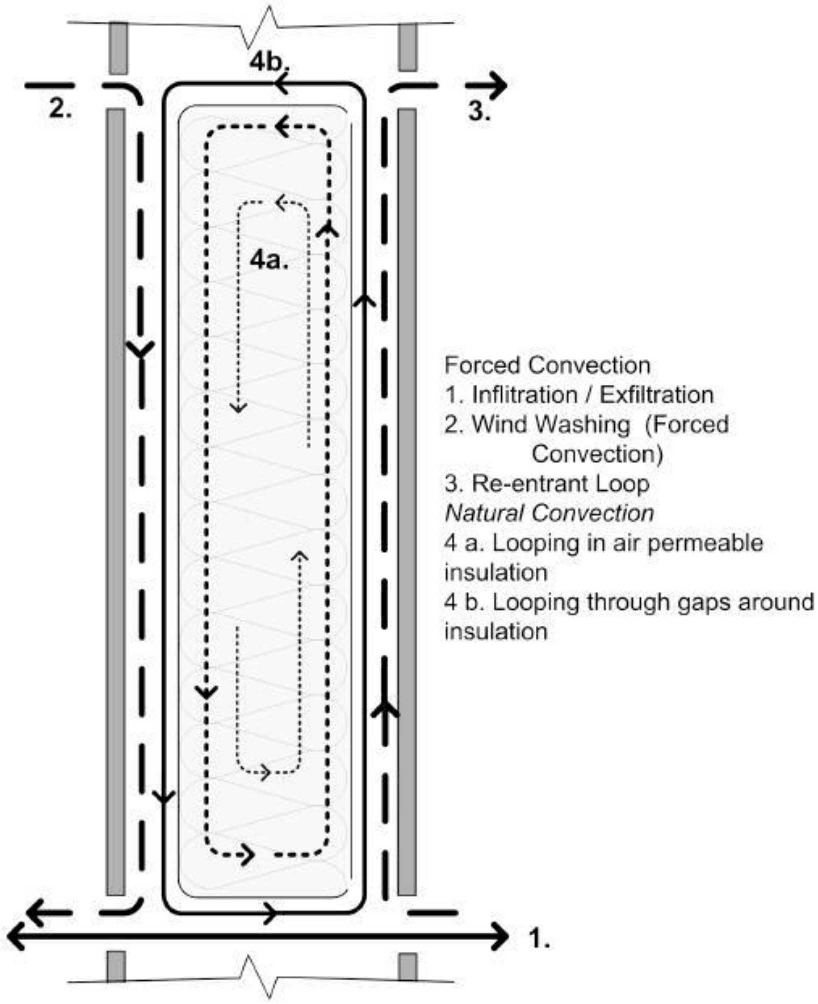


Figure 2-8 Sources of Air Movement in Cavity Insulation (Source: Straube &Smegal, 2009)

Air leakage is often a result of improper workmanship and varies widely depending on the attention to detail undertaken by the builders. It is difficult to account for it in terms of simulation boundary conditions.

The inability to model air leakage through wall assemblies represents a significant limitation in this research. Bulk water transport by vapour contained in air can be orders of magnitude greater than that of vapour diffusion. Without the ability to model air leakage, the effects of condensation, latent heat of vapourization and heat of interior exfiltrating air are not considered. These effects can have considerable effects on the hygrothermal performance of the wall systems, and could significantly alter the results of the research.

2.6 Life Cycle Impact Assessment

Life cycle assessment (LCA), the accounting for negative environmental impacts caused by the resource extraction, manufacturing, transportation, construction and demolition of buildings, is an important consideration in construction. Depending on the service life of the building, it is possible to cause more environmental damage in creating a building, than it mitigates through efficiency design considerations. LCA is a generally accepted means of comparing materials, systems and components by the environmental research community (Cole & Larsson, 1997).

The three principal threats to sustainability are global warming, resource depletion and eco-toxic pollution including ozone depletion (XCO_2 Conisbee Ltd. Undated). Global warming potential is seen by many to be the most pressing issue as the global warming crisis is seen to threaten the whole of the planet's ecological balance.

The Kyoto protocol identified six primary greenhouse gases that deserved the greatest amount of attention in terms of their contributions as agents of global warming potential. These six gases are carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), sulphur hexaflouride (SF6), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) (Burnett, 2006).

The Global Warming Potential for each of the gases is presented in Table 2-9. It can be seen that for some gases, the impact of a small amount of emissions can have a large environmental impact.

Kyoto gas	GWP*
carbon dioxide (CO_2)	1
methane (CH_4)	23
nitrous oxide (N_2O)	296
sulphur hexaflouride (SF_6)	22,200
perfluorocarbons (PFCs)	4,800 – 9,200
hydrofluorocarbons (HFCs)	12 - 12,000

*Note: the 'global warming potential' of a gas is its relative potential contribution to climate change over a 100 year period, where CO_2 =1 (see Glossary for a full definition). Source: IPCC (2001).

Figure 2-9 Kyoto Gases (Source: Lee, Chau, Yik, Burnett, &Tse, 2002)

ATHENA LCA software tool is the North America's only framework for determining the environmental impact caused by whole buildings or assemblies. Using their extensive North American materials impact database, ATHENA claims to be able to model 95% of the building stock on the continent. Used primarily for research and for conceptual stage decision-making, ATHENA Environmental Impact Estimator (EIE) software is capable of generating detailed reports showing the effects of changing parameters such as shape, design or materials intended for a given building (Carmody & Trusty, 2005).

ATHENA EIE is limited however, in its ability to address risks related to toxic releases and site-specific resource extraction effects (Carmody & Trusty, 2005). Data collection is also dependent on industry participation, which has vested interests in submitting favourable data, which raises concern about the realism of the source information. Where ATHENA EIE does not provide direct inputs for, materials must be included through the extra basic materials dialogue boxes that do not include the maintenance component of other materials given the expected service life durations (M. Bowick, personal communication, May 5, 2011).

The Building for Environmental and Economic Sustainability (BEES) software is intended to give designers the information they need to make informed decisions about how product choices may affect environmental impact and/or costs. Similarly to ATHENA, BEES considers life cycle stages such as resource extraction, manufacture, transportation, installation, use, and demolition. Using the ISO 14040 series of standards BEES employs an internationally accepted framework for its analysis (BEES). Unlike ATHENA, BEES is intended for use in later stages of a building's design, namely the specification or procurement stages (Carmody& Trusty, 2005).

Using ATHENA's EIE LCA tool, Trusty et al. undertook a case study comparing the impact of several structural typologies. Their case study of three alternative approaches for a residential home identified naturally occurring products such as lumber exhibit relatively low environmental impact because they do not require much energy input for the manufacturing process. This study also showed that significant environmental impact differences are attributed to selecting light steel framing over wood, and over twice as much embodied energy and air toxicity is caused in insulated concrete form structures over wood (Trusty & Meil, Undated).

Frenette et al. in 2010 used the ATHENA modeling tool to develop an environmental index for light-frame wood wall assemblies. Using global warming potential as the single impact indicator, five wall assemblies situated in Quebec were studied in terms of environmental impact of the materials used and the impact of operational energy for space conditioning. Their results show highest impact for wall assemblies that use brick cladding and extruded polystyrene insulation materials. Conversely, wood siding, fibreboard products and blown cellulose insulation was shown to have a far lower impact (Frenette, Bulle, Beauregard, Salenikovich, & Derome, 2010).

Cladding systems contribute to high levels of direct CO_2emissions as a result of the manufacturing processes. In 2010 Radhi conducted simulation work identifying the impact of cladding materials on a per square meter basis in terms of global warming potential considering stucco, masonry veneer, aluminum siding, vinyl siding and EIFS systems. It was shown that vinyl siding produced the lowest GWP at 1.07 Kg CO_2 eq./m^2 (Frenette, Bulle, Beauregard, Salenikovich, & Derome, 2010).

The selection of insulation materials is also of significant environmental concern. In the cases of foam insulations, high R-values are achieved but at the expense of stratospheric ozone depletion when using blowing agents including HCFCs, which are highly potent greenhouse gases. Alternative blowing agents are possible, but thermal properties are sacrificed. Other foams that use pentane gas contribute to smog and ground level ozone as well as greenhouse gas impact (Papadopoulos, 2005).

An overview of environmental impacts of a series of insulation materials is shown in Table 2-3, resulting in research comparing commonly used building materials with materials with less embodied impacts by Bribian et al. (Bribian, Capilla, & Uson, 2010).

Table 2-3 Evaluation of Insulation Materials (Source: Bribian, Capilla, & Uson, 2010)

Building product	Density (kg/m^3)	Thermal conductivity (W/mK)	Primary energy demand (MJ−Eq/kg)	Global Warming Potential (kg CO_2−Eq/kg)	Water demand (l/kg)
EPS foam slab	30	0.0375	105.486	7.336	192.729
Rock wool	60	0.04	26.393	1.511	32.384
Polyurethane rigid foam	30	0.032	103.782	6.788	350.982
Cork slab	150	0.049	51.517	0.807	30.337
Cellulose fibre	50	0.04	10.487	1.831	20.789
Wood wool	180	0.07	20.267	0.124	2.763

It must be noted however that the representation provided by Bribian et al. does not reflect an entirely fair representation as it involves a per kilogram assessment. The various densities of the materials result in differences for the amount of mass required for a given thermal resistance value. For example wood wool has a low Global Warming Potential, but requires more material to achieve elevated RSI values.

The use of expanded and extruded polystyrene is ubiquitous in the North American residential building sector. Due to its good insulating value, resistance to moisture, strength and costs, their use is common in residential construction (BuildingGreen.com, 2009).

Although polystyrenes play an extremely important role in reducing environmental loads due to reduced heating, it also has important negative consequences to the natural world. The European Chemical Agency has classified the compound as a chemical of “very high concern” and has recommended that its use be limited (Buildinggreen.com, 2009). Research undertaken by Schecter et al analyzed the breast milk of 47 nursing mothers in the U.S., and found that the flame retardant polybrominateddiphenyl ether, used in the manufacture of polystyrenes are ten to one hundred times higher than measures taken from European samples, where the use of the product is limited (Schecter et al., 2003). Among the health concerns, a European study showed that 1Kg of rock wool insulation contributed a global warming potential of 0.39 Kg CO_2 equivalent as compared to the 1.18 Kg CO_2 equivalent generated from 1Kg of expanded polystyrene (Bribian, Capilla, & Uson, 2010).

Insulation materials that use halocarbon blowing agents can have a net negative effect in terms of environmental impact, even when considering the emissions savings from reduced heating and cooling loads due to higher levels of insulation. Research undertaken by Harvey has indicated that the time required for a net positive effect for halocarbon insulations can be up to one hundred years when using foams with halocarbon blowing agents, and ten to fifty years for non-halocarbon blowing agents. Harvey shows that accounting for the net climatic effect of foams with halocarbon blowing agents involves the global warming potential of the emissions related to manufacture the foam, the impact of the leakage of the halocarbons, and the reduction in heating and cooling loads on the building that benefits from the foam.

Polystyrene is the last insulation material to use ozone depleting agents in its production. Polyisocyanurate and polyurethane foams are suitable alternatives, and they do not contain ozone-depleting agents. Polyisocyanurate has a higher resistance to thermal conduction, and is often used with a radiation reflective film that is beneficial when placed toward the interior spaces in cold climates (BuildingGreen.com, 2009).

The holistic performance of building envelopes is dependent on the materials chosen, their amounts and where they are placed. Careful consideration of these materials is the responsibility of the research, design and construction communities. Moving toward higher performance targets, designs need to be durable, excellent thermal performers, affordable and buildable.

2.7 Multi-Criteria Assessments

The difficulty in making multi-criteria evaluations lies in the dilemma of how to judge between items that are not directly comparable. Strategic decision-making strategies are required for rational approaches in comparing unlike terms. Where problems are influenced by perceptions and judgments, or have long-term implications, rational decision-making may be required (Saaty, 2003). There is a need to replace commonly applied ad hoc manner of decision making with a priority on a comprehensive system for unraveling strategic-level decision-making problems. Analytic Hierarchy Process (AHP) is an appealing point of departure for forming a formal decision-making methodology (Bhushan, 2004).

AHP allows for the comparison of dissimilar criteria by establishing pairwise comparison surveys to be completed by key stakeholders. A mathematical operation is applied to generate a single-number indicator that represents a holistic balance between the criteria under consideration (Saaty, 2003).

Research conducted by Frenette et al. (2010), used Multi Criteria Decision Making (MCDA) framework to establish their environmental index for pre-fabricated light-weight wood wall assemblies. By using the MCDA aggregation techniques, a global comparison was possible for a distinct context, according to the needs of the stakeholders (Frenette, Bulle, Beauregard, Salenikovich, & Derome, 2010).

The development of a protocol and an assessment tool, that enables the assessment of light frame building envelopes, was created by Horvat in 2005. The evaluation of air-tightness, structural stability, quality of workmanship, as well as moisture management, thermal, energy, acoustic, and fire performance were included in the framework. If the moisture management performance of a given wall assembly is shown to be acceptable, the assessment tool assigns numerical values to the numerous assessment criteria which enables a single-number indicator result based on previous calculations of a multitude of criteria with their own weighted factors. Validation was performed on five different residential building envelope assemblies, and it was shown to effectively establish the performance characteristics of the building envelopes that were assessed (Horvat, 2009).

To weigh the five assessment categories of a number of promising high-performance wall systems, Straube and Smegal created a simple matrix approach indicating the relative performance of the walls for each criterion. Thermal control, durability, buildability, cost and material use were considered in their assessments. The aggregated sum of separate criteria indicates the relative quality of the wall assembly (Straube & Smegal, 2009).

In order to make parametric comparisons between costs, energy and equivalent CO_2 emissions, Kassab et al., used a weighted normalization process to determine the best alternative wall assembly design. Each alternative was evaluated in all three criteria through the normalization process. The overall normalized score was determined by applying a weighting factor (Kassab, Zmeureanu, & Derome, 2003).

Several approaches to addressing the dissimilar aspects of multi-criteria assessments have been developed and used to determine optimal building envelope assemblies. While some approaches employ a fixed relationship amongst the criteria, others enable stakeholders to contribute their preferences in the form of criteria weighting factors. Each approach represents the distinct elements mathematically and thus establishes a common platform for analysis.

3 Methodology

This research involves the assessments of moisture safety, whole-wall thermal resistance values, environmental impact and costs of several wall assemblies that are currently in production and that will meet the 2012 Ontario Building Code compliance packages' RSI values. The results of the analyses will inform a multi-criteria decision-making matrix that will assist builders in choosing envelope options best suited for their needs.

Many aspects of this research are modeled after Straube and Smegal's approach to multi-criteria assessments of wall assemblies used in the United States of America (Straube & Smegal, 2009). Modifications were made to the methodology where different criteria were used, such as environmental impact, or where more detailed information was sought, as in the case for moisture safety.

3.1 Hygrothermal Modeling

Heat and moisture transport dynamics within the wall assemblies were modeled in WUFI v4.2, an advanced hygrothermal modeling platform jointly developed by Oak Ridge National Laboratory and the Fraunhofer Institute in Building Physics. Used by building envelope consultants, researchers, architects and engineers, the extensively validated software is the internationally preferred hygrothermal modeling platform (Karagiozis, Undated). WUFI is able to accurately model transient heat and moisture dynamics within building materials using hourly regional climatic data, and consider the sorption isotherms that influence liquid and vapour transport. WUFI, however, is unable to model air leakage, which presents an important limitation. This is expected to be included in the software upon its next release (Institut Bauphysik, 2008).

Four analyses were undertaken to determine the moisture safety of all the walls being considered in this research. Although three-year simulations were conducted to qualitatively determine if net moisture accumulation occurred, shorter, more specific time frames were chosen for the in-depth analyses.The modeling periods for the individual analyses are outline below:

RH inboard of sheathing	1 year (October through September)
Inward vapour drive	5 months (May through September)
Drying potential	2.5 months (June to mid-August)
Exfiltration condensation risk	1 year (October through September)

The whole-year period for the RH inboard of the sheathing simulations was selected to observe the RH levels throughout the year, indicating the rate of drying as well as entry into the wall assemblies. The inward vapour drive is primarily a summertime occurrence, necessitating only summer period simulations. The period for observing the drying potential dynamics was chosen to begin in June, after the spring rains that could saturate the wall assembly materials. Finally, the risk of condensation due to exfiltration was selected to be a whole-year simulation to compare the risk of wintertime exfiltration to summertime exfiltration.
A significant limitation of the hygrothermal modeling capabilities is the inability to account for bulk water deposition due to air leakage. The role of air leakage in moisture safety is of utmost importance and must be considered in the holistic durability evaluation of whole buildings due to the mass of moisture potentially introduced into the wall assemblies could be orders of magnitude larger than that of vapour diffusion. It is expected that the following version of WUFI software will contain air leakage calculation capabilities.

3.2 Boundary Conditions

Toronto, Ontario's climatic data for a cold year was used for the hygrothermal simulations. It was determined through modeling several wall assemblies in all four cardinal directions, that the East elevation bore the greatest environmental loadings. For that reason, the east elevation was used as the basis for comparison for all the walls under consideration with a rain load calculation according to ASHRAE Standard 160P Design Criteria for Moisture Control in Building Envelopes.

Vapour diffusion resistance factors were calculated for materials in the simulations. Obtaining permeance data from manufacturers, industry groups and National Research Council publications, the vapour diffusion resistance factors (VDRF) were calculated as per equation 1:

$$\mu = \frac{sd}{s} \qquad \textbf{(Equation 3-1)}$$

(**Source: Institut Bauphysik, 2008)**

Where μ is the dimensionless vapour diffusion resistance factor
Sd is vapour diffusion thickness in meters and
s is the thickness of the material in meters

Although the calculations were performed predominantly in Systeme Internationale (SI), the Sd value is obtained through the application of equation 2 which employs an imperial value:

$$\mathbf{Sd} = \frac{\mathbf{3.28}}{\mathbf{\Delta}} \qquad \textbf{(Equation 3-2)}$$

(**Source: Institut Bauphysik, 2008)**

Where Δ is in perm-inches

Most materials that were entered into the WUFI library as user-defined product specification directly, some materials required a different approach (see Appendix S, T and U). In the case of foil-faced polyisocyanurate, the vapour diffusion resistance of the foil membranes far outweigh the resistance of the insulation itself, thereby making the thickness of the material unimportant. The modeling of this particular material was done by assuming that 1mm polyethylene (VDRF of 50 000) on either side of the insulation equalled the VDRF of the sheet of foil-faced insulation whose VDRF is 100 000.

Interior moisture loads were considered under the assumption that new housing in Ontario is typically equipped with mechanical ventilation that regulate interior temperature and moisture loads within acceptable limits. The National Building Code has published the ratios of outboard insulation to cavity insulation based on interior relative humidity levels of no more than 35% in the heating season (Ontario, 2005). To accommodate this condition, model temperatures ranged sinusoidally from 20°C (winter) and 23°C (summer) with relative humidity levels ranged from 30% to 50% respectively.

Wind driven rain penetrating the cladding is assumed to be 1% of all rain fall, as defined in ASHRAE 160P. In accordance with WUFI technical support recommendations, this moisture source was entered as the innermost grid of the air layer outboard of the weather barrier. Referring to published experimental and simulation research, such as work done by Karagiozis in 2010 as well as Straube and Finch in 2009, cavity ventilation rates for brick and siding were assumed to be 8 and 100air change hours respectively (Karagiozis & Kuenzel, 2010; Straube & Finch, 2009).

3.3 ASHRAE 160P: Mold Growth Minimization Criteria

ASHRAE Standard 160P Design Criteria for Moisture Control in Building Envelopes outlines design and analysis criteria for minimizing the risk of mould growth in a given location of investigation. The Standard specifies three conditions where levels of relative humidity and running average durations, for that must not be exceeded, for any material within a wall assembly. The analysis excludes all relative humidity levels when temperature fall below 5°C and rise above 40°C.

In order to meet ASHRAE's criteria for mould risk minimization, all three of the following criteria must be met:

1. *"24-h running average surface RH < 100% when the 24-h running average surface temperature is between 5°C and 40°C"* (ASHRAE, 2008)
2. *"7-day running average surface RH < 98% when the 24-h running average surface temperature is between 5°C and 40°C"* (ASHRAE, 2008)
3. *"30-day running average surface RH < 80% when the 24-h running average surface temperature is between 5°C and 40°C"* (ASHRAE, 2008)

Microsoft Excel 2007 was programmed to manage the 26280 data points exported from WUFI as hourly data steps for each 3-year simulation. 30-day running averages were performed on the 1095 daily averages obtained of the WUFI simulation data.30-day, 7-day and 24-hour running average calculations were performed on data to analyze compliance with the ASHRAE criteria for the 80%, 98% and 100% criteria respectively. Simplified daily average graphs were created to provide graphical details about each wall's performance. Graphs were created for all four of the hygrothermal analyses, outward vapour drive, inward vapour drive, drying potential and risks of moisture accumulation on the condensation plane analyses.

3.4 Greatest Number of Consecutive Days at Daily Averages above ASHRAE 160P Relative Humidity Thresholds

ASHRAE 160P's analysis is limited in that if even one instance is detected to be beyond its criteria, the test has failed, and no further analyses are required. Analysis beyond pass/fail is not possible within the 160P framework.

In order to extend the moisture safety analysis beyond 160P's limitations, preliminary steps were taken to develop an analysis methodology to interpret the hygrothermal performance of the walls. Averages of daily RH levels were calculated and analyzed to determine how many consecutive days meet or exceed the 80%, 98% and 100% thresholds. This analysis provides important information about the rate at which wall assemblies are able to allow vapour diffusion out of the wall assembly. Choosing the maximum number of consecutive days at or above a given threshold provides a convenient single number indicator of the wall's performance that can be used to interpret the hygrothermal behaviour of the wall assembly.

Using the same exported hourly raw data from the WUFI three-year simulations, Microsoft Excel 2007 was used to calculate the greatest number of consecutive days at the same ASHRAE 160P threshold levels of 100%, 98% and 80% relative humidities.

The limitations of this approach is the lack of a defined threshold of failure that would conclusively determine unsafe walls. It also does not address the frequency of periods, nor does it address what relative humidity levels are between 80% and 98%, until the 98% threshold is reached.

Despite its shortcomings, maximum days over 80% relative humidity does indicate more about the walls rate of humidity management than does the pass/fail ASHRAE Standard 160P assessment.

3.5 Drying Potential of Wall Assemblies

Risks of mould growth within wall cavities are present with elevated levels of relative humidity, but are significantly increased by bulk-water wetting events such as water leakage from improper window flashing detailing. The ability to dry out quickly is critical to the long-term viability of building enclosures. This analysis procedure is an initial attempt to assess the drying potential of various wall assemblies in the events of unforeseen wetting scenarios. It is intended to provide a qualitative assessment of how wall assemblies behave under unplanned water entry conditions. The methodology was modeled after the approach taken by Straube and Smegal in 2009.

The drying rate of the wall assemblies was determined by modeling the walls with elevated initial moisture content in the sheathing (250 Kg/m^3). For walls that do not contain wood fibre based sheathing adjacent to the cavity insulation, a wetting layer was inserted to simulate the conditions encountered by bulk water entry into the wall assembly. The wetting layer composition was adapted from Straube and Smegal's methodology, where a fictitious material was created with the absorption qualities of fibreglass insulation, but an extremely high thermal conductivity was assigned, such that the material did not influence the hygrothermal simulation dynamics.

Wood framed walls with foam insulated sheathings and fibreglass insulation could experience water absorption into the wood framing materials and fibreglass batt insulating material, whereas walls with mineral wool would not be susceptible to fibre saturation as it is fabricated to be hygrophobic. Walls that have combined steel framing and SPF insulation could experience problems due to bulk water entry into the wall assembly, but due to the absence of absorptive materials, they could not be analyzed in this fashion.

ICF construction could also experience bulk water leakage issues, but depending on the amount of leakage, the concrete would readily distribute the moisture throughout its continuous mass, and is therefore not suited to this type of analysis. It is for these reasons that cases 6a, 6b and 7 were omitted from the analysis.

The 10 week summer period for this was chosen because of the warm summer air's ability to absorb the vapour as the wall dries. Moreover, spring rains may induce elevated moisture contents in sheathing if window flashing or weather barrier detailing is sub-optimal. This strategy realistically simulates conditions where hygrophilic materials such as wood sheathing and/or framing store moisture induced by wetting events.

3.6 Inward and Outward Moisture Drive

Although the building codes address outward water vapour drive by regulating the installation of vapour retarders on the inboard side of the interstitial insulation, summertime inward vapour drive presents a significant risk to the moisture safety of building enclosures as well as outward wintertime vapour drive. Particularly susceptible to inward vapour issues are wall assemblies including hydrophilic claddings, that store water, and influenced by direct solar exposure, can experience extremely high vapour pressure gradients. East elevations are prone to low-angle direct solar exposure during morning hours of the summer months due to where it rises above the horizon, thereby experiencing the highest vapour pressure gradients after night-time rains. South facing walls experience solar radiation from an acute angle, whereas the west side, although experiencing low angles of incidence, experience less moisture loads, because of drying throughout the day.

The location of the analysis was the outboard side of the vapour retarder for inward vapour drive conditions, and the inboard surface of the sheathings for outward vapour drive conditions. The ASHRAE Standard 160P criteria were used to determine the moisture safety of these simulations as well as graphs that illustrate each walls relative performance. Furthermore, the maximum number of consecutive daily averages exceeding relative humidity conditions of 80% were quantified and used to facilitate hygrothermal performance interpretation.

3.7 Exfiltration Induced Condensation Risks

As has already been stated a significant weakness of the WUFI simulation software is its inability to analyze the effect of air leakage through the building envelope. Although this presents a limitation to the research, an alternative approach was taken.

The temperature of the condensation plane was graphed in relation to the dew point temperature of the interior air, providing a qualitative visual expression of the risk of condensation if air leakage were to occur as shown by Straube and Smegal (2009). This approach is limited in that neither the mixing of air within the wall cavity, nor the latent heat of condensation is considered in this analysis. It is intended to be a visual guide to the potential complications that could arise in worst case scenarios where poor air-barrier detailing occurs.

There are many cases where interior exfiltrating air, due to insufficient air-tightness detailing could lead to moisture related problems. Warm air, driven outside due to stack pressures encounters the cold condensation plane of the sheathing which will tend to condense, causing sustained and problematic moisture damage along with significant risk of mould growth. Although the importance of air-tight construction cannot be overstated, air-tightness issues are workmanship related and beyond the scope of this research.

For all assemblies that use batt insulation, the inboard side of the sheathing was selected as the mould risk interface due to its role as the condensation plane in outward vapour drive conditions. The sheathings resist vapour flow, therefore are the primary resistor between interior and exterior conditions. As such, the inboard surface of the sheathings is therefore the location where outward driven vapour would condense.

Cases that include SPF insulation, the air barrier of the spray applied foam is assumed to be continuous and therefore, the condensation plane is outboard of the vapour retarder. Similarly for ICF construction, the cast-in-place concrete is assumed to be continuous and therefore the condensation plane is considered to be the inboard surface of the concrete.

3.8 Heat Transfer

THERM, two-dimensional building heat-transfer modeling software was used to determine the effective thermal resistance (RSI) value of the wall assemblies outlined in Table 7-2. Developed by Lawrence Berkeley Laboratories, THERM is based on the finite-element method and used by manufacturers, engineers, researchers and architects. THERM enables the evaluation of a product or assembly’s energy efficiency and temperature patterns (Lawrence Berkeley National

Laboratory, 2011). Although it is an excellent application for calculating thermal conduction, it is limited in for modeling doors, windows and corners. Also, it is limited for radiation predictions on the external surface and is not capable of temperature dependent convection modeling (Centre for Window and Cladding Technology, Undated).

To accommodate the long-wave radiation behaviour of latex painted gypsum board and typical interior air movement patterns, an emissivity coefficient of 8.3 W/(m^2K) was chosen (Hutcheon & Handegord, 1995). The heat transfer through conduction was subsequently calculated based on material conductivities obtained from manufacturers or the National Research Council publications, available in the Appendix S, T and U. Thermal bridging of structural elements was modeled integrating the amount of area that framing components occupy in opaque parts of wall assemblies, known as framing factors. Depending on the spacing of the framing members and the use of double or single top and bottom plates, framing factors were determined for given wall assemblies.

Framing factors of 25%, 16% and 11%were chosen for wall sections in modeling the effect of the thermal bridging contribution to heat loss, when 400mm and 600mm spacing was used with wood stud framing or 600mm spacing with steel studs were used respectively. To approximate the thermal bridging effects presented by the framing factors, the wall sections were modeled with a geometric analogy for their spacing. For example, when 400mm spacing is used in wood stud construction, the modeled stud spacing for the wall section was determined to be 152mm, such that 25% of the wall section was occupied by the framing members. Advanced framing however, employs less structural material as expressed by a lower framing factor (16%), and therefore has a greater distance between the modeled framing members. Although this spacing does not occur in physical construction, the distances between the studs for the purposes of modeling the framing factors was determined through the following formula:

$$distance = t/\ framing\ factor \qquad \textbf{(Equation 3-3)}$$

Where the modeled distance between the studs (d) is in mm, the thickness of the studs, (t) are in millimeters, and the framing factor is expressed as a decimal.

The framing factors, determined by Carpenter and Schumacher's research for ASHRAE, include headers, sill plates, studs, framing surrounding windows and doors, corners, blocking and where floor joists penetrate the insulation at the rim joist (Carpenter & Schumacher, 2003). .

The modeling methodology for each wall was adapted from Straube and Smegal's work in 2009, and done in three steps:

1. Plan view of 2.5m wall section with studs placed at appropriate distance considering framing factor, to model the effect of the framing factor as seen in Figure 3-1.

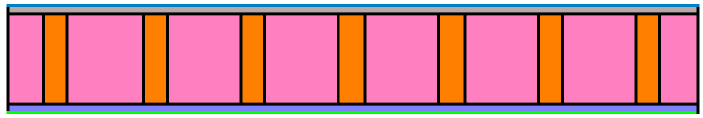


Figure 3-1 Plan View of Wall Section with 25% Framing Factor

2. The floor joists was modeled in plan view as seen in Figure 3-2. The U-value result was included in the THERM library as a fictional material that was included in the simulation of the model in point #3 below.

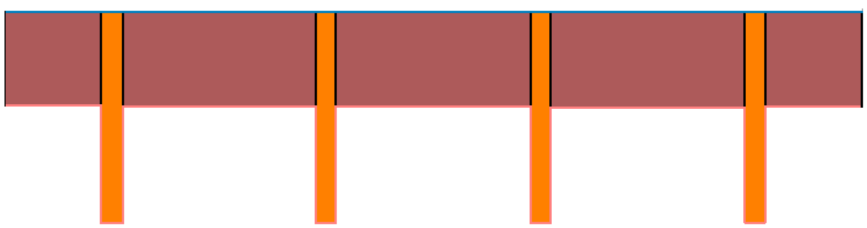


Figure 3-2 Plan View of Floor Joists

3. The rim/floor joist node was modeled as shown in Figure 3-3.

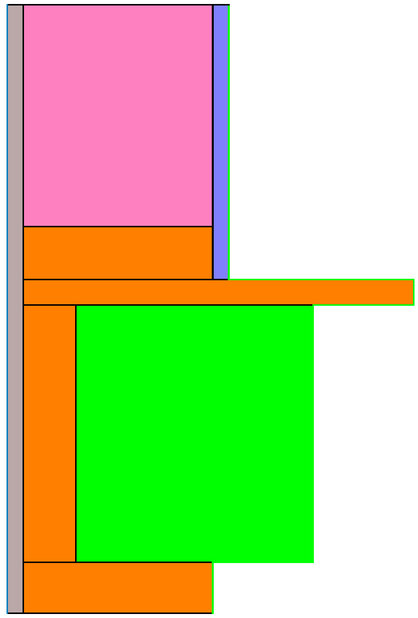


Figure 3-3 Section View of Rim Joist Detail

4. A 203mm portion of the wall, with a double top plate was modeled in section view to determine the effective thermal resistance of the thermal bridging of this junction as seen in Figure 3-4.

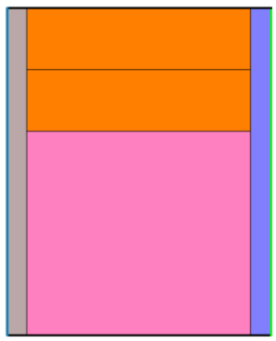


Figure 3-4 Top Plate

The effective RSI value was calculated according the equation 4 as shown below:

$$\text{Total wall R-value} = \text{R-value top plate} \times \frac{\text{height of top plate}}{\text{overall wall height}} + \text{R-value of rim joist} \times \frac{\text{height of rim joist}}{\text{overall wall height}} + \text{R-value of wall section} \times \frac{\text{height of wall section}}{\text{overall wall height}} \quad \textbf{(Equation 3-4)}$$

(**Source: Straube &Smegal, 2009)**

The results from the analyses were calculated and contextualized to the nominal RSI values. The percent deviation indicates the lost efficiency due to thermal bridging.

3.9 Environmental Impact

ATHENA Environmental Impact Estimator for Buildings is a life cycle modeling tool designed to help architect, engineers and researchers compare environmental consequences of design alternatives of buildings or assemblies. It is the only tool of its kind in North America that is based on ISO standards for Life Cycle Assessment .

ATHENA Environmental Impact Estimator addresses the environmental impact of material manufacturing, transportation, on-site construction, regional variation in energy inputs, building life expectancy, maintenance, and eventual demolition. ATHENA is able to indicate the degree of impacts in the areas of primary energy consumption, acidification potential, global warming potential, respiratory effects, ozone depletion potential, photochemical smog potential, eutrophication potential and weighted raw resource use (ATHENA Institute, Undated). Although the ATHENA Impact Estimator is able to model a broad range of impact categories, global warming potential was chosen as the sole indicator to reflect the environmental impact of each wall assembly due to its prominent role in climate change. One square meter segment of each wall was modeled in ATHENA Impact Estimator to allow for parametric analysis and comparison between the wall assemblies.

Table 3-1 Table of Assumption Used in Athena Modeling

Athena Input Assumptions	
Wall Assembly Material	**Assumed Equivalence**
Fibreboard Insulated Sheathing	Oriented Strand Board
Composite EPS/Fibreboard Insulated Sheathing	Oriented Strand Board and EPS
Low density polyurethane spray foam insulation	Polyisocyanurate
Fibreglass mesh for EIFS substrate	1.295 x 1m^2 at 25mm basis of fibreglass insulation (Bowick, 2011)
Plastic portion of stucco rendering	7.407L latex paint (Bowick, 2011)
Mortar portion of stucco rendering	0.00377m^3 mortar (Bowick, 2011)
Blown-in fiberglass insulation	Fiberglass insulation
Low density fiberglass insulation	Fiberglass insulation
High density fiberglass insulation	Fiberglass insulation

Although ATHENA is able to model 400mm and 600mm stud spacing, it assumes differing framing factors than was used in the heat transfer analysis of this research. ATHENA's framing factors assumptions are 22.4% and 19% for 400mm and 600mm wood stud framing spacing as compared to the 25% and 16% framing factors, determined by Carpenter and Schumacher in 2001and Straube in 2009. These framing factor assumptions are not adjustable in the modeling software.

Although many of the wall assembly materials were available in the ATHENA database, adjustment factors were used to accommodate materials that were not included. The assumptions used for this research are outlined in Table 3-1.

3.10 Cost Analysis

The costs of each wall assembly were analyzed through RS Means database analysis. The RS Means analysis was conducted through a detailed material take-off quantity surveying approach with material cost data obtained from the RS Means database and regional cost factor corrections. This part of the research was conducted by David Twiddy under the supervision of Dr. Chris Timusk from George Brown College, School of Construction Management and Trades (Twiddy, 2011).

A representative reference house was used as the model that informed the quantity surveying analysis (see Appendix X). Detailed material take-off analyses were performed and subsequent cost calculations were done based on a combination of RS-Means data and product distributor, builder and manufacturer information.

3.11 Weighted Decision-Making Matrix

A questionnaire designed to obtain detailed costing information and builders' perspectives on the relative importance of the criteria weightings was sent to the builders whose wall assemblies are being assessed. Although costing information was not acquired, valuable information was obtained about how builders weight the value of the four criteria of moisture safety, heat transfer, environmental impact and cost. This information provided the basis of the weighting ratios used in the overall normalized scoring analysis. The questionnaire can be found in Appendix Z.

The results from each criterion category for the wall assemblies that are being considered were normalized to a ranking order between the highest and lowest performers. As shown in Figure 3-5, the wall assemblies will be similarly ranked for each category.

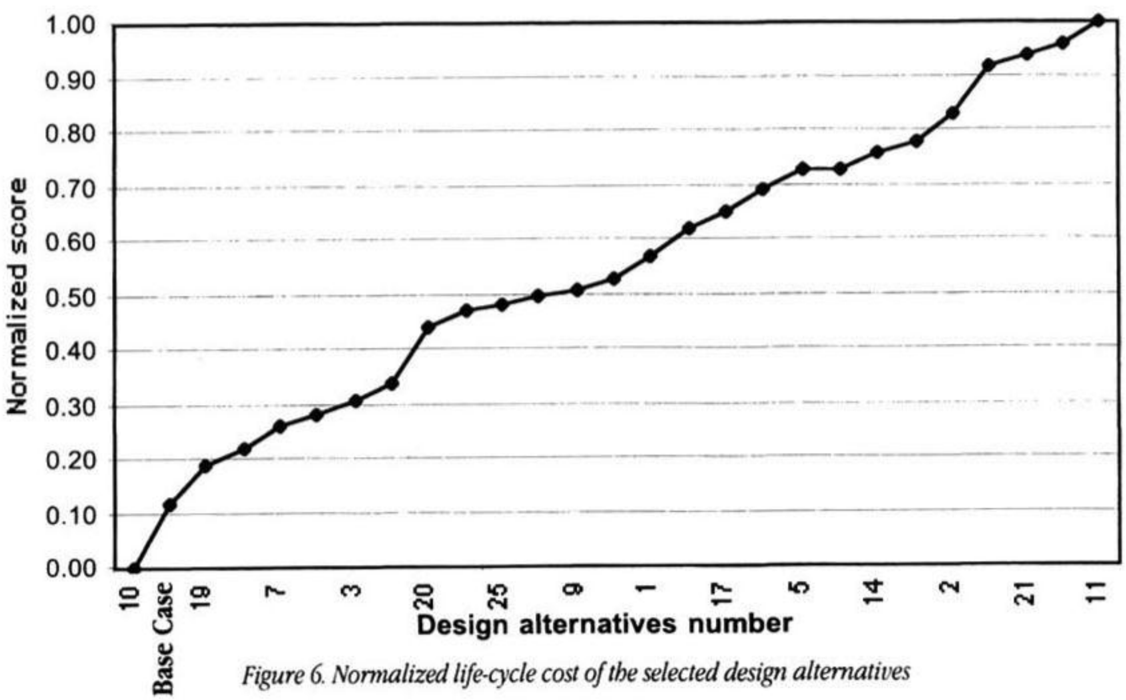


Figure 3-5 Normalized Life-Cycle Costs (Source: Kassab, Zmeureanu, & Derome, 2003)

The following equation was used for each individual criterion. The example below relates to cost:

$$\mathbf{N_{\$}} = (\mathbf{C_j} - \mathbf{C_{min}})/(\mathbf{C_{max}} - \mathbf{C_{min}})$$ **(Equation 3-5)**

Where C_j is the cost for alternative j($)

C_{min} and C_{max} are the minimum and maximum costs for all design alternatives

The overall normalized score (ONS) for each wall design alterative is achieved as follows:

$$\mathbf{ONS} = \mathbf{w_{\$}N_{\$}} + \mathbf{w_{kwh}} \cdot \mathbf{N_{kwh}} + \mathbf{w_{CO2}} \cdot \mathbf{N_{CO2}}$$ **(Equation 3-6)**

Where $w_{\$}$, w_{kwh}andw_{CO2} are weighting factors

The overall normalized score was determined by a weighted multiplication of the normalized scores for heat transfer, costs, global warming potential and moisture safety.

3.11.1 Individual Criterion Normalized Scoring Procedure

The procedure for calculating the normalized score for each criterion is described in the following steps:

1. *Identify the minimum and maximum values of the results for a given criterion and insert those values as x_{min} and x_{max} as shown in equation 3-5*
2. *Calculate normalized score for each wall assembly in the given analysis criterion. Results will be 0 for the minimum value and 1 for the maximum value*

3.11.2 Normalized Scoring Procedure for Moisture Safety

An unweighted overall normalized score was calculated for moisture safety, where two criteria are considered, greatest number of days of 80% for inward and outward vapour drive conditions. The procedure for the moisture safety overall normalized scoring technique is described as follows:

1. *Calculated normalized score for the greatest number of days over 80% relative humidity for inward vapour drive conditions as described in section 5.9.1*
2. *Calculated normalized score for the greatest number of days over 80% relative humidity for outward vapour drive conditions as described in section 5.9.1*
3. *Average out the value obtained from 5.9.2steps 1 and 2*

4. *Calculate the normalized score for the results of 5.9.2step 3 as described in section 5.9.1*

3.11.3 Overall Normalized Scoring Procedure

The overall normalized score is calculated according to the following procedure:

1. *The overall normalized score is calculated with the weighting factors as shown in equation 3-6, where the weighting factors can be adjusted depending on the perceptions or various groups*
2. *As each criterion value indicates an increasingly negative impact as values rise, the reciprocal of 5.9.3 step 1 is calculated*
3. *The normalized score procedure from 5.9.1 is applied to the results of 5.9.3 step 2 to obtain the final overall normalized score*

All categories with the exception of whole-wall RSI resulted in higher numbers that indicated negative effects, such as global warming potential, cost and number consecutive days over 80% relative humidity.

To accommodate this polarity in values, a whole wall U-value was generated so that all category values rose as a negative impact. An interim-overall score was calculated and then the reciprocal taken to produce the overall normalized score for each wall assembly showing higher numbers as positive attributes.

4 Description of the Walls Being Considered

A series of wall assembly configurations were chosen to reflect the wall types currently adopted by production builders in Ontario that would satisfy the code package requirements of the upcoming 2012 Ontario Building Code. Attempting to gather a representative group of wall designs, industry consultation was sought through meetings, questionnaires and interviews amongst the community of builders, consultants, and manufacturers involved in production housing in Ontario.

The 2012 OBC has outlined a series of compliance packages that allow builders flexibility on how they are to meet the code requirements. A number of trade-off alternatives allow builders to choose how they will meet the building code standard. Flexibility is offered through varying degrees of efficiency in insulation levels, mechanical equipment, domestic hot water heating as well as window, door and skylight U-values.

The red highlighted row in Table 4-1 outlines the 2012 OBC compliance packages and the trade-off options that builders can choose for above grade walls that are considered in this research.

Table 4-1 RSI requirements in OBC 2006 Supplementary Standard SB-12 (Source: Ontario Building Code 2006, 2009)

Component	Compliance Package												
	A	B	C	D	E	F	G	H	I	J	K(4)	L(5)	M(5)
Ceiling with Attic Space Minimum RSI (R)-Value(1)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)
Ceiling Without Attic Space Minimum RSI (R)-Value(1)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)
Exposed Floor Minimum RSI (R)-Value(1)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)
Walls Above Grade Minimum RSI (R)-Value(1)	4.23 (R24)	4.75 (R27)	4.75 (R27)	4.23 (R24)	4.23 (R24)	4.23 (R24)	4.23 (R24)	4.23 (R24)	3.87 (R22)	3.87 (R22)	3.87 (R22)	4.23 (R24)	4.23 (R24)
Basement Walls Minimum RSI (R)-Value(1)	3.52 (R20)	3.52 (R20)	3.52 (R20)	3.52 (R20)	3.52 (R20)	2.11 (R12)	2.11 (R12)	2.11 (R12)	3.52 (R20)	2.11 (R12)	3.87 (R22)	3.87 (R22)	3.52 (R20)
Below Grade Slab Entire surface > 600 mm below grade Minimum RSI (R)-Value(1)	0.88 (R5)	-	-	-	-	-	-	-	-	-	-	-	-
Edge of Below Grade Slab ≤ 600 mm Below Grade Minimum RSI (R)-Value(1)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)
Heated Slab or Slab ≤ 600 mm below grade Minimum RSI (R)-Value(1)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)
Windows and Sliding Glass Doors Maximum U-Value(2)	1.6	1.6	1.8	1.8	1.8	1.8	1.8	2	1.8	1.8	1.8	1.8	1.8
Skylights Maximum U-Value(2)	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Space Heating Equipment Minimum AFUE	90%	90%	94%	94%	90%	94%	92%	94%	92%	94%	90%	94%	90%
HRV Minimum Efficiency	-	-	-	-	55%	60%	60%	70%	55%	60%	-	-	-
Domestic Hot Water Heater Minimum EF	0.57(3)	0.57(3)	0.62	0.67	0.57(3)	0.57(3)	0.62	0.67	0.62	0.67	0.57(3)	0.57(3)	0.80
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14

4.1 Contextual Information Regarding Specific Wall Assemblies

The walls described in Table 4-2 are in current production in Ontario. Detailed Tables of wall constructions are in Appendix A. Similar wall types were gathered in parent case numbers with minor variations identified in letter names. Lower case roman letters indicate a further differentiation based on less vital differences, but still worthy of analysis comparisons. Because all wall assemblies use polyethylene as a vapour retarder, this detail was omitted from the table.

Table 4-2 Overview of Wall Assemblies Considered

Case	Framing Configuration	Cavity Insulation	Sheathing	Cladding	Nominal RSI ($m^2 \cdot K/W$)	OBC Code Package
Reference Case 1ai	38x140mm at 400mm o/c	140mm Low density fiberglass (0.043 W/m-K)	12.5mm OSB	89mm brick	3.71	N/A
Case 1aii	38x140mm at 400mm o/c	140mm High density fiberglass (0.036 W/m-K)	11mm OSB	89mm brick	4.04	I,J,K
Case 1b	38x140mm at 600mm o/c	140mm Blown in fiberglass (0.034 W/m-K)	8mm OSB	Vinyl siding	4.13	I,J,K
Case 2a	38x140mm at 400mm o/c	140mm High density fiberglass (0.036 W/m-K)	12.7mm fibreboard	89mm brick	4.22	I,J,K
Case 2b	38x140mm at 400mm o/c	140mm Mineral wool (0.036 W/m-K)	Composite fibreboard/EPS	89mm brick	4.66	A,D,E,F,G,H
Case 3	38x140mm at 400mm o/c	140mm High density fiberglass (0.036 W/m-K)	11mm OSB	Stucco finish	5.45	B,C
Case 4a	38x140mm at 400mm o/c	140mm High density fiberglass (0.036 W/m-K)	25mm XPS	89mm brick	4.83	B,C
Case 4b	38x140mm at 600mm o/c	140mm Blown in fiberglass (0.034 W/m-K)	25mm XPS	Vinyl siding	5.01	B,C
Case 4c	38x140mm at 400mm o/c	140mm Spray polyurethane (0.04 W/m-K)	35mm XPS	89mm brick	4.94	B,C
Case 4d	38x140mm at 400mm o/c	140mm Low density fiberglass (0.043 W/m-K)	25mm XPS	89mm brick	4.48	A,D,E,F,G,H
Case 5a	38x140mm at 400mm o/c	140mm High density fiberglass (0.036 W/m-K)	19mm Polyiso	89mm brick	4.75	B,C
Case 5b	38x140mm at 600mm o/c	140mm Low density fiberglass (0.043 W/m-K)	25mm Polyiso	89mm brick	4.66	A,D,E,F,G,H
Case 6a	Steel 38x92mm at 600mm o/c	92mm Spray polyurethane (0.04 W/m-K)	51mm XPS	89mm brick	4.23	A,D,E,F,G,H
Case 6b	Steel 38x92mm at 600mm o/c	92mm Spray polyurethane (0.04 W/m-K)	51mm EPS	EIFS	3.88	I,J,K
Case 7	6" 20mPa Concrete	2 x 67mm EPS (0.036 W/m-K)	11mm OSB/ 51mm EPS	89mm brick	4.7	A,D,E,F,G,H
Case 8a	38x92mm + 76mm EPS + 38x64mm at 600mm o/c	280mm Mineral wool (0.036 W/m-K)	11mm OSB/ 25mm polyiso	Wood siding	8.97	B,C
Case 8b	38x89mm+25mm EPS+38x64mm at 400mm o/c	178mm Mineral wool (0.036 W/m-K)	Composite fibreboard/EPS	Vinyl siding	5.71	B,C

The selected wall assemblies were organized into case groups according to their principal features. Cases were differentiated based on sheathing or structural qualities. The major category divisions are listed in Table 4-3.

Table 4-3 Case Categories and Principal Features

Case Category	Principal Features
Case 1	OSB sheathing with no exterior insulation
Case 2	Wood fibre or composite insulated sheathing
Case 3	EIFS over OSB substrate
Case 4	Extruded polystyrene insulated sheathing
Case 5	Polyisocyanurate insulated sheathing
Case 6	Light weight steel framing
Case 7	Insulated concrete form
Case 8	Double stud walls

4.2 Case 1: OSB Sheathing

The principal differentiator of this case category of wall assemblies is the use of OSB sheathing with no exterior insulation. This group of wall assemblies use 38mmx140mm wood stud framing with fibreglass batt insulation, OSB sheathing with housewrap weather barrier and no exterior insulation. Claddings used are brick and vinyl siding.

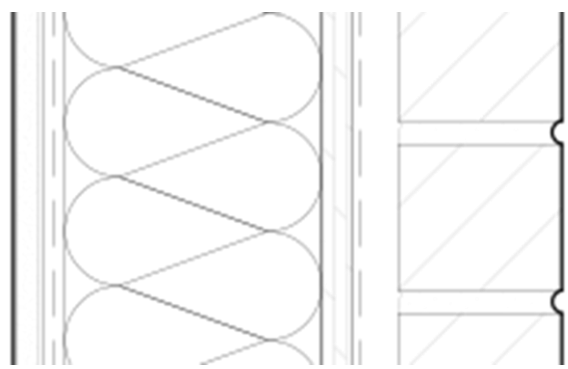


Figure 4-1 Case 1 with OSB Sheathing (Source: Twiddy, 2011)

By replacing low density fiberglass (k-value 0.043 W/m-K) with high density fiberglass insulation(k-value 0.036 W/m-K), builders can achieve the compliance packages I, J or K (Table 6.1) when 38mm by 140mm wood framing is used, where above grade wall assemblies require RSI 3.87m^2·K/W, without changing other aspects of the wall fabric design.

As the standard construction for the 2006 OBC, Case 1ai is the reference case against which the other walls were compared. Although it does not meet the lowest RSI value for the 2012

OBC, case 1ai was chosen as the baseline because of its proven performance, particularly in moisture safety. The absence of failure complaints justifies this assertion.

4.3 Case 2: Fibreboard or Composite Fibreboard Sheathing

The principal differentiator of this case category of wall assemblies is the use of wood fibreboard or composite fibreboard insulated sheathing (see Appendix S, T and U). The wall assemblies in case 2 use 38mmx140mm wood stud framing with fiberglass or mineral wool batt insulation, fibreboard or composite EPS/fibreboard insulated sheathing. The fibreboard insulated sheathing was taped as a weather barrier and the composite sheathing received an additional layer of “20 lb.” building paper as a weather barrier. Both wall designs use brick cladding.

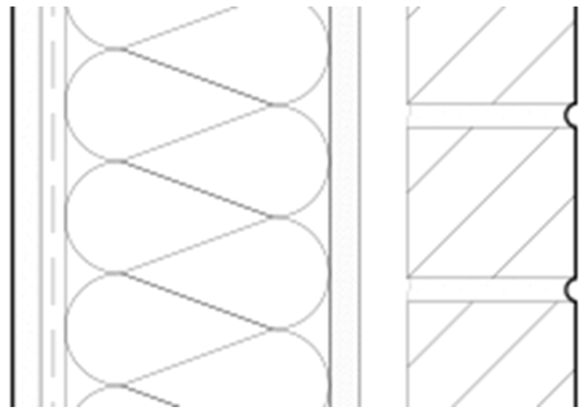


Figure 4-2 Case 2 with Fibreboard Sheathing (Source: Twiddy, 2011)

With the use of fibreboard (k-value 0.049 W/m-K)and composite fibreboard/EPS insulated sheathings, (k-value 0.038 W/m-K), builders can conform to compliance packages I, J or K, where RSI values must exceed 3.87 m^2·K/W or A, D, E, F, G, H and I, which requires RSI values of 4.23m^2·K/W. The targets of I, J or K can be achieved by using low density fiberglass insulation and changing the sheathing material only, or to use mineral wool or high density fiberglass insulation and insulated sheathing to achieve A, D, E, F, G, H or I. Installation procedures differ minimally from the conventional methods of construction.

4.4 Case 3 EIFS with OSB Substrate

The principal differentiator of this case category of wall assembly is the use of EIFS over an OSB substrate. This wall assembly uses 38mmx140mm wood stud framing with high-density fibreglass batt insulation, OSB sheathing with EIFS cladding.

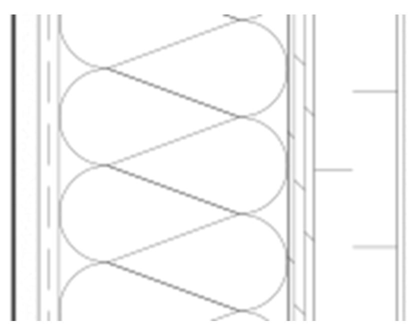


Figure 4-3 Case 3 with EIFS (Source: Twiddy, 2011)

Many production builders favour the EIFS design because of the low cost and rapid production methods. High density fiberglass with the 51mm of EPS achieves an RSI value of 5.45m^2·K/W, complying with packages B or C.

4.5 Case 4 Extruded Polystyrene Insulated Sheathing

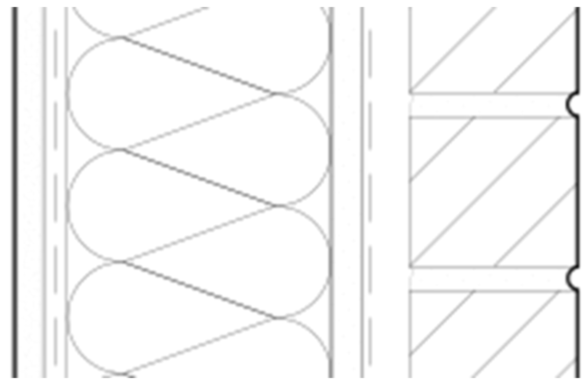


Figure 4-4 Case 4 with Extruded Polystyrene (Source: Twiddy, 2011)

The principal differentiator of this case category of wall assemblies is the use of XPS insulated sheathing. The wall assemblies in case 4use 38mmx140mm wood stud framing with low-density glass fibre batt, high-density glass fibre batt or blown-in-blanket glass fibre insulation and XPS sheathing. Weather barriers used in this case are housewrap, the XPS itself or '20lb' building paper. The cladding used is either brick or vinyl siding. There are two different manufacturers of XPS for these assemblies with different permeances. The difference in permeance is substantial and affects the moisture dynamics in the wall assemblies significantly. Case 4a and b use the lower permeance XPS (45 ng/Pa·S·m^2 on a 25mm basis) and the cases c and d use the higher permeance XPS (200 ng/Pa·S·m^2 on a 25mm basis).

The use of XPS insulated sheathing allows builders to achieve higher RSI values in their wall constructions when market demands warrant the higher costs of initial investment. Low-density fiberglass insulation in the stud cavities with 25mm XPS sheathing achieves a nominal RSI of 4.48 which complies with code packages A, D, E, F, G, H and I, whereas cases 4a, 4b and 4c comply with code packages B and C with RSI values of 4.83m^2·K/W, 5.01m^2·K/W and 4.94 m^2·K/W respectively.

4.6 Case 5 Foil-Faced Polyisocyanurate Insulated Sheathing

The principal differentiator of this case category of wall assemblies is the use of foil-faced polyisocyanurate insulated sheathing. The wall assemblies in case 5use 38mmx140mm wood stud framing with low-density and high-density fibreglass batt insulation, polyisocyanurate sheathing. Weather barriers used in both cases are silver-foil tape, and the cladding used is both cases is brick.

Due to polyisocyanurate's high RSI/thickness quality, builders opt for its use when high insulation levels are sought and priority is placed on wall thickness minimization. Cases 5a and 5b comply with code packages B and C with RSI values of 4.75 $m^2 \cdot K/W$ and 4.66 $m^2 \cdot K/W$ respectively.

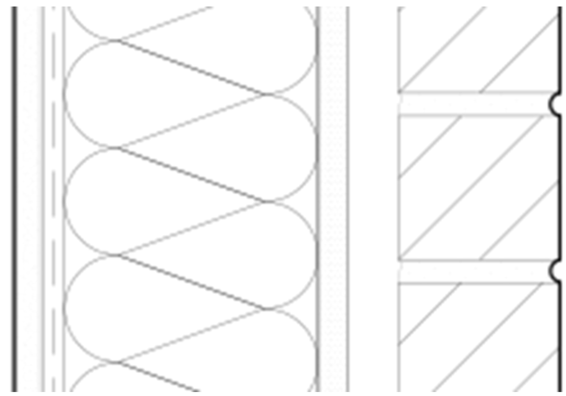


Figure 4-5 Case 5 with Foil Faced Polyisocyanurate (Source: Twiddy, 2011)

4.7 Case 6 Light-Weight Steel Framing

The principal differentiator of this case category of wall assemblies is the use of light-weight steel framing. The wall assemblies in case 6use 38mmx92mm steel stud framing with low density polyurethane spray-foam cavity insulation and either XPS sheathing or EIFS. Weather barriers used in both cases of XPS sheathing is housewrap, and brick cladding is used. In the EIFS example, the weather barrier and cladding roles are met by the EIFS.

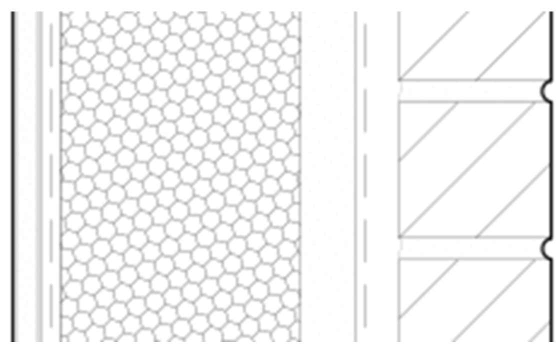


Figure 4-6 Case 6 with Steel Studs (Not Shown) (Source: Twiddy, 2011)

The uniform and dependable quality of steel framing allows production builders to minimize costs on production labour. Use of 600mm stud spacing, single top and bottom track and 51mm of polystyrene offer a high ratio of outboard to inboard insulation thereby reducing the otherwise enormous reductions in thermal efficiency due effects of thermal bridging with steel studs.

4.8 Case 7 Insulated Concrete Form

The principal differentiator of this case category of wall assemblies is the use of insulated concrete form. This wall assembly uses 152mm of poured concrete with 67mm of EPS insulation on both sides of the concrete. There is no weather barrier used and the cladding is brick. The two layers of 67mm of EPS achieves an RSI value of 4.87 $m^2 \cdot K/W$ which complies with code packages A, D, E, F, G, H and I.

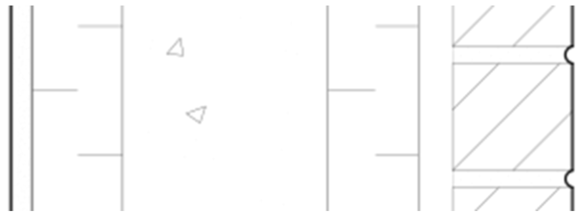


Figure 4-7 Case 7 with Insulated Concrete Form (Source: Twiddy, 2011)

Benefits of ICF include fast production, excellent acoustic control, minimized thermal bridges and excellent moisture safety performance.

4.9 Case 8 Double Stud Construction

The principal differentiator of this case category of wall assemblies is the use of double-stud framing. One framing configuration uses 38mmx140mm wood stud framing, and 38mmx64mm wood stud framing on 600mm centres separated by 76mm of EPS. Two sheathings are used in combination, OSB and polyisocyanurate sheathings, and the cavity is filled with mineral wool insulation, weather barrier is silver-foil taped polyisocyanurate and the cladding is wood siding.

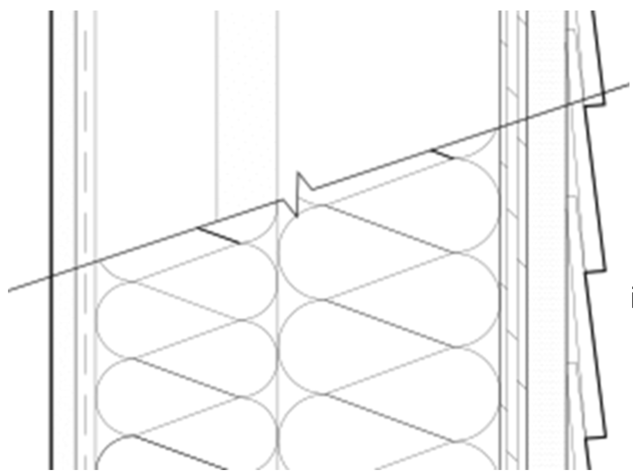


Figure 4-8 Case 8 with Double Stud Construction (Source: Twiddy, 2011)

The other framing configuration uses 38x89mm and 38x64mm wood stud framing on 400mm centres separated by 25mm of EPS. The sheathing is a composite fibreboard/EPS insulated sheathing, the cavity is filled with mineral wool insulation, weather barrier is houswrap and the cladding is vinyl siding.

Builders who prioritize energy efficiency and can justify the increased thickness of walls use double stud framing to achieve improved thermal bridging control due to the EPS spacers and custom wall thicknesses allowing for elevated levels of insulation. Cases 8a and 8b achieve RSI levels of 8.97 $m^2 \cdot K/W$ and 5.71$m^2 \cdot K/W$. These insulation levels far exceed all the building code packages' RSI thresholds.

4.10 Cladding

The cladding types used for wall assemblies in this research are brick, EIFS, vinyl siding and wood siding. Particular emphasis was placed on brick veneer claddings because of their hygrophilic nature and how stored moisture can affect inward vapour drive in warm weather and sunny conditions after wetting events.

4.11 Wall Typology Code Description

A shortened code is used to provide summary information regarding the materials used in each wall assembly. An example of the code is shown in Figure 4-9 describing the reference case 1ai. Each item is described by an intuitive short form such as AF for advanced framing of VS for vinyl siding.

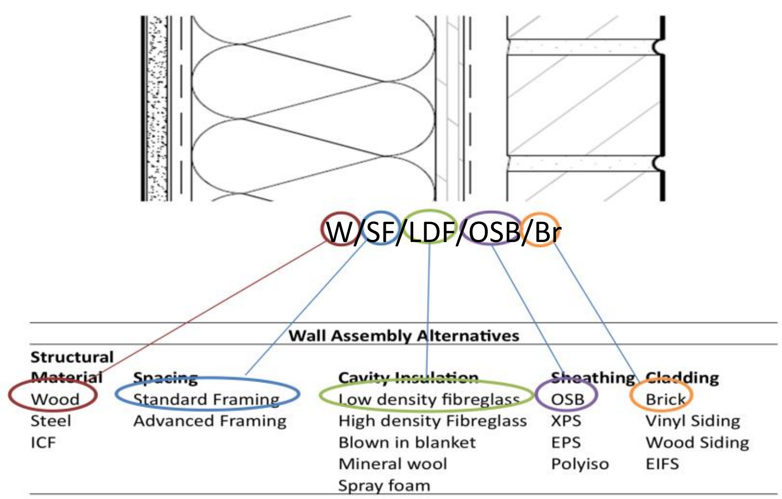


Figure 4-9 Wall Summary Code for Case 1ai (Source:Twiddy, 2011)

5 Results and Discussion

5.1 Hygrothermal Analysis and Moisture Safety

The results from the hygrothermal analyses including ASHRAE Standard 160P Criteria for Minimizing the Risk of Mould Growth analysis, as well as greatest number of consecutive days over 80% relative humidity are presented in Table 5-1. It must be declared that the resulting values could vary if air leakage was factored into the analyses. It is also assumed that although ASHRAE standard 160P requires 1% of wind-driven rain to reach the weather barrier, the amount of water transported by capillary suction is negligible.

Table 5-1 Results from ASHRAE 160P and Greatest Numerber of Days Over 80% RH

Case #	Analysis	Hygrothermal					
		Outward Vapour Drive			Inward vapour drive		
		>80%	>98%	100%	>80%	>98%	100%
1ai	Number of Days Over RH Threshold	6	0	0	**9**	0	0
	ASHRAE 160P Results	P	P	P	***F***	P	P
1aii	Number of Days Over RH Threshold	**2**	0	0	0	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 1b	Number of Days Over RH Threshold	1	0	0	2	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 2a	Number of Days Over RH Threshold	2	0	0	3	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 2b	Number of Days Over RH Threshold	1	0	0	2	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 3	Number of Days Over RH Threshold	**9**	0	0	4	0	0
	ASHRAE 160P Results	***F***	P	P	P	P	P
Case 4a	Number of Days Over RH Threshold	**16**	0	0	0	0	0
	ASHRAE 160P Results	***F***	P	P	P	P	P
Case 4b	Number of Days Over RH Threshold	**15**	0	0	0	0	0
	ASHRAE 160P Results	***F***	P	P	P	P	P
Case 4c	Number of Days Over RH Threshold	**2**	0	0	3	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 4d	Number of Days Over RH Threshold	1	0	0	5	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 5a	Number of Days Over RH Threshold	**45**	**10**	0	**9**	0	0
	ASHRAE 160P Results	***F***	***F***	P	***F***	P	P
Case 5b	Number of Days Over RH Threshold	**45**	4	0	2	0	0
	ASHRAE 160P Results	***F***	P	P	P	P	P
Case 6a	Number of Days Over RH Threshold	2	0	0	3	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 6b	Number of Days Over RH Threshold	3	0	0	0	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 7	Number of Days Over RH Threshold	0	0	0	0	0	0
	ASHRAE 160P Results	P	P	P	P	P	P
Case 8a	Number of Days Over RH Threshold	**42**	0	0	**70**	0	0
	ASHRAE 160P Results	***F***	P	P	***F***	P	P
Case 8b	Number of Days Over RH Threshold	2	0	0	0	0	0
	ASHRAE 160P Results	P	P	P	P	P	P

5.1.1 Outward Vapour Drive – Wintertime Conditions

5.1.1.1 ASHRAE Standard 160P Analysis – Outward Vapour Drive

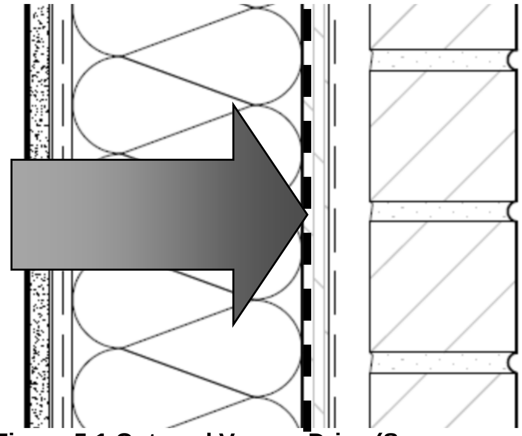


Figure 5-1 Outward Vapour Drive (Source: Twiddy, 2011)

The following results and discussion relates to ASHRAE Standard 160P's three criteria for minimizing the risks of mould growth. The conditions indicated in quotation marks, outline conditions required for safe relative humidity performance at the location of measurement as per the Standard. For the outward moisture drive analyses, the relative humidity levels were measured at the inboard face of the sheathing as shown in the dark dotted line in Figure 5-1.

> *"24-h running average surface RH < 100% when the 24-h running average surface temperature is between 5°C and 40°C" (160P)*

All calculated24-hourrunning averages for the inboard face of the sheathings were below 100% relative humidity for all walls assemblies considered. Within this criterion of ASHRAE Standard 160P, all walls are acceptable.

> *"7-day running average surface RH < 98% when the 7-day running average surface temperature is between 5°C and 40°C" (160P)*

All but two cases, 5a and 5b, calculated7-dayrunning averages for the inboard face of the sheathings were below 98% relative humidity. These high levels of relative humidity are the result of the low permeance of the foil facings that significantly reduce the outward vapour diffusion. For cases 5a and 5b, ASHRAE Standard 160P deems these walls to be assume too great a risk for mould growth.

> *"30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5C and 40C" (160P)*

Relative humidities at the inboard face of the sheathings, calculated for 30-dayrunning averages exceeded 80% relative humidity for cases 3,4a, 4b, 3, 4a,4b, 5a, 5b and 8a. High relative humidities were experienced due to the low permeance materials used outboard of the framing materials. For Case 4a and 4b, it was due to the use of low permeance XPS, in cases 5a, 5b and 8a, it was due to the foil layers over the polyisocyanurate insulation. The exception is Case 3 that uses OSB sheathing which contains moisture in an adsorbed state that releases it again gradually. According to these results, ASHRAE Standard 160P deems these walls to be assume too great a risk for mould growth.

Although the ASHRAE Standard 160P attempts to provide a framework for determining safe moisture levels in building envelopes, it provides a simplistic output consisting of a pass or fail judgment. Little is known about the validity of the assumptions that were used in the development of the standard. In the absence of a proven methodology for the prevention of the onset of mould growth, the validity of the methodology proposed by ASHRAE Standard 160P is questionable.

5.1.1.2 Daily Average Humidity Analysis

Providing further details to the humidity management capabilities of the walls under consideration, the daily average humidity levels were calculated and compared to the ASHRAE 160P analysis results. As seen in Table 5-1, the consecutive daily average humidities above ASHRAE's threshold levels are shown to provide a numerical value to support the extent to which the walls failed the ASHRAE analysis.

It can be seen in Table 5-1, that casex 5a failed the ASHRAE 160P analysis for the 98% relative humidity condition. Maximum numbers of days at daily average relative humidity levels over 98% were observed at 10 days due to the presence of the foil facings. This relative humidity level is extremely close to conditions for condensation and due to the duration of the exposure, this wall assembly deserves close investigation as to its humidity management capabilities.

Other cases, such as 4a and 4b experienced slightly higher maximum consecutive daily average over 80%, by 16 and 15 days due to the slow vapour diffusion caused by low permeance XPS. Cases 3 experienced 9 days over 80% relative humidity due to the EIFS and the presence of OSB substrate that holds moisture in the form of bound water. Cases 5a, 5b and 8a experienced consecutive daily average over 80%, of45, 45 and 42 days respectively. At upwards of 40 days over 80% RH, the walls are shown to allow diffusion at a very slow rate.

Cases 1ai, 1aii, 2a, 2b, 4c, 4d, 6a, 6b, 7 and 8b experienced maximum consecutive daily average over 80% by 6, 2, 1, 2, 1, 2, 1, 2, 3, 0 and 2 respectively, yet passed the ASHRAE 80% threshold analysis for outward vapour drive. These wall assemblies allow vapour to pass through the sheathing materials more readily and therefore experience shorter durations above 80% relative humidity.

As seen in Figure 5-2, the range of consecutive daily averages over 80% range from 1 to 45 days. The cases that failed the ASHRAE 160P analysis by exceeding the 3 criteria for the minimization of mold growth are indicated in grey, whereas the cases that passed the ASHRAE 160P analysis yet experience daily average relative humidity levels over 80% are shown in black.

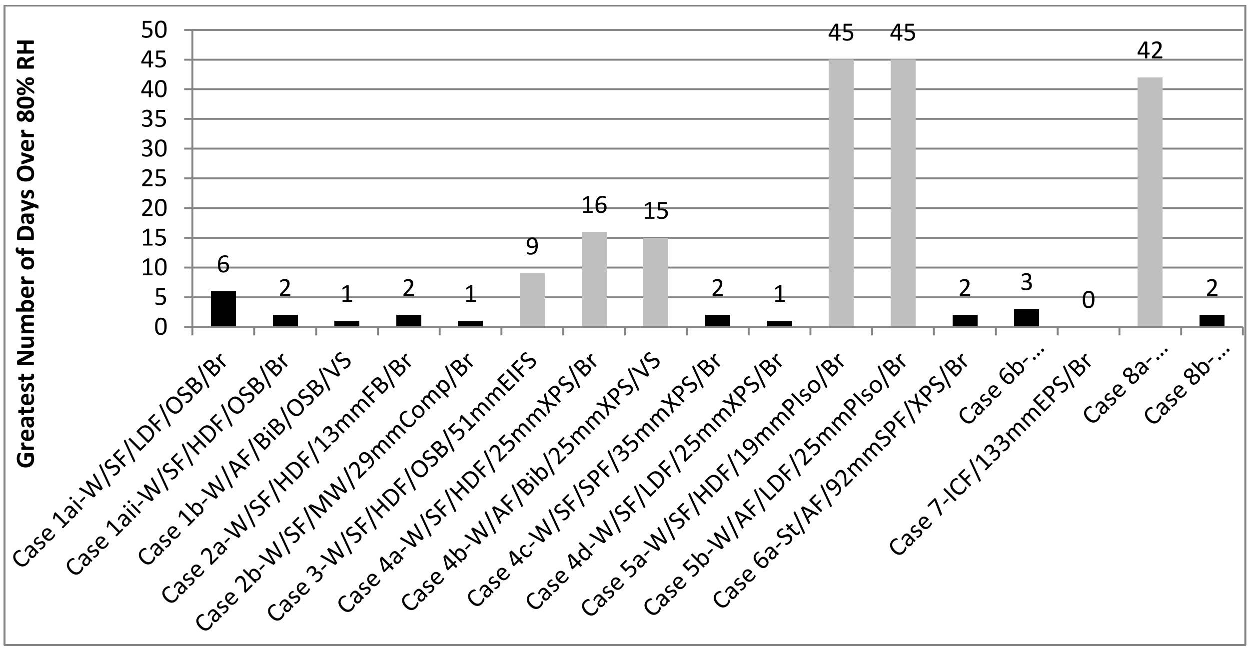


Figure 5-2 Greatest Number of Consecutive Days Above 80% RH

5.1.2 Outward Vapour Drive – All Walls Contextualized

It is evident that many walls with foil faced polyisocyanurate sheathing (cases 5a, 5b and 8a), as shown in Figure 5-3,experienced high levels of relative humidity throughout the winter season, although it must also be noted that walls with extruded polystyrene, shown in blue, were able to allow vapour to pass sufficiently to avoid problems by keeping the RH levels down below 80% much of the cold season. The orange family of curves show the relative uniformity of how high permeance sheathings allow moisture to pass, thereby managing the moisture to be predominantly below 80% RH. As there was no net moisture accumulation in any of the wall assemblies, year to year, only one year periods were shown graphically.

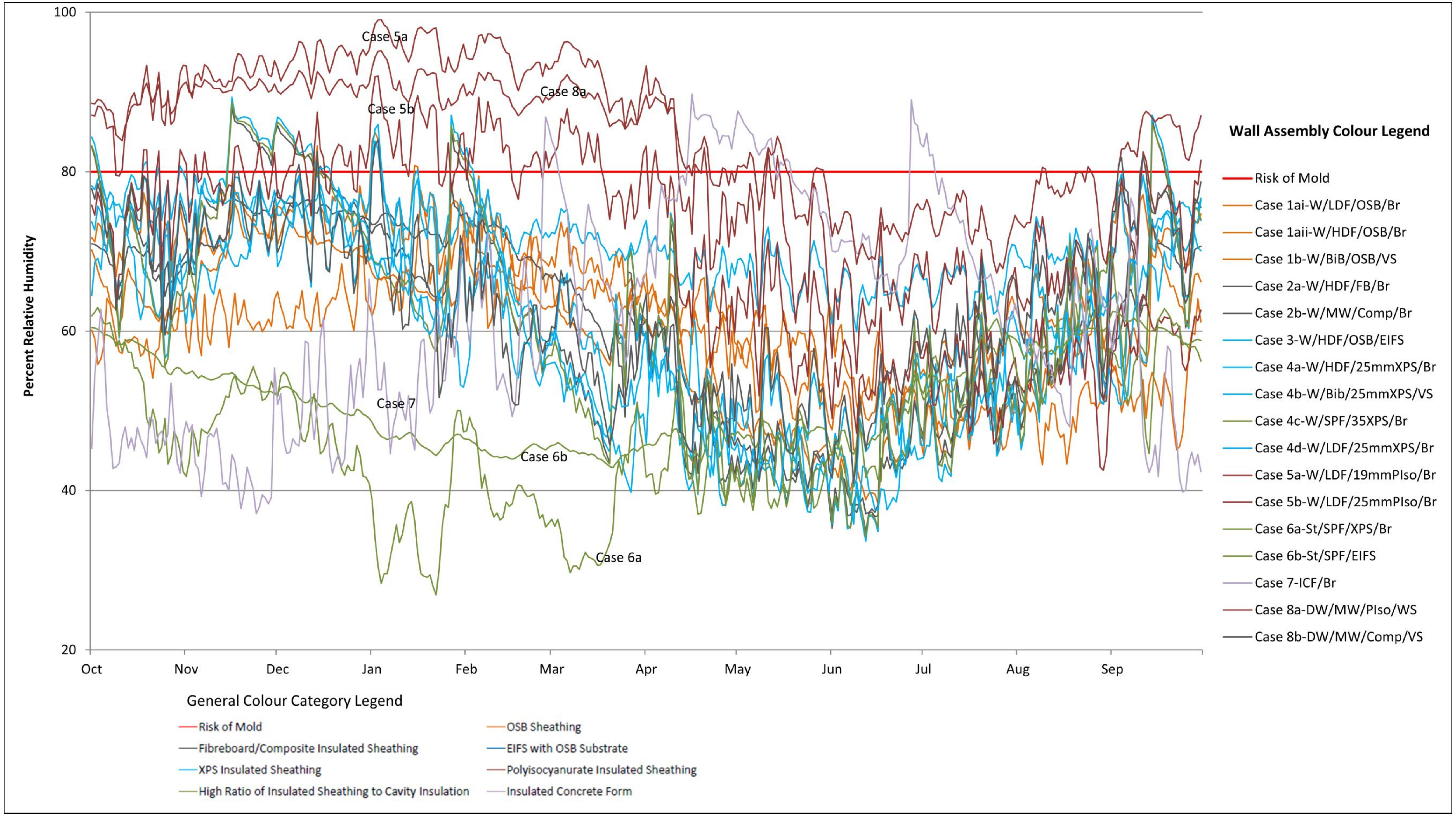


Figure 5-3 RH at Sheathing - Outward Vapour Drive

Unexpected performances of Cases 6a and 6b – the steel frame walls, (curves in the green colour) show RH levels generally at below 60%, which are exceptionally low in comparison to the other wall assemblies. This is due to the high ratio of insulated sheathing to cavity insulation that keep the temperature of the inboard surface of the sheathing at higher temperatures during the heating season. Cases 6a and 6b with 51mm of XPS and EPS in relation to 92mm of SPF have ratios of 0.73 and 0.58 insulated sheathing to cavity insulation. These ratios are high in comparison to the OBC's minimum ration of 0.2 for insulated sheathing to cavity insulation for Toronto's climate.

5.1.2.1 Outward Vapour Drive for Walls with Lower Permeance Sheathing

The wall assemblies that performed worst, in that they exhibited RH levels above 80% for a significant amount of time, are the walls that contain foil faced polyisocyanurate insulated sheathings as seen in Figure 5-4. Case 5a exhibited high levels of RH throughout the cold season. This is not surprising considering the two layers of extremely low permeance foil facings, with a combined permeance of 1.7 $ng/Pa{\cdot}S{\cdot}m^2$, which is close to half of the permeance of 0.15mm polyethylene.

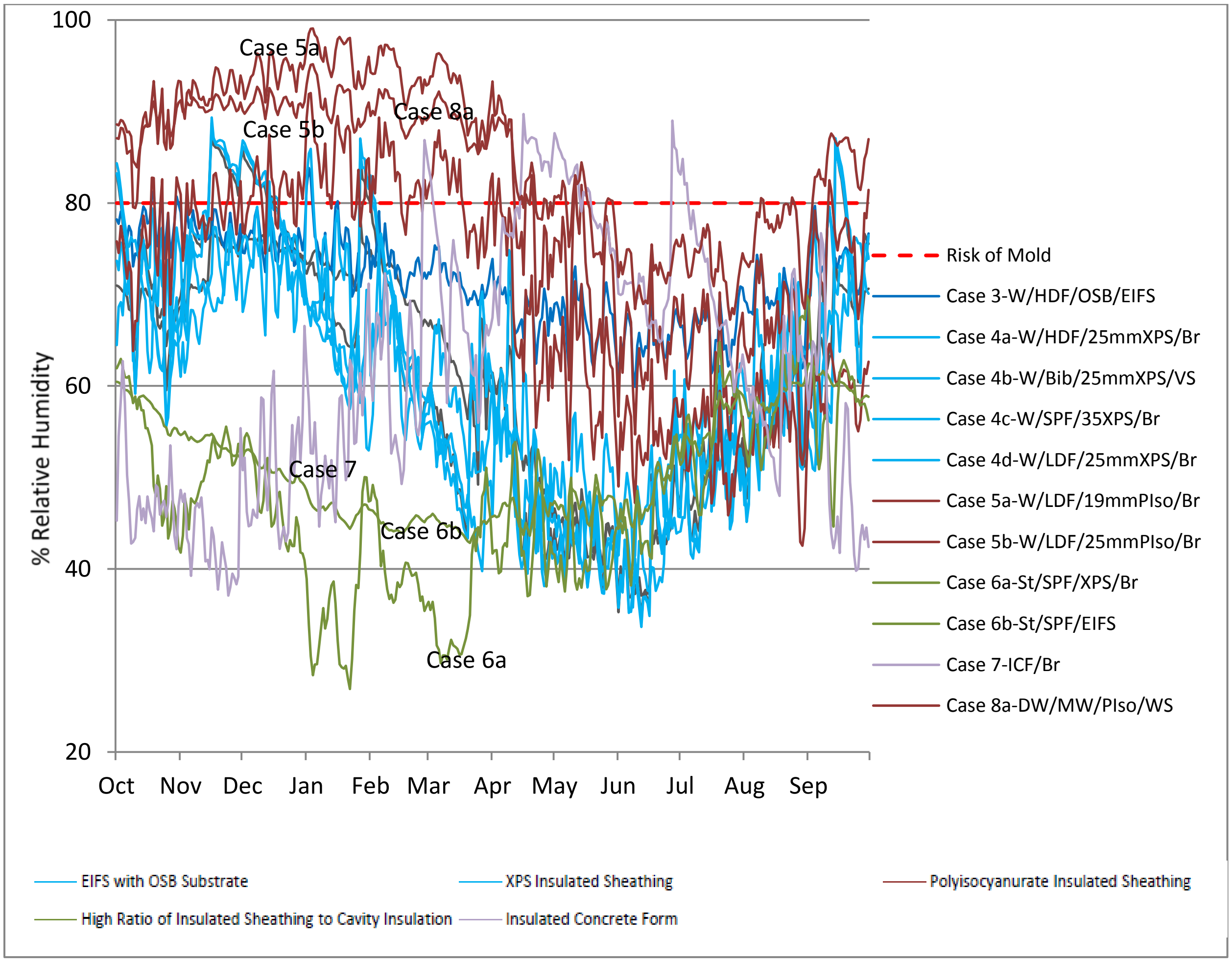


Figure 5-4, RH at Sheathing - Lower Permeance Sheathings

With 19mm of polyisocyanurate, the relatively low ratio of insulated sheathing to cavity insulation of 0.23, combined with properties of very low rate of vapour diffusion, cause excessive humidity conditions for Case 5a. Exceeding 80% RH for 45 days as well as exceeding the 98% threshold by three days raises concerns about the moisture safety of this wall assembly.

Similarly, Case 5b's 25mm of foil faced polyisocyanurate contributed to exceeding the 80% relative humidity level by 45 days. Case 5b performed better than Case 5a because of the higher ratio of insulated sheathing to cavity insulation of 0.3.

Case 8a, also due to the combined foil faced polyisocyanurate and OSB sheathing, performed poorly. This wall performed slightly better than Case 5a due to the hygric buffer characteristics of the OSB sheathing. As this wall is particularly sensitive to mould growth because of the OSB sheathing interior of the polyisocyanurate, moisture content of the OSB sheathing was checked for safe levels, and its descending moisture profile suggested that in terms of moisture accumulation, the sheathing was determined not to be in jeopardy. However, exceeding the 80% threshold by 42 days, this wall assembly's moisture safety is questionable.

As is evident in Figure 5-4, there are many more consecutive days of RH above 80% than those accounted for in the maximum consecutive days at RH threshold analysis, but because the sheathing temperature is below 5°C much of the time, those exposures are not considered in the analysis because there is no risk of mould growth below this temperature.

5.1.2.2 Outward Vapour Drive for Walls with High Permeance Sheathing

High permeance sheathings allow the self-regulation of elevated relative humidity levels. Figure 5-5 shows how the humidity levels for all walls had the same tendency for wintertime RH levels to be in the range of 70 to 80%. Case 1ai is shown in the black dotted line, with assumed adequate moisture performance, it is included as a reference.

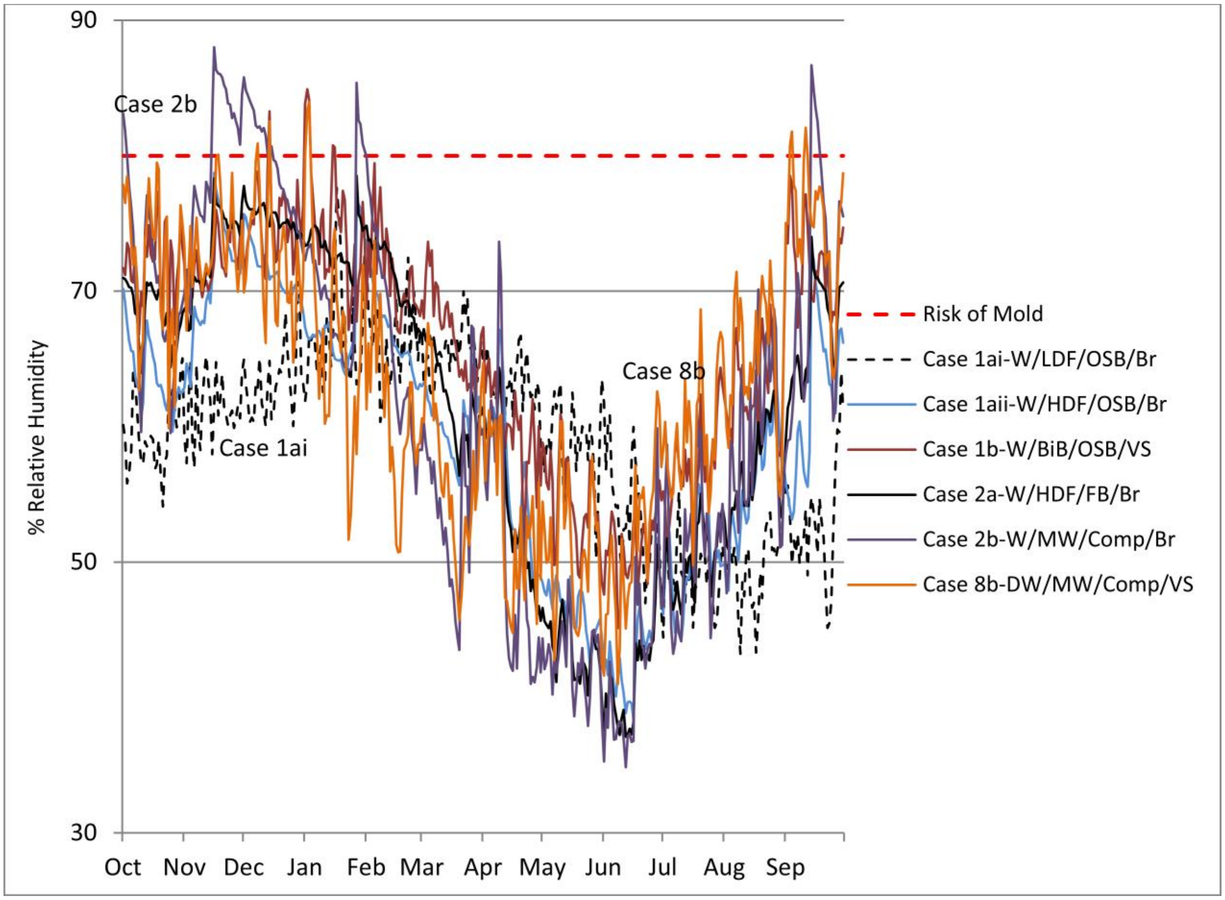


Figure 5-5 RH at Sheathing – Higher Permeance Sheathings

Case 1ai experienced lower wintertime RH because the sheathing temperature is higher on account of the low density fibreglass insulation (RSI 3.34 $m^2 \cdot K/W$), whose RSI is lower than the higher density insulations such as high-density fibreglass (RSI3.87), mineral wool (RSI 3.87 $m^2 \cdot K/W$), and blown-in fibreglass (RSI 4.05 $m^2 \cdot K/W$), as used in the other walls with higher permeance sheathings.

The spikes seen in Figure 5-5, for Case 2b, are due to sudden temperature drops and delayed relative humidity mitigation due to the use of “20-lb” building paper as a weather barrier, with a considerable vapour with a permeance of 230 $ng/Pa \cdot S \cdot m^2$. A similar spike was experienced by Case 2a, but due to its higher permeance and absence of another weather barrier membrane, was able to allow moisture to pass through the sheathing quicker.

5.1.3 Inward Vapour Drive – Summertime Conditions

5.1.3.1 ASHRAE Standard 160P Analysis – Inward Vapour Drive

The inward vapour drive data was measured at the outboard side of the vapour retarder membrane by means of the hygrothermal computer modeling. The moisture sources in summer conditions originate from high-temperature and high-moisture content ambient air, as well as by moisture driven inward from hydrophilic cladding that has absorbed water and is exposed to solar radiation.

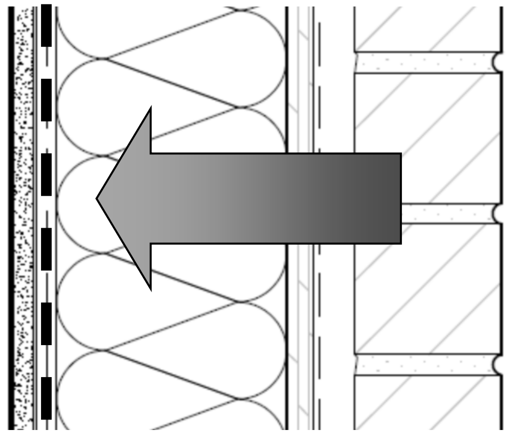


Figure 5-6 Inward Vapour Drive (Source: Twiddy, 2011)

The following results and discussion relate to ASHRAE Standard 160P three criteria for minimizing the risks of mould growth. The conditions indicated in quotation marks, outline conditions required for safe relative humidity performance at the location of measurement. For the inward moisture drive analyses, the relative humidity levels were measured at the outboard face of the vapour as shown in the dark dotted line in Figure 5-6.

> *"24-h running average surface RH < 100% when the 24-h running average surface temperature is between 5°C and 40°C" (160P)*

All calculated 24-hour running averages for the outboard face of the vapour retarder were below 100% relative humidity for all walls assemblies considered. Within this criterion of ASHRAE Standard 160P, all walls are acceptable.

> *"7-day running average surface RH < 98% when the 7-day running average surface temperature is between 5°C and 40°C" (160P)*

All calculated 7-day running averages for the outboard face of the vapour retarders were below 98% relative humidity for all walls assemblies considered. Within this criterion of ASHRAE Standard 160P, all walls are acceptable.

"30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5C and 40C" (160P)

Relative humidities at the outboard face of the vapour retarders, calculated for 30-day running averages exceeded 80% relative humidity in cases, 5a, 7 and 8a. According to these results, ASHRAE Standard 160P deems these walls to assume too great a risk for mould growth, even though the risk of mold growth is unlikely at that interface due to the inorganic nature of polyethylene.

A table showing maximum daily average of 80% RH for inward vapour drive conditions for all the walls was created. It can be seen in the Figure 5-7, that inward vapour drive days over 80% were shown in black for walls that pass the ASHRAE Standard 160P and in grey for the walls that failed.

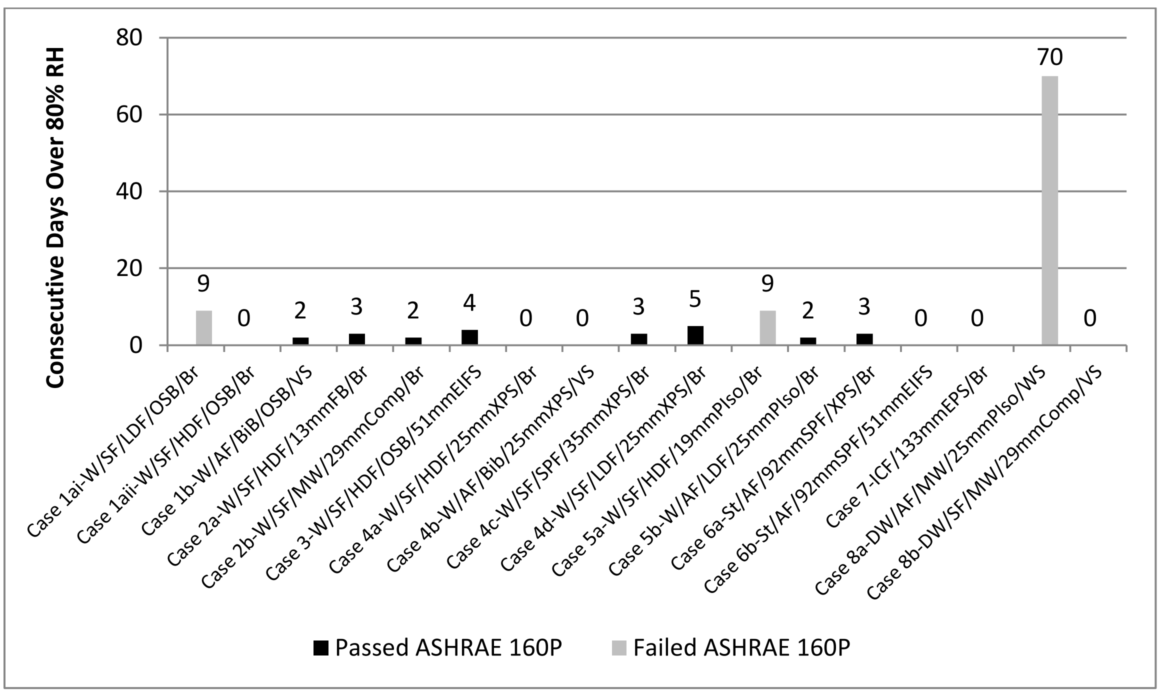


Figure 5-7 Inward Vapour Drive – Greatest Number of Consecutive Days Above 80%

It can be seen that Case 1ai failed the ASHRAE analysis, yet it was assumed for this research that this wall construction is a proven-performer in terms of moisture safety. This calls into question the validity of the assumptions used for the ASHRAE 160P framework.

According to the initial assumption that Case 1ai, the reference case

The wall assemblies in Figure 5-8 are arranged according to colour, where blue indicates walls with low permeance sheathing, orange indicates walls with high permeance sheathings, tan indicates walls with high ratios of insulated sheathing to cavity insulation and purple indicates ICF construction.

Similarly to the outward vapour drive conditions, walls with foil faced polyisocyanurate sheathings with low permeance experience long durations of elevated relative humidity outboard of the vapour retarder. This is not due to an inward vapour drive from summertime humidity levels, but due to trapped moisture that entered the wall cavity by diffusion in the winter as seen in Figure 7-8. With foil faced polyisocyanurate(1.7 $ng/PaSm^2$), there is very little vapour transport to the exterior, resulting in most of the drying to occur toward the interior.

Walls with high permeance sheathings (Cases 1 through 2) can be seen in Figure 5-8 to experience lower RH levels outside the vapour retarder. The modeling indicates that walls with XPS sheathing such as cases 4a, 4b, 4c and 4d will allow sufficient outward movement of vapour not to cause concern during periods of inward vapour drive, by keeping RH levels below 80%. Although the XPS resists inward vapour drive in the summers, the resistance to vapour transport is not sufficient to cause outward vapour drive concerns in the winter.ICF (Case 7) exhibits exemplary performance due to thermal mass. During summertime inward vapour drive conditions, this wall experiences RH levels between 60 and 50% throughout the summer.

Figure 5-8 RH Outboard of Vapour Retarder

5.1.3.2 Inward Vapour Drive for Walls with Low Permeance Sheathing

RH levels for wall assemblies with low permeance sheathing, as shown in Figure 5-9, are arranged according to colour, where blue indicates walls with XPS sheathing, red indicates walls with polyisocyanurate insulate sheathings, tan indicates walls with high ratios of insulated sheathing to cavity insulation and purple indicates ICF construction.

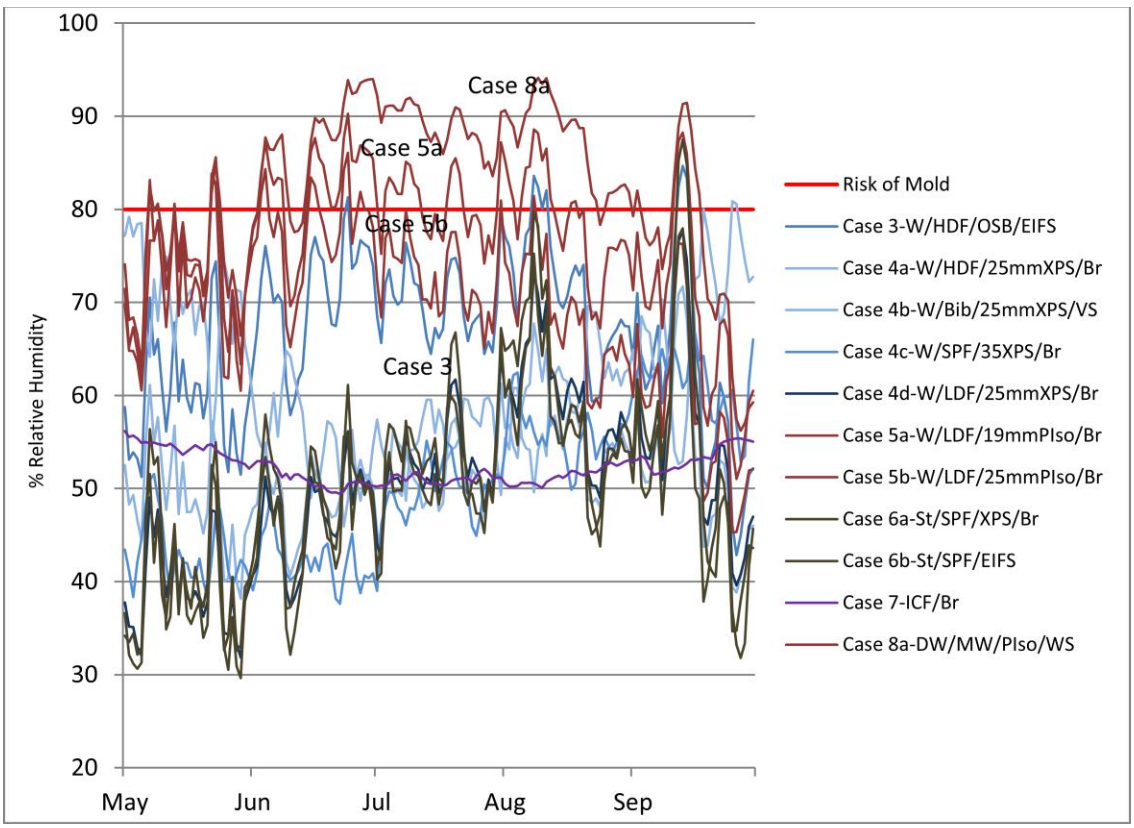


Figure 5-9 Inward Vapour Drive Outboard of Vapour Retarder – Lower Permeance Sheathing

A benefit of the use of low permeance sheathing is its function in resisting inward vapour drive during the summer months from moist and warm summer air, as well as vapour driven inward from drying cladding after wetting events. XPS sheathing performs this function well, and can be seen in Figure 5-9 that the walls coloured in blue exhibit RH levels ranging from 40% to 60% for much of the summer period. Difficulties occur when permeances are so low that they prevent the escape of moisture driven into the wall assemblies throughout the winter season, which occurs for polyisocyanurate, but not XPS.

Moisture that remains in the wall assemblies from the wintertime outward vapour transport creates a summertime moisture issue as well, with extended periods of RH above 80%.

Case 8a (double stud wall with combined OSB and polyisocyanurate sheathing) as seen in Figure 5-10, performed the worst, due to trapped moisture between the polyethylene vapour retarder and the inward side of the foil faced polyisocyanurate, both shown in black dotted lines. Higher RH levels are exhibited due to the hygric buffer capacity of the OSB sheathing inward of the polyisocyanurate which stores moisture from wintertime outward vapour drive and releases it in summertime conditions when temperatures are elevated. The hydrophilic wood siding did not contribute to the inward vapour drive because the vapour resistance of the foil, to the exterior of the polyisocyanurate.

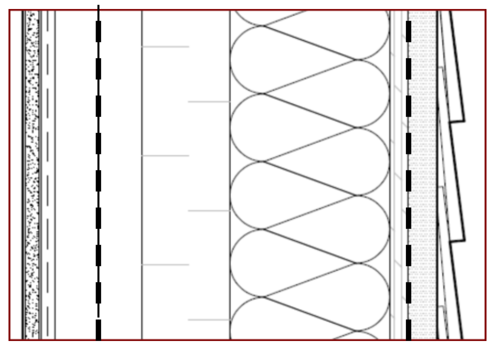


Figure 5-10 Case 8a - 38mmx140mm stud removed to show insulation (Source: Twiddy, 2011)

Cases 5a and 5b perform similarly to Case 8a due to the foil face polyisocyanurate's nearly impermeable vapour resistance levels, although they do not contain the OSB sheathing. Cases 5a and 5b exceeded 80% by 45 days each. Case 5a's higher RH levels are due to the use of high density fibreglass insulation. This cavity insulation is more effective at resisting the inward heat transfer, thereby keeping a lower temperature inside the cavity, increasing the RH level to 91% at times. Case 5b's low density fibreglass insulation is responsible for higher cavity temperatures, causing lower vapour pressures for the same amount of moisture that entered through the vapour retarder in the winter. Although Case 5a's polyisocyanurate thickness is 6mm less than in Case 5b, the whole-wall RSI of the Cases 5a and 5b are 3.2 and 3.64 $m^2 \cdot K/W$ respectively, a large enough difference to explain the RH difference.

5.1.3.3 Inward Vapour Drive for Walls with High Permeance Sheathing

RH levels for wall assemblies with high permeance sheathings, as shown in Figure 5-11, are arranged according to colour, for quick differentiation between wall constructions.

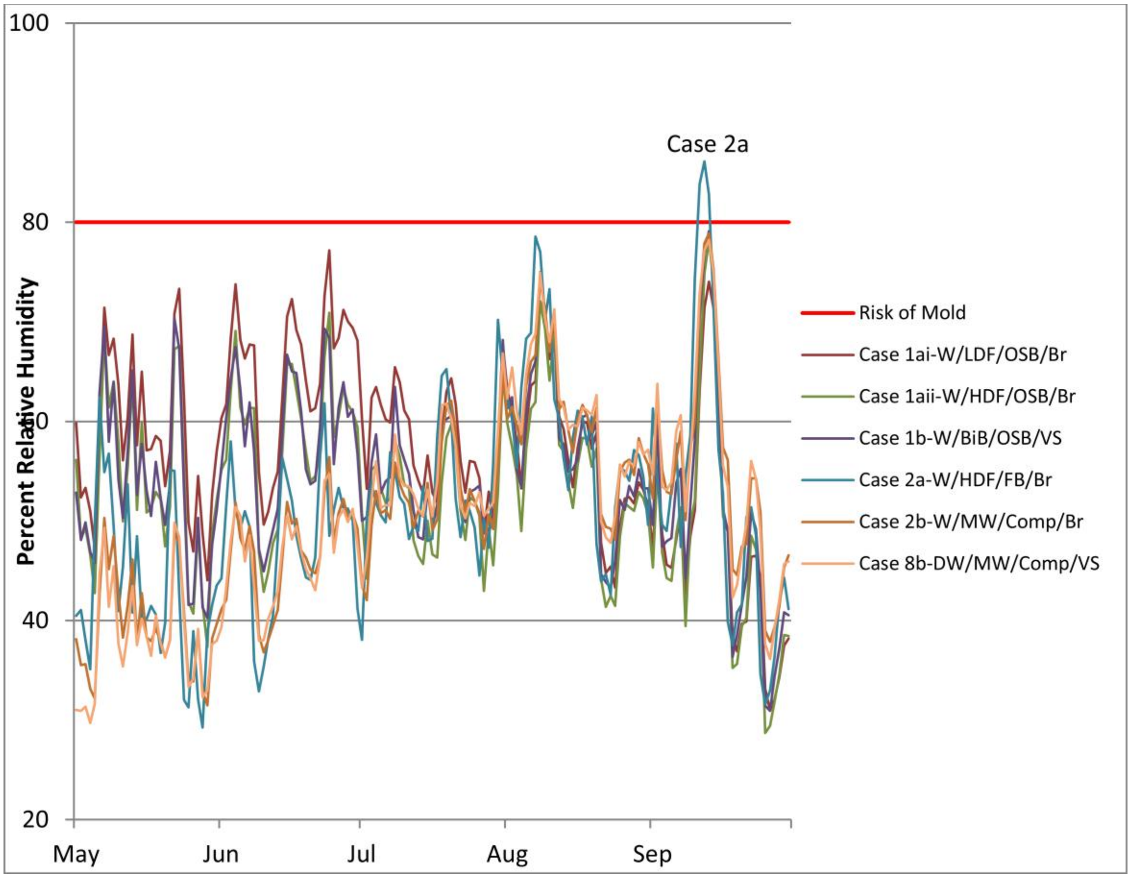


Figure 5-11 RH Outboard of Vapour Retarder – Higher Permeance Sheathings

Although higher permeance sheathing are less able to resist inward moisture drive, there were no indications of excessive humidity in any wall with higher permeance sheathing regardless of cladding type as can be seen in Figure 5-11. This aspect is also dependent on the hygrophilic nature of the cladding and the cavity ventilation rates.

For the first half of the graph , a relatively wide range of performance is seen in Figure 5-11. After mid-summer, the walls begin to perform more uniformly. This is due to an acclimatization period where the differences in sorption isotherms characteristics of the different materials within the assembly and their various thicknesses are adapting to more humid summer conditions. After a period of 3 months, they begin to behave very similarly to each other, due to having reached sorption equilibrium within the materials.

It can be seen that all the high permeance walls are able to safely manage moisture conditions within the wall assemblies. The brief spike in mid-September for all the walls, is inconsequential because of the short duration over 80% RH.

5.1.4 Drying Potential

In order to observe the drying behaviour of the wall assemblies, an elevated moisture content of 250 Kg/m^3 was used.

5.1.4.1 Drying Potential: All Walls in Context

Moisture contents, as shown in Figure 5-12, were arranged according to colour, where blue indicates walls with lower permeance sheathing and orange indicates walls with higher permeance insulate sheathings.

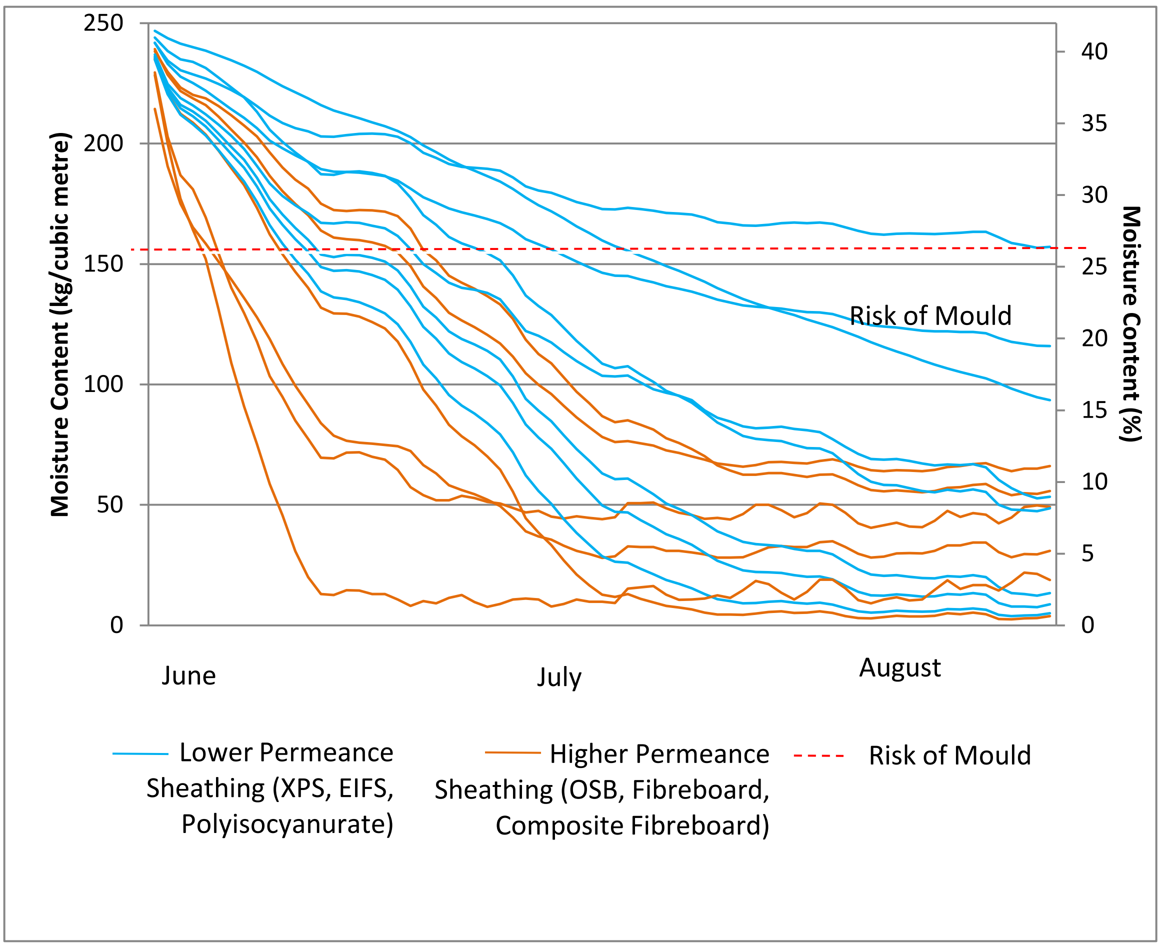


Figure 5-12 Drying Potential – Coloured by Higher and Lower Permeance Sheathings

5.1.4.2 Drying Potential: Walls with Lower Permeance Sheathing

The drying potential of all the walls with lower permeance sheathings are primarily influenced by the thermal resistance of the insulated sheathing. Better insulators create a higher temperature difference from the exterior to the interior side of the sheathing. The wetting layer, subject to lower vapour pressures caused by lower temperatures, have reduced tendencies to dry. This can be seen in Figure 5-13, where Case 5a, with 19mm of polyisocyanurate (RSI 0.79 $m^2 \cdot K/W$) dries at a faster rate than 5b with 25mm polyisocyanurate (RSI 1.06 $m^2 \cdot K/W$).

Most walls experienced a steeper slope at the beginning of the drying period than at the end. This is due to the higher vapour pressure gradient between the wetted layer and its surroundings, which promotes a quicker rate of drying.

The difference in drying rates for walls with higher permeance XPS and lower permeance XPS can be seen in Figure 5-13. Case 4a and 4b have lower permeance XPS, both with a permeance of 45 $ng/Pa \cdot S \cdot m^2$ dry slower than 4d, that contains the higher permeance XPS with a permeance of 201 $ng/Pa \cdot S \cdot m^2$. 4b dries slower than 4a due to the increased ventilation rate of vinyl siding that introduces exterior air sources moisture.

Cavity insulation also contributes to the temperatures of the wetting layers, shown by the increasing speeds of drying of cases 4b, 4a and 4d shown in green, purple and blue respectively. Case 4b dried slowest of the three, due to the contribution of blown-in-batt insulation, with a k-value of 0.033 W/m•K, followed by Case 4a with high density fibreglass with a k-value of 0.036 W/m•K, and finally Case 4d with low density fibreglass with a k-value of 0.043 W/m•K.

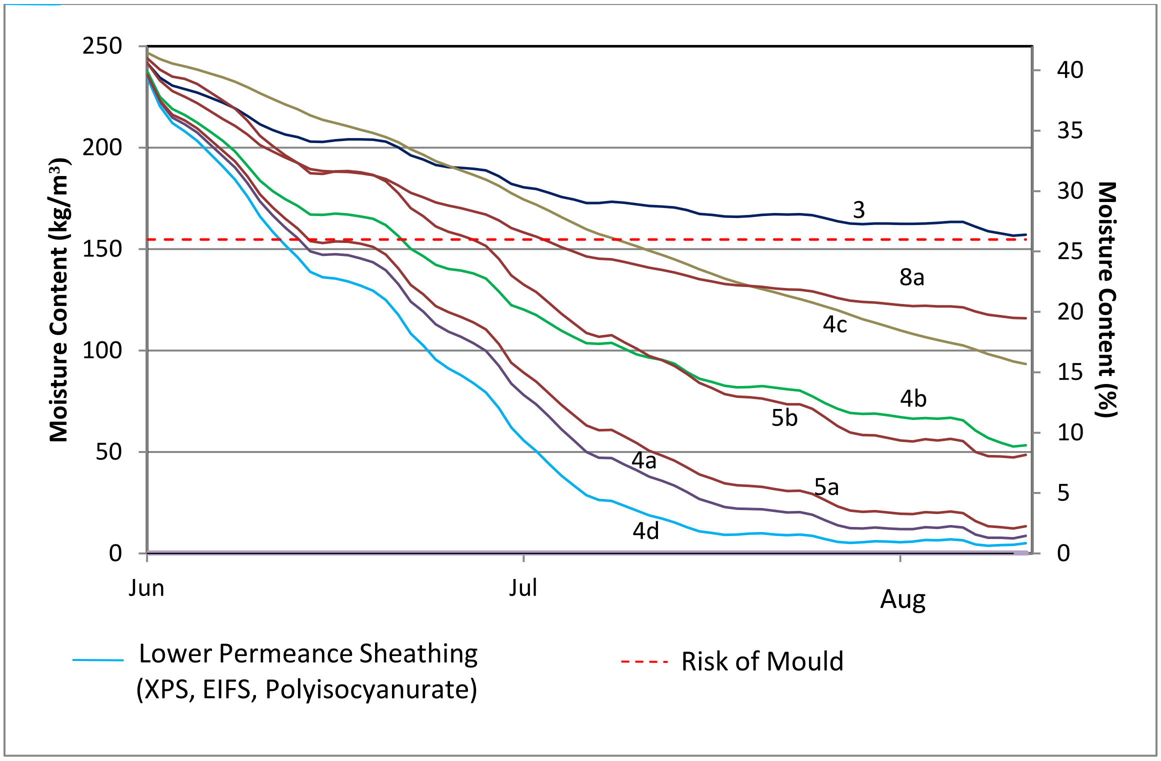


Figure 5-13 Drying Potential – Lower Permeance Sheathing

The exception to that relationship is seen with Case 5a, where the insulated sheathing RSI value is less than Case 4a and also contains high density fibreglass insulation. Expected results would be that the curve would lie below that of Case 4a, but due to inability to dry to the exterior because of the foil faced polyisocyanurate, it has a reduced drying rate.

Resistance to vapour transfer to the exterior influences the speed of drying. In cases where the vapour diffusion resistance level is extremely high, as in cases 3, 8a, 5a and 5b, see Figure 5-13, most of the drying occurs toward the interior, through the polyethylene, albeit at a reduced rate.

Case 4c dries rather slowly, in part because of the 37mm of XPS sheathing, with a permeance of 143 ng/Pa·S·m^2, exhibits a substantial resistance to vapour transfer to the exterior. Compounding the slowing of Case 4c's drying potential rate is the vapour diffusion resistance encountered by the SPF insulation, with a permeance of 221 ng/Pa·S·m^2. Reduced drying potential in both directions and with no ability to freely transfer moisture within the stud cavity, Case 4c's drying slope is rather consistent, unlike the other curves.

5.1.4.3 Drying Potential: Walls with High Permeance Sheathing

The wood based sheathings such as OSB (399ng/Pa·S·m^2), fibreboard (856 ng/Pa·S·m^2) and composite fibreboard/EPS (200 ng/Pa·S·m^2), with higher permeances themselves, are not separated from ventilated cavities by low permeance materials as the cases of wetting layers behind lower permeance sheathings. This allows for effective vapour transport to the exterior. In Figure 5-14, walls with OSB sheathing are shown in orange, and walls with fibreboard or composite fibreboard/EPS sheathings are shown in grey.

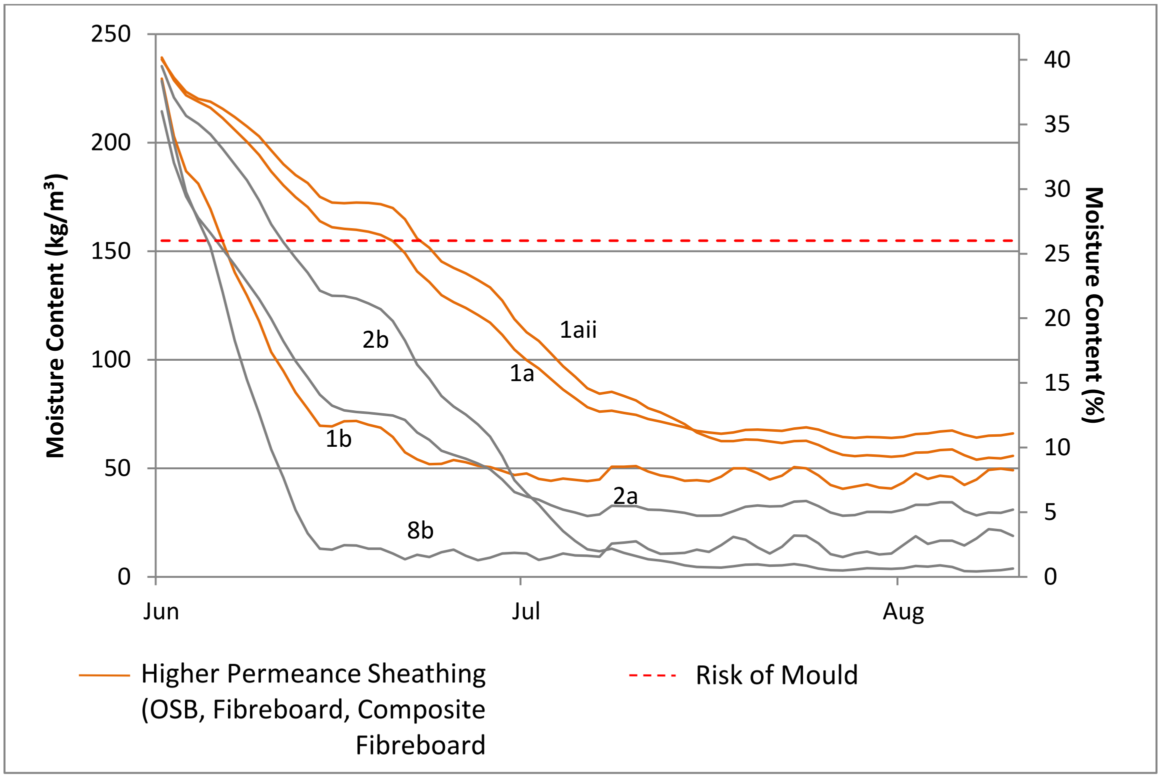


Figure 5-14 Drying Potential – Higher Permeance Sheathing

The sheathing types that dry to the lowest moisture content and at the fastest rate, are the composite fibreboard/EPS insulated sheathings. This is explained by the fibreboard portions of the insulated sheathings are outboard of the EPS, which has a tendency to keep the wet fibreboard closer to the warm summertime temperatures, and thus eperience higher vapour pressure gradients.

The fibreboard insulated sheathing of Case 2a, owing to its lower bulk density, thus open fibre structure with less opportunities for bound water than OSB, has an increased ability for allowing moisture to escape, as the gaps between the fibres contain moisture in the form of free water. For this reason, Case 2a dries at a quicker rate than any of the walls in the Case 1 category, as they are all sheathed in OSB.

The walls sheathed in OSB were slowest to dry, due to OSB's tendency to keep moisture as bound water and due to their cavity insulation effectivenesses. Slowest to dry was case 1ai, because of the low density fibreglass insulation. The higher conductivity of low density fibreglass insulation (RSI 0.043 W/m·K), has the tendency to allow the sheathing to cool toward the temperature of the interior conditioned space, thus lowering the vapour pressure within the OSB, and slowing its rate of drying. Cases 1aii and 1b, experience this less as high density and blown-in fibreglass insulations have progressively lower conductivities of RSI 0.036 W/m·K, and RSI 0.034 W/m·K, thus keeping the sheathing temperature nearest the warmth of summer temperatures.

Wall assemblies with brick cladding have more stable drying curves than walls with vinyl siding. Vinyl siding's higher ventilation rates (100 ACH) introduce moist summer air that leads to moisture loads that are not experiences by brick (8 ACH). This can be seen in the relatively stable results after July, for the curves for all but Cases 1b and 8b. Although Case 8a has wood siding and would likely experience similar variations due to higher ventilation rates, also assumed to be 100 ACH, the effectively impermeable foil faced polyisocyanurate prevents the inward migration of exterior air-borne humidity.

5.1.5 Risks of Exfiltration-Related Condensation

All wall assemblies that use batt insulation such as low density, high density, blow-in-blanket fibreglass insulation materials, or mineral wool insulation, take on a substantial risk of condensation due to exfiltrating interior air passing the condensation plane, shown in dark black dotted line in Figure 5-15. This assessment is based on the assumption that interior detailed polyethylene air barrier/vapour retarder is too difficult to effectively create a continuous air barrier and thus air leakage will occur. For walls that use batt insulation with polyethylene as the air barrier, the condensation plane is determined to be the inboard side of the sheathing materials. Although many sheathing materials are insulated, their inboard surface temperatures fall below the dew point temperature of exfiltrating air during most of the winter period.

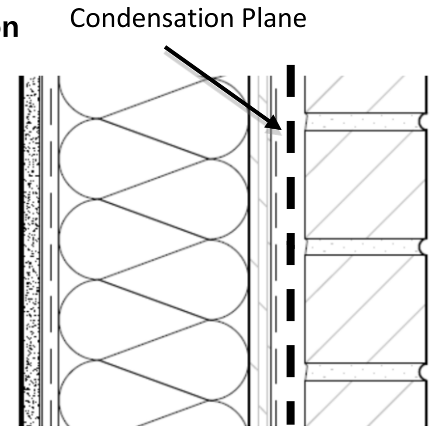


Figure 5-15 Condensation Plane for Walls with Batt Insulation (Source: Twiddy, 2011)

Although it is conceivable that spray foam polyurethane insulation can detach from its substrate materials, in this research the assumption is made that it is a continuous air barrier. Cases 4c, 6a, 6b and 7 have substantially higher temperatures at the condensation planes and thus do not take on the risk of exfiltrating related condensation. Of these, Cases 4c, 6a and 6b are walls with SPF cavity insulation and have condensation planes inboard of the cavity insulation where temperatures are well above the dew point of interior air as shown in Figure5-16 in black dashed line. This is due to the relative impermeability to air movement of the SPF.

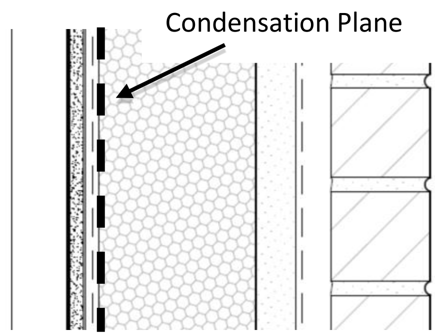


Figure 5-16 Condensation Plane for Walls with Spray Foam Insulation (Source:Twiddy, 2011)

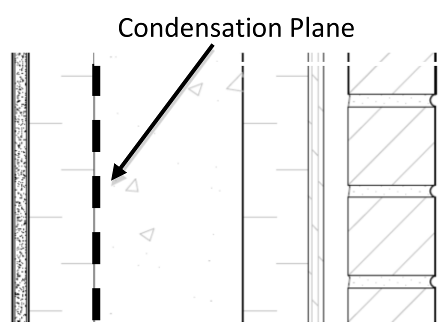


Figure 5-17 Condensation Plane for ICF Construction (Source:Twiddy, 2011)

Similarly for ICF construction in Case 7, the poured concrete is assumed to provide a continuous air barrier and therefore has a condensation plane on the inboard side of the cast in place concrete, as seen in Figure 5-17.

The results of the analysis as shown graphically in Figure 5-18, illustrate that cases with continuous air barriers such as Case 4c, 6a, 6b and 7 do not assume risks of exfiltration-related condensation. The condensation planes of spray foam insulation assemblies and ICF construction is close enough to the interior environment that condensation would not occur. Conversely, all wall using batt insulation such as glass fibre and mineral wool products that use interior detailed polyethylene air barriers, are determined to assume great risk of condensation due to air leakage because the sheathing temperatures are low.

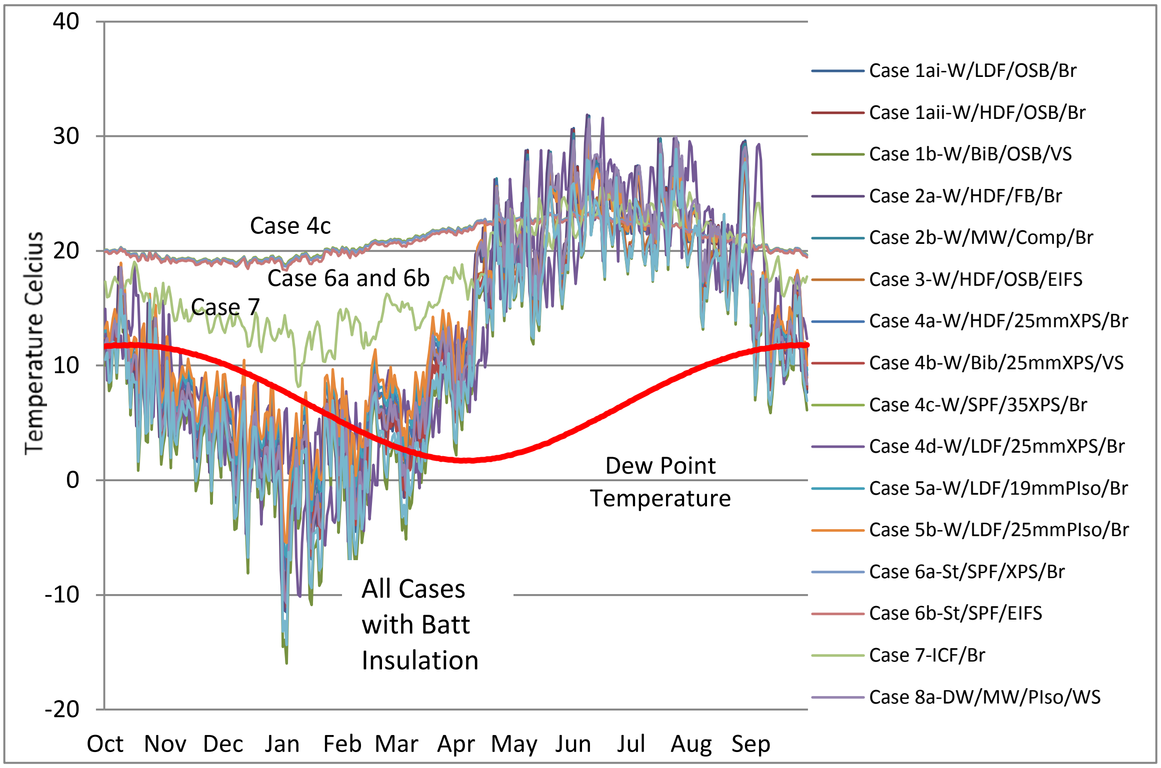


Figure 5-18 Condensation Plane and Dew Point Temperatures

5.2 Heat Transfer

5.2.1 THERM Analysis

Out of the walls considered in this research, there was a wide spectrum of RSI levels. Case 1ai was used as a reference against which to gauge the heat transfer improvements of the walls. In terms of nominal RSI values and excluding the reference wall Case 1ai, two walls were below RSI 4.0, eleven were within the range of RSI 4.0 m^2·K/W and RSI 5.0 m^2·K/W and four walls were above RSI 5.0 (m^2·K/W) as seen in the heat transfer analysis results in Table 5-2.

There was also a broad range of deviations of whole-wall RSI values from nominal RSI values used to determine appropriate OBC compliance packages. Percent deviations of whole-wall RSI losses ranged from 9% to 35%.

For wood stud framing designs, the double top plate section represented the greatest losses in terms of thermal bridging, followed by wall sections and finally rim joist sections. Exceptions to that are steel framed, ICF and double framed wall constructions that yielded different results based on individual construction idiosyncrasies.

The range of whole wall thermal improvements as compared to the reference case 1ai was a relatively even distribution of improvements up to 54% increases, with a large jump up to 142% increase.

Table 5-2 Results of THERM Analysis

Case #	Descriptor	THERM Analysis				Nominal RSI (m^2·K/W)	Deviation from nominal RSI
		Wall section (m^2·K/W)	Rim joist section (m^2·K/W)	Top plate (m^2·K/W)	Whole-wall (m^2·K/W)		
1ai	W/SF/LDF/OSB/Br	2.48	2.61	2.20	2.48	3.71	-33%
1aii	W/SF/HDF/OSB/Br	2.66	2.70	2.31	2.63	4.04	-35%
Case 1b	W/AF/BiB/OSB/VS	3.12	2.73	2.31	2.92	4.13	-29%
Case 2a	W/SF/HDF/13mmFB/Br	2.81	2.84	2.49	2.78	4.22	-34%
Case 2b	W/SF/MW/29mmComp/Br	3.34	3.33	2.75	3.27	4.66	-30%
Case 3	W/SF/HDF/OSB/51mmEIFS	4.08	4.06	3.77	4.04	5.45	-26%
Case 4a	W/SF/HDF/25mmXPS/Br	3.47	3.51	3.20	3.45	4.83	-29%
Case 4b	W/AF/Bib/25mmXPS/VS	4.00	3.59	3.25	3.80	5.01	-24%
Case 4c	W/SF/SPF/35mmXPS/Br	3.70	3.84	3.43	3.70	4.94	-25%
Case 4d	W/SF/LDF/25mmXPS/Br	3.26	3.32	3.03	3.25	4.48	-27%
Case 5a	W/SF/LDF/19mmPIso/Br	3.18	3.35	3.02	3.20	4.75	-33%
Case 5b	W/AF/LDF/25mmPIso/Br	3.77	3.51	3.23	3.64	4.66	-22%
Case 6a	St/AF/92mmSPF/XPS/Br	3.16	2.79	3.31	3.09	4.23	-27%
Case 6b	St/AF/92mmSPF/51mmEIFS	2.90	2.42	2.92	2.79	3.88	-28%
Case 7	ICF/133mmEPS/Br	4.70	2.84	3.87	4.23	4.70	-10%
Case 8a	DW/AF/MW/25mmPIso/WS	7.89	5.32	7.84	7.21	8.97	-20%
Case 8b	DW/SF/MW/29mmComp/VS	4.39	3.80	4.56	4.26	5.71	-25%

The reference case 1ai is a good example of how thermal bridging in the three sections, wall section, rim-joist section and top plate section are influenced by the amount of timber within the wall (see Table 5-2). The nominal RSI for the wall is 3.71 m^2·K/W. The double top plate contains more timber than the other two sections, with correspondingly lower RSI value of 2.2 m^2·K/W. The next largest losses are found in the wall section with an RSI of 2.48 m^2·K/W since 25% of the cavity space is occupied by wood. The rim joist with an RSI of 2.61 m^2·K/W suffers least losses due to the fact the structural members are in part, covered by insulation. Thus when these results are calculated as per equation 3-4, they give an overall RSI of 2.48 m^2·K/W, which is a reduction of 33% compared to the nominal RSI.

The other single stud Cases (1-5) all show a reduced RSI in the top plate and rim joist areas for the same reasons, however the use of insulated sheathing does reduce the impact. Thus, cases with EPS (51mm), XPS (25mm or 37mm) or polyisocyanurate sheathing (19mm or 25mm) such as in cases 3, 4 and 5, reduce the reduction of RSI down to 22%- 25%. Even greater improvements could be expected with additional insulated sheathing.

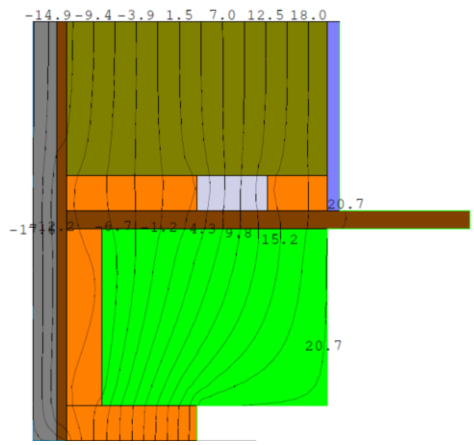


Figure 5-19 Rim Joist Section - Case 8a

Double stud construction such as Cases 8a and 8b, suffer relatively high thermal resistance losses in the rim-joist section due to exposed lumber in the construction and direct contact from floor joist members to the rim-joist, as can be seen from much lower RSI values for the rim-joist section than the other two sections. Case 8a has a nominal RSI of 8.97 m^2·K/W but lost 37% of its RSI value in the rim-joist section with a RSI of 5.32 m^2·K/W as compared to the wall section, as seen in Figure 5-19, shows the isotherms with concentrations at the exposed timber below the rim joist. On the other hand the top plate of double stud walls shows a smaller

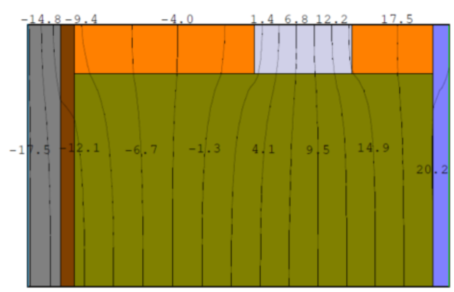


Figure 5-20 Top Plate Section –Case 8a

reduction in RSI to 7.84 m^2·K/W for Case 8a because of the discontinuity provided by the EPS spacer of the top plate as seen in Figure 5-20. Similarly for steel frame construction (case 6), the rim-joist section suffered greatest relative losses in RSI value as compared to its top plate and wall sections, where the relative reductions in RSI are 16% and 17% for Cases 6a and 6b respectively as compared to the top plate sections. The advanced framing technique helps to reduce the RSI losses, as well with only a single top rail, steel framing designs encounter less effects from thermal bridging than wood construction with a double top plate design.

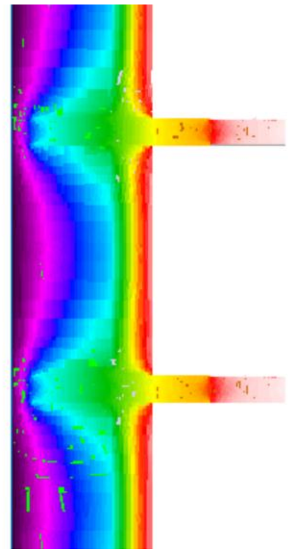


Figure 5-21 Plan View of ICF Rim Joist Section – THERM Colour Flux Magnitude

Insulated Concrete Form structures perform exceedingly well in terms of thermal bridging losses, with a nominal RSI of 4.7 m^2·K/W and a reduction of whole wall by only 9% to RSI of 4.3 m^2·K/W. However, the rim-joist section experiences much more losses compared to the wall section, due to its steel rim joist inserts that penetrate half way into the concrete, bypassing the inward layer of EPS as seen in Figure 5-21. At this junction, ICF rim joist section has a relative reduction of 37% to RSI 2.84 m^2·K/W as compared to its wall section.

Wall section RSI values approach rim-joist sections with advanced framing, such as Cases 1b, 4b and 8a, due the significant reduction in framing materials used in the wall sections when the studs are spaced by 600mm. The benefits of advanced framing are not extended to top plate or rim-joist section because they run the length of the wall, which explains the RSI value relationship change, where wall sections rise in relative RSI values compared to rim-joist and top plate sections.

Without the benefit of insulated sheathing, higher deviations from nominal insulation levels are found corresponding to the effectiveness of the cavity insulation. Comparing Cases 1ai and 1aii, the percent deviation from nominal RSI values, rises from 33% to 35% because the high density fibreglass insulation nominally achieves higher RSI values than low density fibreglass, but is still faced with the same amount thermal bridging losses. Higher percent deviations would be expected for Case 1b due to the

Blown-in-Blanket insulation with a higher nominal RSI value, but is substantially less, due to the advanced framing at 600mm spacing, which reduces the framing factor to 16% from 25% and therefore much less thermal bridging losses. Case 1aii and 1b vary only by RSI 0.29 m^2·K/W nominally, due to the conductivity difference between blown in blanket and high density fibreglass insulation. With the latter having a 600mm stud spacing, the improvement of the whole wall RSI to 4.13 m^2·K/W for Case 1b as compared to 3.71 m^2·K/W. This results in a whole-wall RSI difference of 10% as compared to the nominal RSI difference of 2%

Even minimal amounts of insulated sheathing such as the fibreboard sheathing with an RSI of 0.26 m^2·K/W, such as in Case 2a, immediate benefit are seen from the reduction in percent deviation from 1aii, that also has high density fibreglass insulation. Case 2a's RSI value climbs to 4.22 m^2·K/W from RSI 4.04 m^2·K/W, but percent deviation from nominal decreases to 34% from 35%.

25mm and 35mm thicknesses of insulated sheathings reduced the percent deviations to between 24% and 29% where 400mm stud spacing is used as seen in cases 4a, 4b, 4c and 4d. The best performing wood stud wall in terms of approaching the nominal insulation values however is Case 5b, with a 22% deviation, owing to its 600mm stud spacing and 25mm of high RSI value polyisocyanurate (RSI 1.06 m^2·K/W).

The steel framing designs of cases 6a and 6b performed fairly well considering the high thermal conductivity of steel. Due to the insulated sheathing of 51mm of XPS for case 6a and 51mm of EPS insulation in case 6b, the ratio of insulated sheathing to cavity insulation of 0.74 and 0.59 for cases 6a and 6b respectively, were able to blunt the effects of thermal bridging fairly effectively. In addition the reduced framing factor due to 600mm spacing of studs also helped to reduce. Their percent deviations were 27% and 28% for Cases 6a and 6b respectively. The EPS spacers used to separate the lumber in the double framed wall designs in cases 8a and 8b, allow for excellent deviation values of 20% and 25% (see Figure 5-19). The deviation values would be lower if the rim-joist section's exposed wood framed detailing were addressed.

5.2.2 Whole-Wall Thermal Resistance

The walls were arranged according to increasing nominal RSI values as well as colour coded according to which RSI value grouping they belonged to, as part of the OBC compliance packages as seen in Figure 5-22. The red columns indicate the whole-wall thermal resistance of each wall. Walls satisfying compliance packages compliance packages I, J and K (RSI 3.87m^2·K/W), are shown in green, those satisfying compliance packages A, D, E, F, G, H and I (RSI 4.23 m^2·K/W)are shown in purple and walls satisfying compliance packages B and C (RSI 4.75 m^2·K/W)are shown in blue. The colourless wall is reference wall Case 1ai, and does not meet the minimum RSI level for any OBC compliance package.

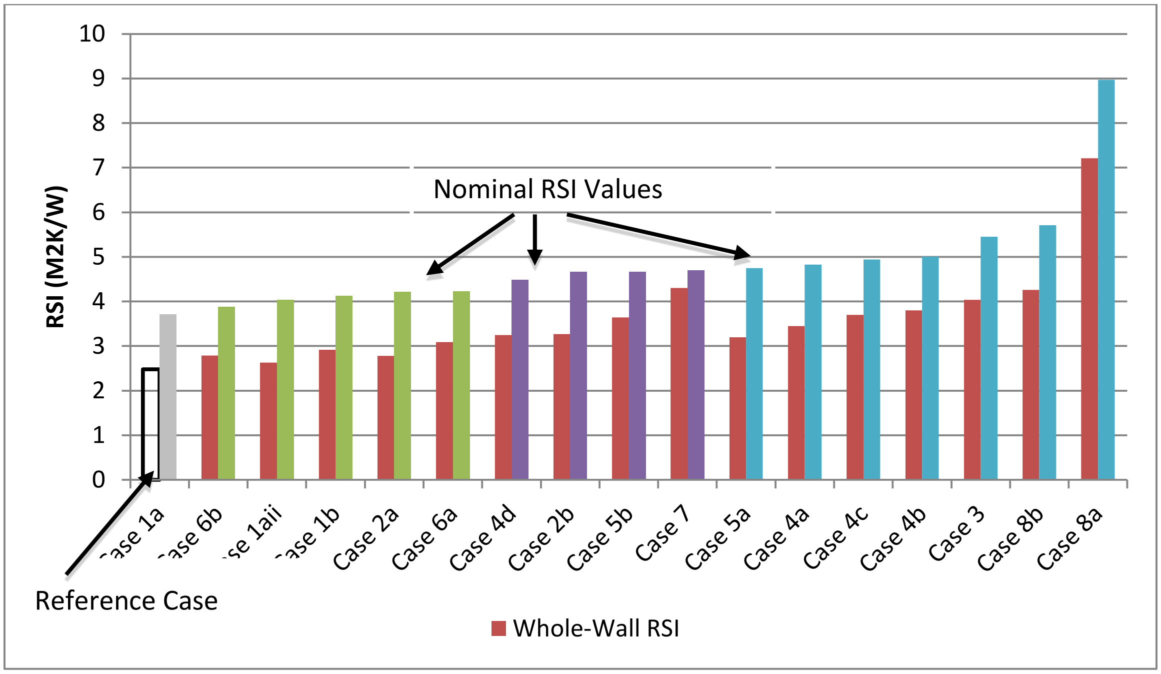


Figure 5-22 Results from THERM Analysis - Walls Arranged According to Increasing Nominal RSI Values

RSI values increase in relatively even increments until the latter part of compliance packages B and C, because there is no upper limit on RSI values for code packages B and C, thus the last three walls, cases 3, 8a and 8b are pushing the boundaries of thermal efficiency.

The wall assembly designs were re-arranged according to their whole-wall RSI values as shown in Figure 5-23. It can be seen that the whole-wall RSI values fluctuate in value, according to construction and material selection.

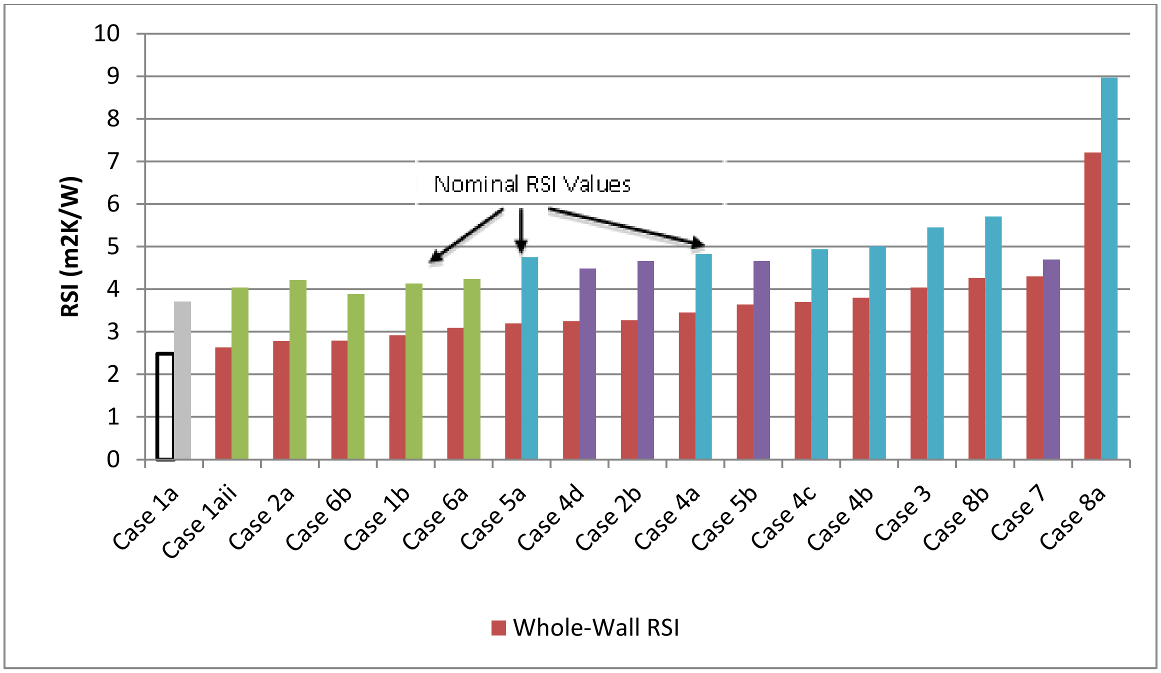


Figure 5-23 Results from THERM Analysis - Walls Arranged According to Increasing Whole-Wall RSI Values

For walls that satisfy compliance packages A, D, E, F, G, H and I, (purple) as well as B and C (blues), significant rearrangement was observed with important consequences to builders. This analysis shows the importance of using whole wall RSI values rather than nominal RSI. Although Case 5a with a nominal RSI of 4.75 m^2·K/W would be acceptable for packages B or C (which require an RSI of 4.23 m^2·K/W and 4.75 m^2·K/W respectively), its whole wall RSI is actually only 3.20 m^2·K/W which does not meet the requirements of any of the packages. This applies to most walls (particularly the framed walls) when placed in the context of its realistic performance, are seen to perform much worse than the nominal RSI values suggest. The ICF wall in Case 7 stands out as having the least differential and is the second best performing wall despite its much lower nominal RSI than Case 8b.

It is evident that the OBC's nominal RSI requirements are too simplistic to address the reality of thermal bridging losses in building envelope designs

5.3 Global Warming Impact

Table 5-3 Results From ATHENA Modeling

Case #	Wall Descriptor	GWP (Kg CO_2/m^2)
1ai	W/SF/LDF/OSB/Br	59.29
1aii	W/SF/HDF/OSB/Br	59.51
Case 1bii	W/AF/BiB/OSB/VS	53.95
Case 2a	W/SF/HDF/13mmFB/Br	59.51
Case 2b	W/SF/MW/29mmComp/Br	72.20
Case 3	W/SF/HDF/OSB/51mmEIFS	19.65
Case 4a	W/SF/HDF/25mmXPS/Br	61.74
Case 4b	W/AF/Bib/25mmXPS/VS	38.83
Case 4c	W/SF/SPF/35mmXPS/Br	58.00
Case 4d	W/SF/LDF/25mmXPS/Br	61.74
Case 5a	W/SF/LDF/19mmPIso/Br	62.60
Case 5b	W/AF/LDF/25mmPIso/Br	63.81
Case 6a	St/AF/92mmSPF/XPS/Br	86.50
Case 6b	St/AF/92mmSPF/51mmEIFS	47.33
Case 7	ICF/133mmEPS/Br	112.60
Case 8a	DW/AF/MW/25mmPIso/WS	100.36
Case 8b	DW/SF/MW/29mmComp/VS	106.14

The results from the environmental impact assessment yielded a broad range of global warming potential (GWP) impacts as can be seen in Table 5-3. Ranging from 19.65 to 112.6 Kg CO_2/m^2, the design implications are considerable where the largest impact is 5.7 times higher than the least. The majority of results were between 50 and 73 Kg CO_2/m^2, with lowest impact walls between 19 and 33 Kg CO_2/m^2, and the highest impact walls between 100 and 113 Kg CO_2/m^2.

The walls with the lowest (GWP) impact were found to be cases 3, 4b, 6b and 1b as can be seen in Figure 5-24. By using non-brick cladding, which avoids a source of high global warming potential, these wall assemblies perform better from an environmental impact perspective. “Ontario” brick, a clay brick often used in the GTA, is a clay brick that is required to be raised to 1100°C to vitrify the material. EIFS as used in Case 3, and vinyl siding as used in 4b, 6b and 1b designs, have significantly lower energy inputs than the manufacturing of brick.

The GWP for Case 2b is substantially higher than case 5b with 72.2 Kg CO_2/m^2 and 63.81Kg CO_2/m^2 because of the presence of mineral wool insulation. Mineral wool, which involves the melting of rock, requires extremely high energy inputs and subsequently contributes to a high GWP value.

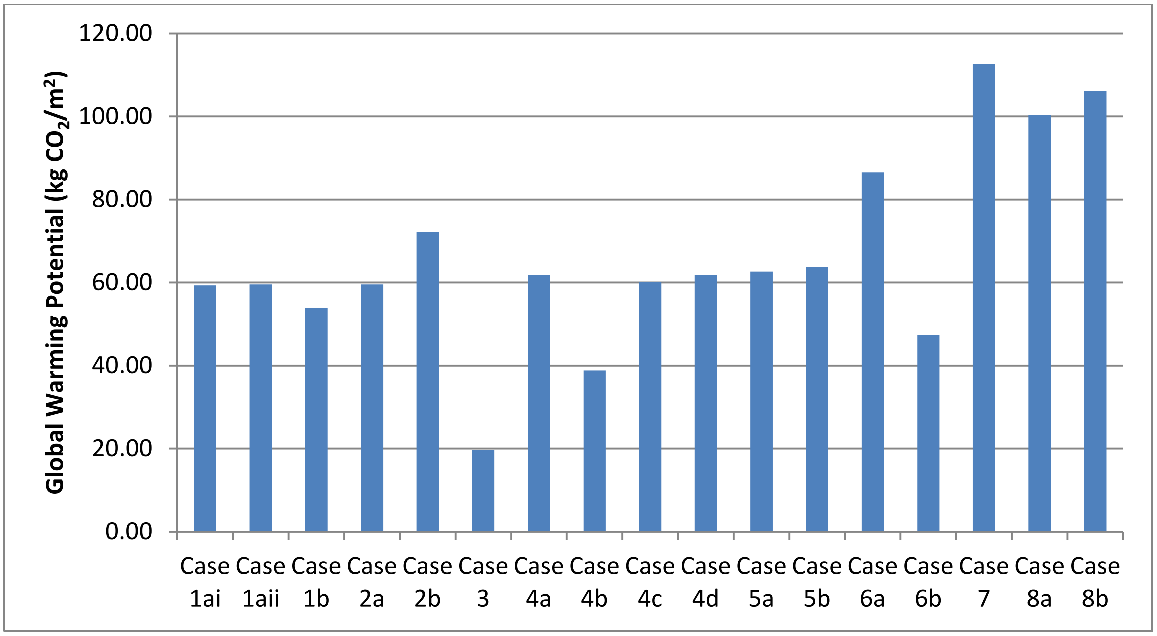


Figure 5-24 Results for Global Warming Potential Analysis

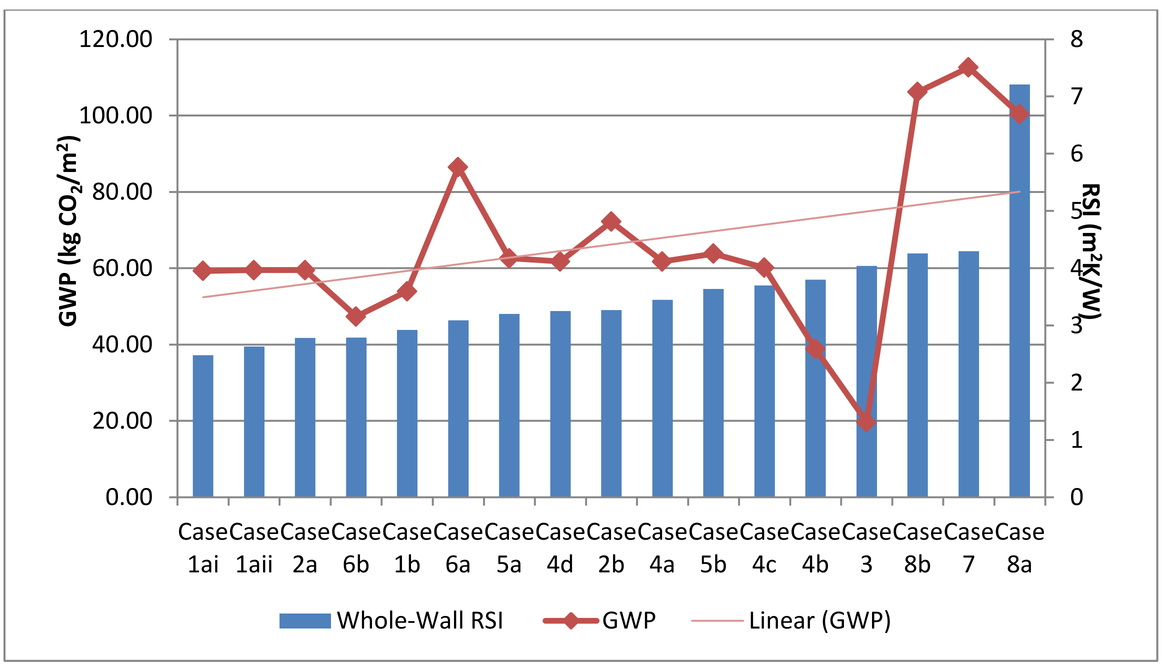
A significant increase in GWP for case 6a due in part to the Hydrofluorocarbons (HFC) used as blowing agents in XPS, which generate 1430 times the global warming potential of CO_2. The large amount of XPS used in this wall assembly, combined with the steel used for framing combine to yield such a high GWP of 86.5 Kg CO_2/m^2.

Case 8a, surprisingly resulted in a lower GWP than Case 8b despite seemingly more material inputs. The rather thick double stud construction design of Case 8a contains a large amount of mineral wool, but this is somewhat tempered by Case 8a`s use of wood siding rather than Case 8b's vinyl siding which requires more energy in its production. Polyisocyanurate has lower GWP than EPS, thereby increasing the GWP for Case 8b. The use of advanced framing as done in Case 8a, also had a large effect on a comparative reduction in GWP as compared to Case 8b.

The wall design that resulted in the highest GWP was Case 7. Concrete manufacturing is an extremely energy intensive process that is responsible for considerable environmental impacts. This wall design also uses a combined thickness of 133mm of EPS which also contributes to its poor GWP performance due to the use of pentane gas as the blowing agent.

GWP was used as the only indicator for environmental impact in this research, because it is an important element in the fight against climate change, and is sometimes used as an indicator of overall environmental impact. Due to resource limitations it was used here as a low level indicator of the impacts of manufacturing the walls. It must be noted that there are limitations to the analyses, as global warming potential is the sole indicator for environmental impact, as well as a square meter assessment does not include many of the items of a whole house. There are other elements that were not considered in this research that require periodic maintenance, and could affect the results of the assessments.

Whole-wall RSI values were plotted against the global warming potential to identify what correlations if any exist. It can be seen in Figure 5-25, that although there is a high degree of variation of global warming potential for the given wall assembly configurations, a general trend can be discerned. GWP trend line shows an increasing GWP at an approximately similar rate to the average rise of RSI values across the wall assemblies, but other factors such as type of insulation and cladding materials are also major variants.



5-25 Whole-Wall RSI and Global Warming Potential

5.4 Costs

In order to support the research with costing information, David Twiddy from George Brown College was approached to perform the costing analysis. A detailed material take-off approach was taken based on a generic reference house, and reduced to a per-square-meter value as shown in Appendix X.

Table 5-4 Results from RS-Means Analysis

Case #	Wall Descriptor	Cost ($/m^2)
1ai	W/SF/LDF/OSB/Br	$198.40
1aii	W/SF/HDF/OSB/Br	$198.15
Case 1bii	W/AF/BiB/OSB/VS	$165.85
Case 2a	W/SF/HDF/13mmFB/Br	$197.59
Case 2b	W/SF/MW/29mmComp/Br	$201.26
Case 3	W/SF/HDF/OSB/51mmEIFS	$153.12
Case 4a	W/SF/HDF/25mmXPS/Br	$201.85
Case 4b	W/AF/Bib/25mmXPS/VS	$157.28
Case 4c	W/SF/SPF/35mmXPS/Br	$318.68
Case 4d	W/SF/LDF/25mmXPS/Br	$202.97
Case 5a	W/SF/LDF/19mmPIso/Br	$195.69
Case 5b	W/AF/LDF/25mmPIso/Br	$198.30
Case 6a	St/AF/92mmSPF/XPS/Br	$356.57
Case 6b	St/AF/92mmSPF/51mmEIFS	$323.46
Case 7	ICF/133mmEPS/Br	$375.80
Case 8a	DW/AF/MW/25mmPIso/WS	$252.08
Case 8b	DW/SF/MW/29mmComp/VS	$233.32

The costing analysis yielded a range of costs from $170.20 to $375.80 for cases 3 and 7 respectively as seen in Table 5-4. Due to those range of wall assembly configurations, general interpretations are difficult to make. It can be seen, however that the EIFS cladding is the most cost effective way to enclose buildings. Using vinyl siding, cases 1b and 4b costs approximately 25% less than most of the other walls of case category 1 and 4, due to high costs of brick cladding. Vinyl siding and brick cladding, at per square meter costs of $6.59 and $12.26 respectively, result in a price difference of just over twice the costs.

SPF insulation is clearly a large contributor to cost indicated by the extreme increase in costs for Case 4c. At $120.35 per square meter, SPF represents an increase in insulation costs of sixteen times the cost of low density fibreglass insulation, with a cost of $7.49 per square meter.

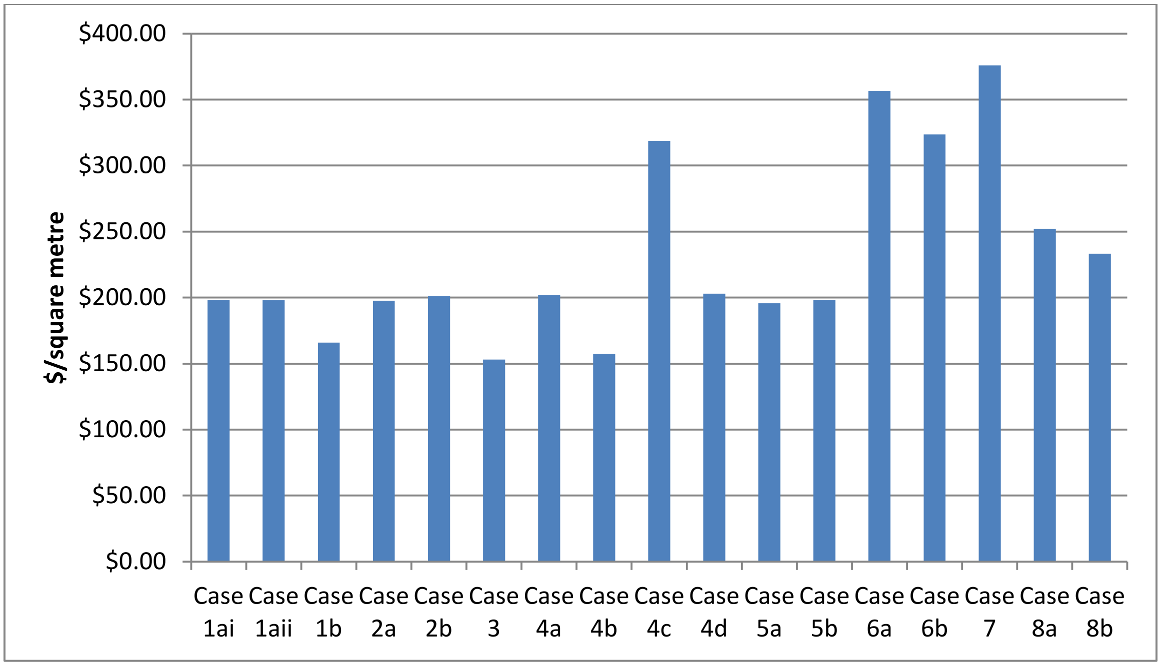


Figure 5-26 Results of the Cost Analysis

Combined costs of brick cladding, SPF insulation and steel framing, as in case 6a, the costs peak at $356.57 as seen in Figure 5-26. Steel framing, at a cost of $126.48 per square meter is almost three times the cost of 38mm x 140mm wood stud framing, at $43.24 per square meter.

Double stud construction such as Cases 8a and 8b, have much higher insulation levels than typical 38mm x 140mm wood stud framing such as Cases 1aii and 2a, but the costs do not have a direct correlation to the additional RSI values. In comparing Cases 8a and 1b, that both use the advanced framing technique, batt insulation and use siding instead of brick, the price/RSI yields a value of $34.95/RSI/m^2$ whereas Case 1b, and a value of $56.79/RSI/m^2$ for Case 8a. Further research could correlate and identify opportunities to yield maximum RSI values per dollar spent.

5.5 Overall Normalized Score

The objective of this research was to provide the building community with information regarding the wall assemblies that are being used in production housing. As such, the criteria weighting questionnaire was directed at them to ascertain what criteria they find most and least important.

The value of the category weighting was determined through averaging of the responses from the eight builders who responded to the category weighting questionnaire. The questions posed to the builders were how they would weight the importance of each category: heat transfer, cost, environmental impact and moisture safety (see Appendix Z). The averaged results are shown in Figure 5-27 where 0 is least important and 5 is most important. The results were used as weighting factors in the calculation of the overall normalized score.

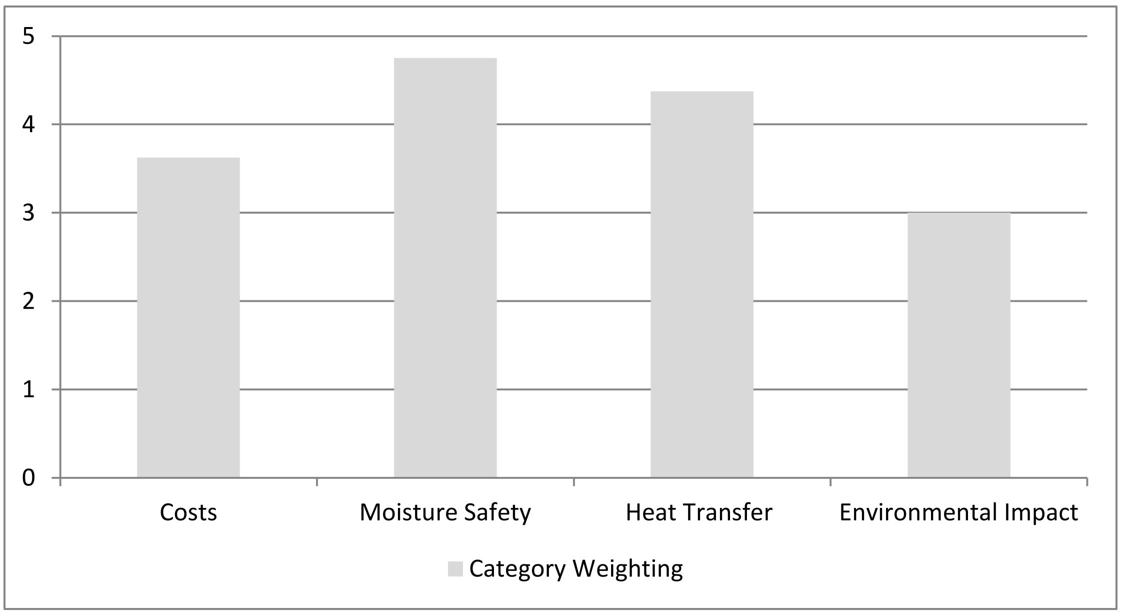


Figure 5-27 Results of Averaged Responses from Category Weighting Questionnaire

There are limitations to the overall normalized scoring technique used in this research. Due to the nature of the mathematical structure of the analysis, within each criterion, at least one wall assembly will receive a score of 0 and at least one will receive a score of 1. Although this indicates the best and worst performing walls within a given category, it could be inferred that a wall scoring of 0 would have none of the effects of the criterion under consideration. A score of 0 simply indicates that that wall's results in that category of analysis received the lowest value out of the ones considered.

As described in the methodology, the values used for generating the normalized scores indicated a rising value with an increasingly negative impact, for example Case 7 had the highest global warming potential with 112.6 Kg CO_2 eq./m^2. To maintain consistency, U-values were calculated so that an increasing number indicated a more conductive wall assembly. The overall normalized score is a reciprocal result, showing higher numbers as positive outcomes (see Appendix Y). Figure 5-28 shows the results of the normalized scores per category with the stacked bars, and the line indicating the overall normalized score. The longer bars indicate a more negative outcome.

It can be seen that Case 3 is the most desirable wall assembly overall. This is due to it being the lowest in cost at $153.12 and global warming potential at 19.65 Kg CO_2 eq./m^2, as well as having a moderately low whole wall U-value of 0.25 W/m^2K (RSI 4.04 m^2 K/W) and marginal number of maximum days over 80%, at 9 days.

Case 4b scores well too, owing to its lower whole-wall U-value of 0.26 W/m^2K (RSI 3.8 m^2·K/W), relatively short period above 80% at 15 consecutive days, a cost of $157.28 per square meter and a global warming potential of 38.83 Kg CO_2 eq./m^2.

Although Case 6a only experience 3 consecutive days over 80%, other category results were high with a cost of $302.33, a high U-value of 0.36 W/m^2K (RSI 2.79 m^2·K/W) and global warming potential of 47.33 Kg CO_2 eq./m^2.

It can be seen that when several category results are poor in performance for the same wall, the overall normalized score reflects that reality. Inversely, overall normalized scoring awards the wall assemblies that are effective at minimizing resources, such as advanced wood framing and lower impact insulations such as glass fibre and mineral wool, as well as managing humidity levels sufficiently below 80% within the wall assembly with higher scores.

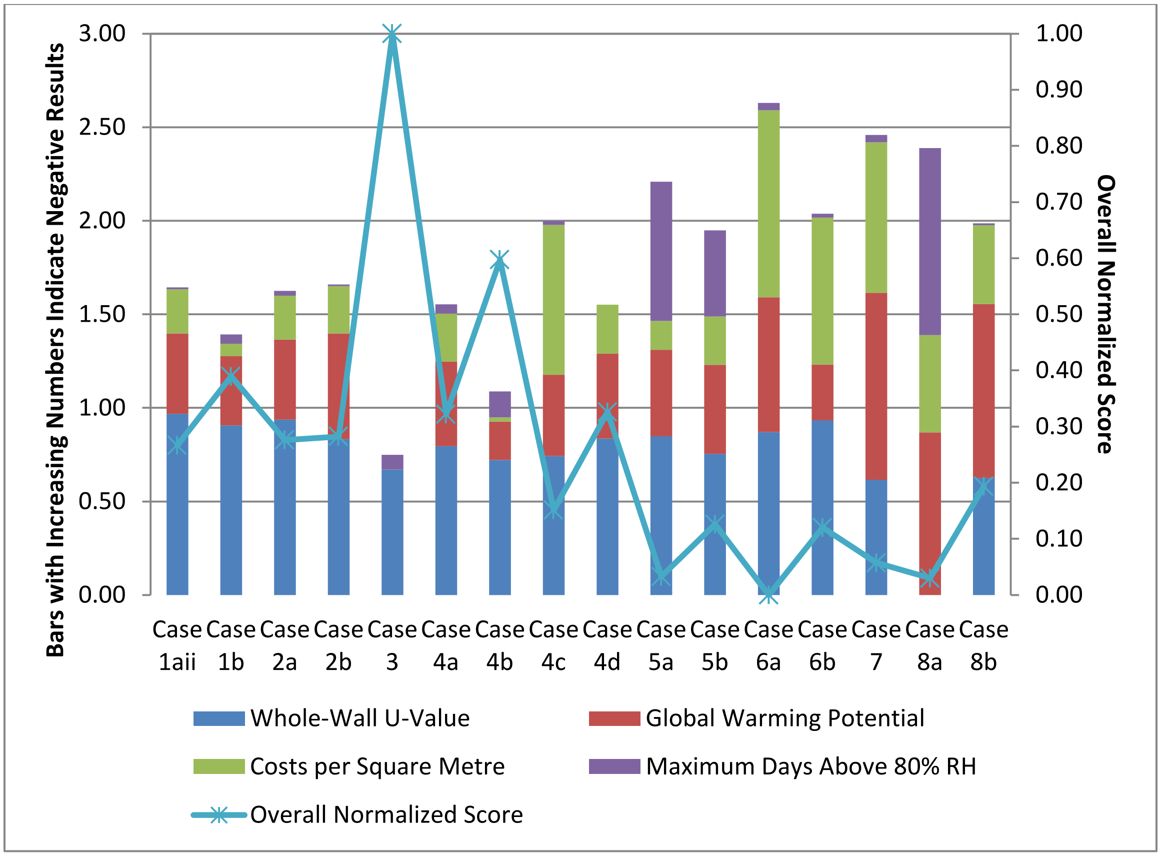


Figure 5-28 Overall Normalized Score

6. Conclusions

A series of analyses were performed on several residential wall assembly typologies that are currently in production. These wall designs are expected to satisfy the requirements for the upcoming 2012 Ontario Building Code. Analyses were conducted for whole-wall heat transfer, moisture safety, environmental impact and costs for seventeen wall assemblies. Category weighting was determined by industry consultation, and an overall normalized scoring technique was used to determine the best performing walls.

The process of evaluating wall assemblies within a series of criteria presents inherent limitations, as the research scope for several criteria is done at the expense of more rigorous research in any one given area. Given the time constraints of a Master's Thesis research, all of the assessment were conducted using computer modeling, or in the case of cost analyses, were done by a student from another institution.

The primary focus of the set of analyses was placed on moisture safety, as this category is the only criterion that could directly affect the health of the occupants, and the durability of the building envelope. Transient hygrothermal modeling was used to determine the heat and moisture related behaviours of the wall assemblies. Three-year simulations using Toronto's climatic conditions provided the hourly time-step data that was used for the analyses.

To determine the safe relative humidity and exposure durations of the walls, ASHRAE Standard 160P Design Criteria for Moisture Control in Building Envelopes was used as the framework for analysis. Although important conclusions can be made from the hygrothermal modeling of the wall assemblies, the absence of air leakage presents an important limitation in the research as bulk moisture transport due to air leakage can be orders of magnitude higher than by vapour diffusion alone. Nevertheless, given the results from the hygrothermal modeling, the ability of each wall assembly to manage the drying process generated important information for the building community about the moisture safety of the wall assemblies in production.

Limited information can be gleaned from the pass/fail determinations of ASHRAE Standard 160P. Building upon the methodology for assessing the Minimization of the Risk of Mould, calculating the greatest number of consecutive days over 80% relative humidity provided insight into the abilities of the wall assemblies to manage moisture by vapour diffusion.

THERM two-dimensional finite element analysis software was used to determine the effective RSI values of the wall construction details. RSI values for wall and rim-joist sections were obtained, and subsequently underwent an area weighted averaging operation to determine the final whole-wall RSI. This analysis showed that the nominal R-values can significantly (up to 35%) under-predict the heat loss through a wall, and more accurate energy calculations require a more sophisticated way to calculate R-values than the use of nominal R-values.. The heat transfer modeling provided conclusions useful for parametric comparisons of the wall assemblies. Limitations exist in that three-dimensional heat loss is not calculated, which can contribute to greater heat loss values in corners and other wall assembly junctions. The process to identify appropriate framing factors for the Ontario building practices involved assumptions due to the absence of Canadian studies. The framing factors for the clear wall sections could be as framing-heavy as the worst-case scenario in the U.S.

The environmental impact of the wall assembly materials was determined through the use of ATHENA Environmental Impact Estimator software tool. Using global warming potential as the impact indicator, one square meter of each wall was modeled to ascertain its potential impact on the planet. Less priority was placed on the environmental impact criterion than on heat transfer and moisture safety, due to strategic research scope planning in favour of criteria that were most important to builders. Due to the per square meter assessment of the wall assemblies, the maintenance component of the life-cycle was significantly lower than a whole house analysis due to a focus on wall sections in isolation, that do not require much maintenance throughout its life expectancy of 60 years. The purpose of the assessment was to provide a basis for comparison to provide some guidance for decision-makers to choose materials.

The quantity surveying portion of this research was performed by George Brown College's David Twiddy. A detailed material take-off approach was taken using RS-Means database to obtain material, labour and incidental costs.

An overall normalized score was awarded to each wall assembly that involved individual category weighting factors. These weighting factors were an average value of the responses from the eight builders who completed to the category weighting questionnaire. The scoring technique was chosen because of its adaptability to stakeholder criteria weighting values and that the technique can incorporate any number of criteria. These attributes can be beneficial for future assessments with more walls and a wider pool of criteria. It also allows other groups such as investors, or purchasers to develop their own weightings based on their perceptions and concerns.

Limitations exist in how the final results show the relative performances in that in each category, at least one wall will score a 0 value and at least one wall will score a 1 value, with the others falling somewhere in between. This relative determination implies that some walls have none of a given criteria or a maximum of a given criteria, while neither is true. The 0 and 1 extremes only represent a mathematical relationship between the criteria and the relative scoring of each wall for that criterion. It may be possible to adapt this methodology to reduce some of the problems outlined above.

Case 3, a wood frame structure with glass fibre insulation and EIFS cladding scored the best due to performing the best in cost and global warming potential categories.. It performed well in the moisture category and was a middle performer for R-value. The lowest scoring wall was Case 6b, with steel framing, sprayed polyurethane foam, 51mm of XPS and brick cladding. This wall scored poorly in all categories with the exception of moisture safety, where it performed well with only 3 days over 80% relative humidity.

A broad range of observations can be made from the many sided aspects of this research. Although many general statements can be made, it is difficult to separate causal effects from multi-factorial influences, the following statements can be made about the heat transfer properties of the wall assemblies in this research:

- Whole-wall RSI deviations range from 18% to 35% lower than the nominal insulation values
- Comparing the whole-wall heat transfer properties of all 17 walls against the reference wall design, Case 1ai,a relatively even distribution of RSI increases were observed, up to 70% improvements, and then a large jump up to 190% improvement for one particular wall, Case 8a
- RSI values of the rim joist section of wood framed assemblies compared to the wall RSI values range +/- 5%
- Double stud constructions such as Cases 8a, experienced a 36% reduction in RSI value at the rim-joist section as compared to the wall section due to exposed lumber and floor joists that penetrate the insulation. Although there was a larger influence from the rim joist section, the overall deviation from nominal RSI was found to be 20%

- The best performing wood framed wall in terms of approaching the nominal insulation values however, is Case 5b, with a 22% deviation. This relatively high performance is owing to the 25mm of high RSI value polyisocyanurate, and advanced framing technique of 600mm stud spacing
- Rim joist sections were found to be a localized area for significant heat loss potential in ICF construction as well, at a 42% reduction as compared to the wall section. This reduction is due to the steel floor-joist inserts that penetrate the interior EPS layer and midway through the concrete
- Although much of the reductions in thermal bridging for Case 8a is due to the 76mm EPS spacers between the double framing, it also owes a significant portion of its low deviation from nominal insulation value to its 600mm stud spacing.
- Similarly for steel frame constructions such as Cases 6a and 6b, the 51mm layers of polystyrene insulated sheathing does much to blunt the thermal bridging effects, but by reducing number of thermal bridges, their deviation from nominal insulation values are 27% and 28% respectively. These values are positive for steel frame construction
- The wall assembly that was determined to have the highest whole-wall RSI deviation from nominal insulation values, at 35%, was Case 1aii, due to the absence of insulated sheathing

Given that the construction industry is responsible for a large environmental, attention must be paid to the selection of materials used in wall designs. Choices in insulation, cladding and strategies such as advanced framing, can significantly reduce the environmental impact of a wall design. Some of the research finding related to environmental impact can be summarized as follows:

- The results from the environmental impact assessment analyses yielded a broad range of impacts, ranging from 19.65Kg CO_2/m^2 to 112.6 Kg CO_2/m^2
- The wall with the lowest environmental impact was determined to be Case 3, with 19.67 Kg CO_2/m^2. This low GWP value is due to lower impact fibreglass insulation and its EIFS cladding, that avoids the use of brick
- The use of advanced framing as done in Case 8a, also had a large effect on a comparative reduction in GWP as compared to Case 8b with 8a and 8b having 100.36 and 106.14 Kg CO_2/m^2 respectively
- The wall design that resulted in the highest GWP was Case 7 with 112.6 Kg CO_2/m^2. Concrete manufacturing is an extremely energy intensive process that is responsible for

considerable environmental impacts. This wall design also uses a combined thickness of 133mm of EPS which also contributes to its poor GWP performance

ASHRAE Standard 160P was determined to be a simplistic and overly conservative framework. Wall assemblies, such as Case 1ai, that are proven to be successful in terms of moisture safety such as the standard OBC 2006 wall with OSB sheathed 38x140mm wood framing and glass fibre insulation failed the ASHRAE analysis.

A methodology was developed to support the ASHRAE 160P analysis framework by using the same raw data from the modeling exports, to determine the greatest number of consecutive days at or above the relative humidity levels matching the ASHRAE 160P thresholds. Valuable information concerning the durations that wall assemblies experienced elevated levels of relative humidity was observed.

The most important consideration in building envelope design and construction is the employment of appropriate moisture management strategies, by the selection of materials, and their placements within the assemblies. Complex interactions occur due to the combined physics of heat, air and moisture, and can result in problems due to deterioration or mould. The following conclusions were drawn from the hygrothermal analysis of wintertime outward and summertime inward vapour transport through the wall assemblies:

- There were no instances of daily averages at 100% relative humidity for any wall assembly, on neither the inboard faces of the sheathings, nor the outward faces of the vapour retarders. Within this criterion of ASHRAE Standard 160P, all walls are acceptable.
- No instances of daily average relative humidity reaching 98% on the outward face of the vapour retarders when analysing the dynamics of summertime inward vapour drive.
- The wall assemblies that performed the poorest in this part of the hygrothermal assessment are the walls that contain foil faced polyisocyanurate insulated sheathings with all of them failing the ASHRAE Standard 160P analysis and exhibiting in the range of 42 to 61 maximum consecutive days at daily average relative humidity levels above 80% in outward vapour drive conditions and a 18 to 71 days in inward vapour drive conditions.
- Wintertime outward vapour drive contributed to Case 5a exceeding 98% RH for9 days due to the trapped vapour between the polyethylene and metal foil surfaces

- Many wall assemblies experienced periods above 80% RH. During summertime inward vapour drive conditions, only cases 2a, 5a, 5b, 8a and 8b experienced RH levels above 80%, whereas in wintertime outward vapour drive conditions, all cases experienced 80% RH levels.
- It can be seen that all the high permeance walls are able to safely manage moisture conditions within the wall assemblies.
- Unexpected performances of Cases 6a and 6b resulted in exceptionally low humidities at the inboard surface of the sheathing, in comparison to the other wall assemblies, due to the high ratio of insulated sheathing to cavity insulation.
- Case 7, using ICF construction displayed excellent wintertime humidity management
- Case category 4, with extruded polystyrene, performed well with respect to vapour transport outward in wintertime conditions and inward during summertime conditions. The adequate ratio of insulated sheathing to cavity insulation was in all cases sufficient to avoid high levels of RH, and were able to allow vapour diffuse sufficiently to avoid moisture concerns

In an attempt to characterize the wall assemblies according to their rates of drying after non-design condition wetting events, the walls were modeled with elevated initial moisture contents. In cases with wood based sheathing, the sheathing itself was brought to elevated moisture contents. In cases of low permeance sheathing, a wetting layer inboard of the low permeance sheathing was introduced to simulate the repercussion of a wetting event. The results can be summarized as follows:

- The drying rate of the walls with lower permeance sheathings are primarily influenced by the thermal resistance of the insulated sheathing and cavity insulations. The less effective the cavity insulation, the higher the rate of heat flux, which increases the vapour pressure gradient between the wetting layer and its surroundings.
- Walls with SPF cavity insulation with exterior low permeance insulated sheathing experience markedly reduced drying potential because resistance to vapour diffusion is provided in both directions, and with no ability to freely transfer moisture within the stud cavity, the drying slope is rather consistent, unlike the other curves

Higher permeance insulated sheathing exhibit different behaviour than the low permeance sheathings discussed above, as they are able to manage moisture in a more efficient manner.

The following is a summary of the results from the hygrothermal aspect of the research that involves higher permeance sheathings.

- Cavity insulation k-values affect the drying rate of walls but inversely to how it work with lower permeance sheathings. The more effective the cavity insulation, the faster the sheathing dries, as it will be closer to the warm exterior temperatures.
- The walls sheathed in OSB dried at a slower rate than fibreboard and compostite insulated sheathings, due to OSB's tendency to keep moisture as bound water.

An attempt to assess the likelihood of condensation within wall assemblies due to wintertime exfiltration of interior air was done by plotting the temperature of the condensation planes against the dew point temperature of the interior air. Various building material selections allowed for different condensation plane locations within the wall assemblies. The following conclusions were made based on the assessment described above:

- All wall assemblies that use batt insulation assume a substantial risk of condensation due to exfiltrating interior air passing the condensation plane.
- Walls that contain SPF as combined cavity insulation and air barrier have the condensation plane just outside the vapour retarder which stays above the dew point all year
- ICF construction has a continuous cast-in-place concrete air barrier whose interior surface is at a higher temperatures than the dew point of exfiltrating air

As a driving force in the construction industry, costs are an important influence in decision-making. The RS-Means analysis, undertaken by David Twiddy from George Brown College shows the variety of costs per square meter of wall assembly construction including material and labour costs. The following conclusions can be drawn from the cost analysis:

- The costs of brick cladding at $132 per square metre is the most expensive single item for any of the wall assemblies considered
- Advanced framing technique with studs placed at 600mm spacing. Based on lumber saved as compared to conventional framing, there is a 36% reduction in material costs when the framing factors of 25% and 16% are considered.
- The wall with the highest costs is Case 6a because of a combined used of expensive materials: steel framing, SPF insulation and brick cladding.

Although it was not intentionally part of the research, it was observed that Wall assemblies with brick cladding have more stable drying curves than walls with vinyl siding. Vinyl siding's higher ventilation rates (100 ACH) introduce moist summer air that leads to moisture loads that are not experiences by brick claddings (8 ACH). This can contribute to the ongoing debate about the benefits or detractions of ventilated versus non-ventilated cavities.

Implications of this research suggest possible improvements to minimum performance threshold in the Ontario Building Code. It is evident that moisture safety is not simply a determination of the likelihood of condensation within the wall assemblies, but also the duration and levels of elevated relative humidities. Although only beginning to address the risks of low permeance materials, this research suggests the importance of addressing relative humidity levels as a determinant of appropriate envelope construction.

The degree to which thermal bridging can affect the performance of the wall assemblies ought to also be considered in the building code RSI value standards. Cavity insulation can contribute to a nominal RSI value that misrepresents the reality of heat loss dynamics in wall constructions. Framing materials and spacing influence the whole-wall RSI values to such a great extent that it is a conspicuous oversight. It is conceivable that regulating the minimization of thermal bridging and global warming impact of the wall assembly components could have widespread implications to Canada's long-term carbon reduction targets.

7 Recommendations

The results of the research show important areas to consider when designing residential exterior wall assemblies. Multi-factorial influences must be taken into account as the performance of wall assemblies vary depending on materials, their thicknesses, spacing and their placements within the assembly. Performance also varies depending on climatic conditions and time of year. The following recommendations can be made based on this research:

- Employ advanced framing whenever possible, as it incurs less costs, better thermal performance and lower environmental impact
- Avoid using foil faced polyisocyanurate as insulated sheathings outside wood framed construction in a cold climate
- When using lower permeance sheathings, ensure adequate ratio of outboard insulation to inboard cavity insulation, as per Figure 2-6, to avoid elevated relative humidity levels in wintertime conditions
- Ensure optimal air tightness detailing for wall assemblies, particularly for walls with batt insulations because of the high risk of infiltration related condensation against the sheathing
- When using higher permeance insulated sheathings, select highest RSI-value insulations to ensure rapidity of drying in summer conditions in the event of bulk water penetration
- When considering environmental impact, avoid brick cladding, steel framing, XPS and EPS insulations
- Consult with ICF material suppliers for alternative floor joist hangers to optimize heat transfer performance
- When considering double stud wall designs, ensure that rim joist sections are well insulated
- Consider whole-wall thermal performance when selecting wall assemblies
- When using ICF and SPF (over 140mm), insist on avoiding polyethylene as a vapour retarder to optimize inward drying potential, as the SPF insulation and EPS concrete forming components provide sufficient resistance to vapour transfer in the outward direction

8 Future Work

This research work is a preliminary step toward a thorough and conclusive method of evaluating criteria that are difficult to compare. The methodology used in this research can expanded to include other wall systems and more criteria. The weighting of the criteria can be developed further to reflect various interests from the spectrum of stakeholders in the housing industry such as regulators, researchers and consumers.

The influence of air leakage is an important factor in determining the moisture safety of wall assemblies. As exfiltrating air, with capabilities to deposit bulk water within the wall systems, is arguably the most important aspect in moisture safety assessments. It is expected that the upcoming release of WUFI hygrothermal modeling software will include air leakage modeling capabilities.

Other criteria could be added to the assessment structure without substantive overhauls to the analysis methodologies. Aspects such as mechanical efficiency ease of construction, acoustic control, fire control and the incorporation of renewable energy among others could be added to the list of criteria. The overall normalized scoring method readily accepts the addition of criteria.

Robustness of the assessments would be improved with the addition of experimental measurements. Inclusion of higher performing walls and designs such as dynamic walls and those from standards such as Passivhaus, could be analyzed according to the methodology outline in this research.

Expanding the research to include a reference house would allow the incorporation of lifecycle analyses over the expected service life that also could include operational energy usage. Such a strategy would contextualize the global warming impact of the wall assemblies themselves and how they relate to their influence on heating and cooling loads throughout the year. The inclusion of other important assessments within lifecycle analysis frameworks would provide more holistic view of the impacts of wall designs on the planet.

The methodology outlined in this research can be developed further to include more wall assemblies and criteria. Other important aspects such as air leakage, experimental measurements and other criteria can be readily included into the normalized scoring method without substantial changes to the procedures outlined in this thesis work. By also including operational energy consumption, a more holistic assessment would be possible.

Appendix A - Case 1ai

Case 1ai is the standard wall complying to the 2006 building code with brick cladding, spun-bonded polyolefin, OSB sheathing, low density glass fibre insulation, polyethylene vapour retarder and air barrier and finished with gypsum board. This wall assembly is used as a reference only, because it does not comply with any of the code compliance packages for the 2012 OBC but is assumed to be safe in terms of moisture safety.

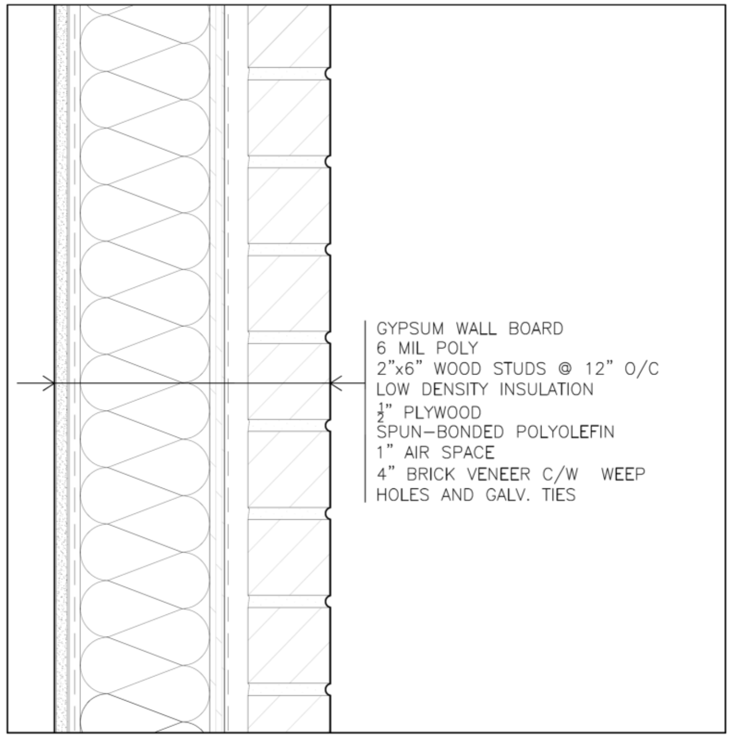


Figure A-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table A-1Summary of Results

Analysis Description			Days over RH Threshold	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	6	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	9	F
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	2.48	
		Rim joist section	2.61	
		Top plate	2.20	
		Whole-wall	2.48	
	Nominal RSI		3.71	
	Whole Wall RSI Deviation from nominal RSI		-33%	
Env. Impact	Kg CO2 eq./sq. Meter		59.29	
Cost	$/sq.meter		**$198.40**	

Heat Transfer

Highlighted in the black dotted line in Figure A-2, Case 1ai performs at the lowest of the walls considered ,with a whole-wall RSI value of 2.48. The use of standard framing at 400mm o/c, and no insulated sheathing, significant thermal bridging accounts for 33% loss of RSI from its nominal value.

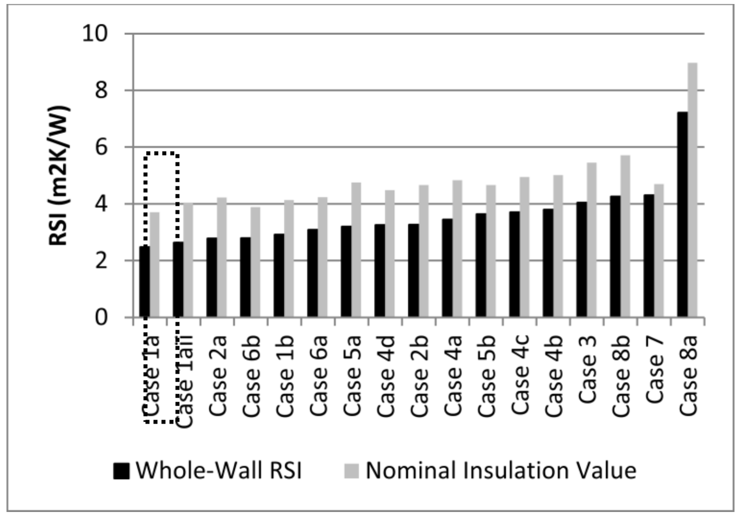


Figure A-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

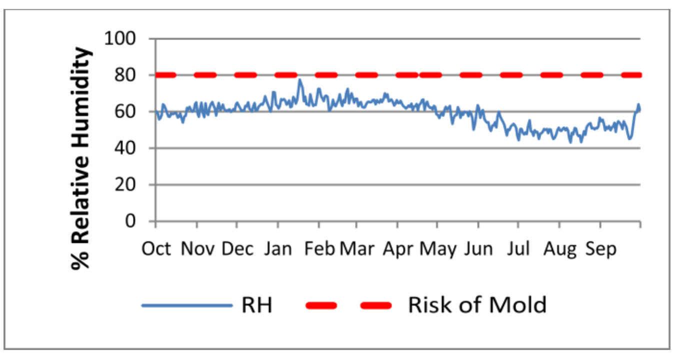


Figure A-3 Relative Humidity Inboard of Sheathing

Outward vapour drive does not cause problems for this wall at the inboard surface of the sheathing. Relative humidities remain below 80% consistently throughout the year, thereby not contribution to elevated moisture conditions due to vapour passing through the polyethylene toward the exterior.

Inward Vapour Drive Outboard of Vapour Retarder

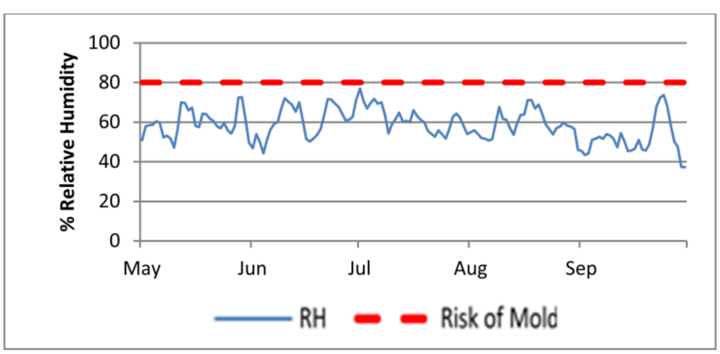


Figure A-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating problematic inward vapour drive.

Temperature of Condensation Plane

The condensation plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure A-5. This envelope design requires careful air barrier detailing.

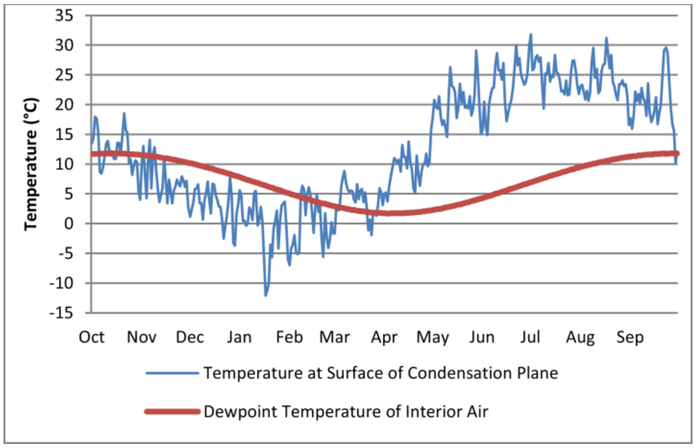
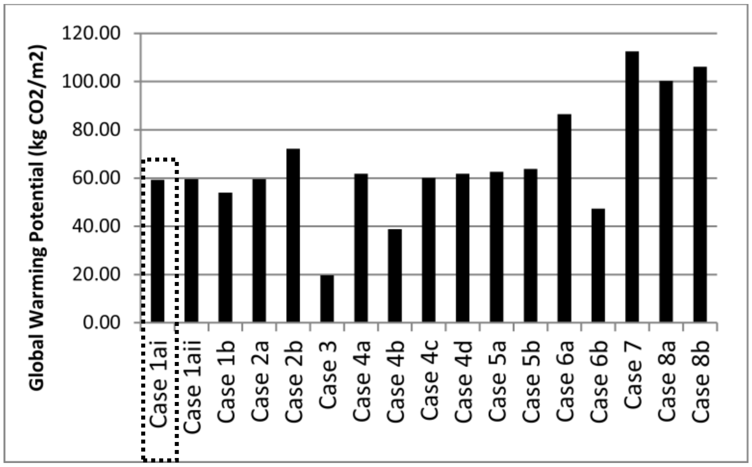


Figure A-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Case 1ai's global warming potential is modeled at 59.29 kg CO_2 eq./m^2. The use of brick cladding is the single highest contributor to its global warming potential. The use of advanced framing could lower its environmental impact.

Figure A-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $198.40, Case 1ai is an average performer in terms of cost. Brick cladding accounts for much of its costs. Savings could be found by using advanced framing technique, which also contributes to lower RSI and environmental impact.

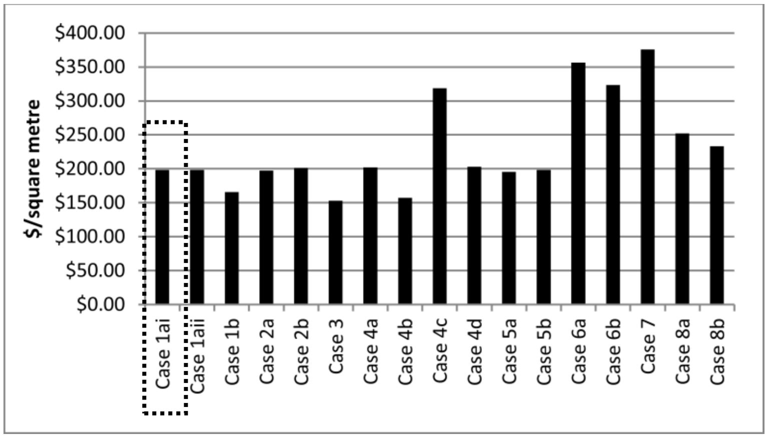


Figure A-7 Costs of Wall Assemblies per Square Meter

Appendix B - Case 1aii

Case 1aii, as shown in Figure B-1, is very similar to the standard wall complying to the 2006 building code with brick cladding, spun-bonded polyolefin, OSB sheathing, high density glass fibre insulation, polyethylene vapour retarder and air barrier and finished with gypsum board. The principal difference is the use of high-density glass fibre insulation that, by its own RSI value of 3.87 complies with compliance packages I, J and K.

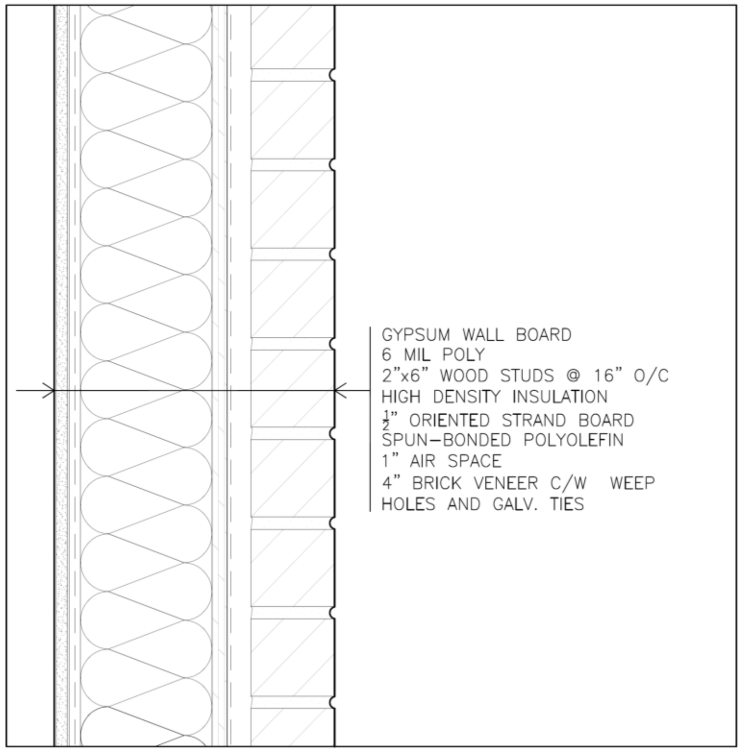


Figure B-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table B-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	2	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	0	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	2.66	
		Rim joist section	2.70	
		Top plate	2.31	
		Whole-wall	2.63	
	Nominal RSI		4.04	
	Whole Wall RSI Deviation from nominal RSI		-35%	
Env. Impact	Kg CO2 eq./sq. Meter		59.51	
Cost	$/sq.meter		**$198.15**	

Heat Transfer

Highlighted in the black dotted line in Figure B-2, Case 1aii is among the poorest performing assemblies of the walls considered, with a whole-wall RSI value of 2.63. The use of standard framing at 400mm o/c, and no insulated sheathing, significant thermal bridging accounts for 35% loss of RSI from its nominal value.

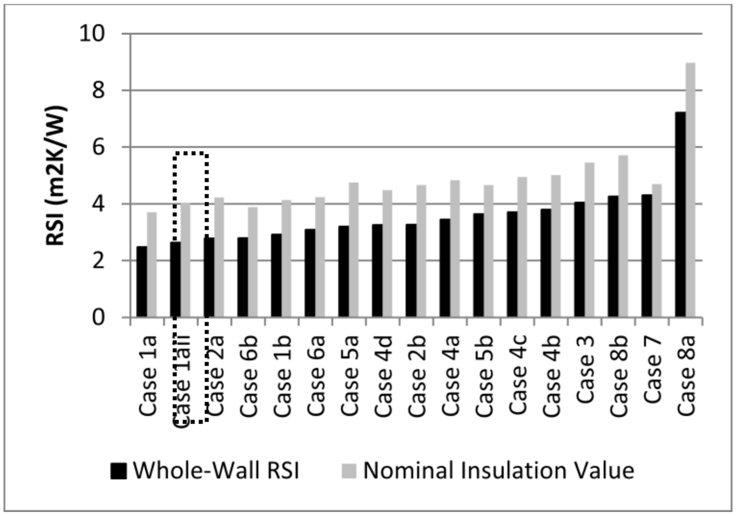


Figure B-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

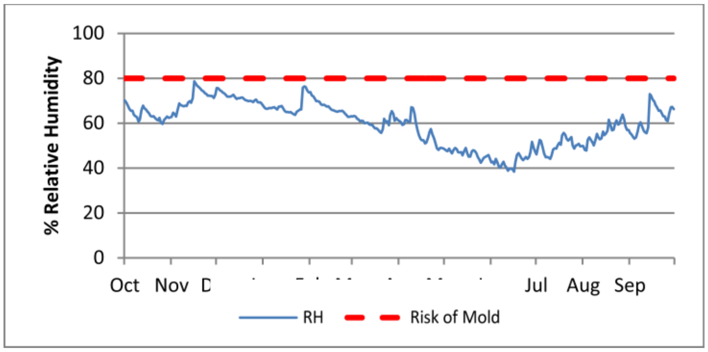


Figure B-3 Relative Humidity Inboard of Sheathing

Outward vapour drive does not cause problems for this wall at the inboard surface of the sheathing. Relative humidities remain below 80% consistently throughout the year, thereby not contribution to elevated moisture conditions due to vapour passing through the polyethylene toward the exterior.

Inward Vapour Drive Outboard of Vapour Retarder

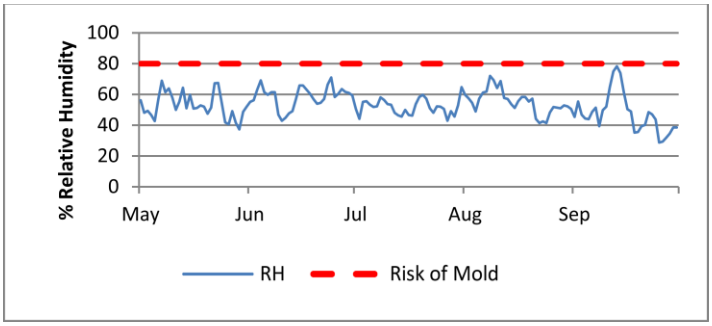


Figure B-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure B-5. This envelope design requires careful air barrier detailing.

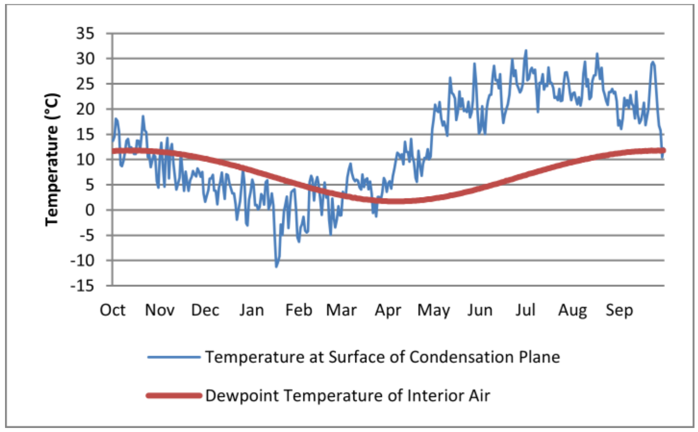
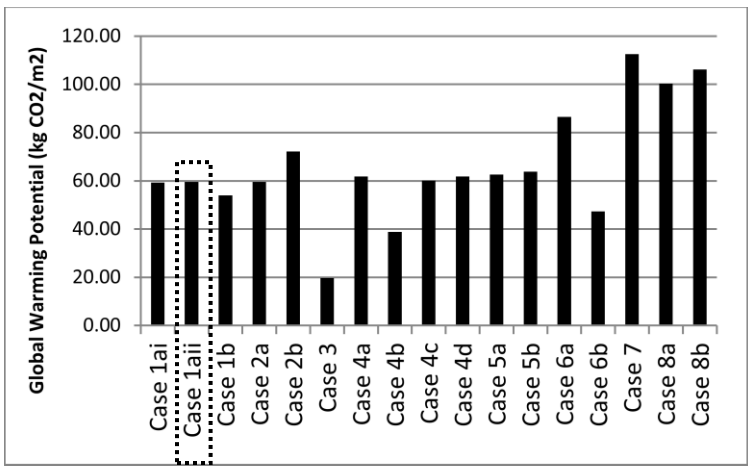


Figure B-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



With slight differences from the reference wall, case 1aii's global warming potential is modeled at 59.51 kg CO2 eq./m^2. The 1% increase is due to the use of spun-bonded polyolefin, with slightly lower impacts than building paper.

Figure B-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $198.15, Case 1aii is an average performer in terms of cost. Brick cladding accounts for much of its costs. Savings could be found by using advanced framing technique, which also contributes to lower RSI and environmental impact.

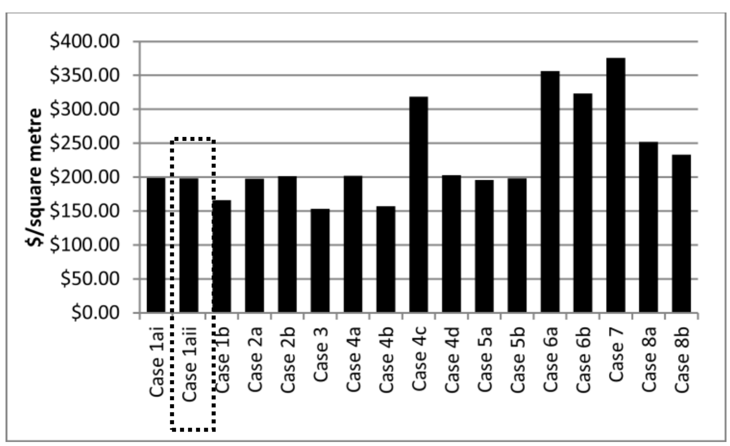


Figure B-7 Costs of Wall Assemblies per Square Meter

Appendix C - Case 1b

Case 1b, as shown in Figure C-1, differs from the standard wall complying to the 2006 building code because of the use of vinyl siding and blown in glass fibre insulation. It also uses spun-bonded polyolefin, OSB sheathing, blown in glass fibre insulation, polyethylene vapour retarder and air barrier and finished with gypsum board. This wall complies to code packages I, J and K.

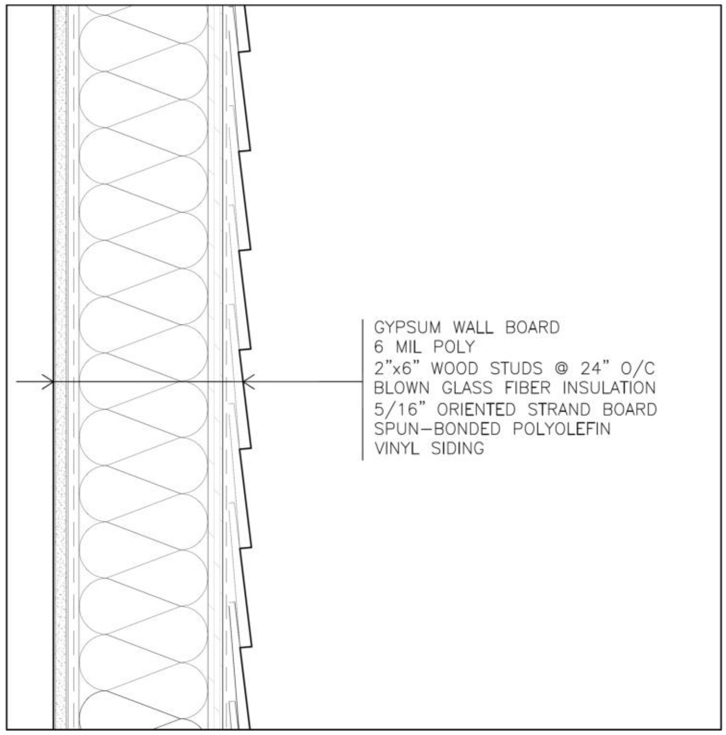


Figure C-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table C-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	2	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	2	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.12	
		Rim joist section	2.73	
		Top plate	2.31	
		Whole-wall	2.92	
	Nominal RSI		4.13	
	Whole Wall RSI Deviation from nominal RSI		-29%	
Env. Impact	Kg CO2 eq./sq. Meter		53.95	
Cost	$/sq.meter		**$165.85**	

Heat Transfer

Highlighted in the black dotted line in Figure C-2, Case 1b has below average thermal characteristics with a whole-wall RSI value of 2.92. The use of advanced framing at 600mm o/c, and higher RSI value blown in glass fibre insulation improves its performance.

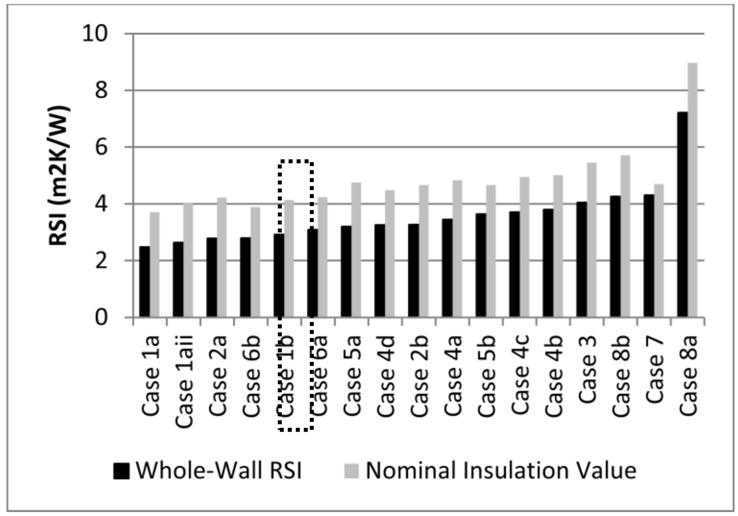


Figure C-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

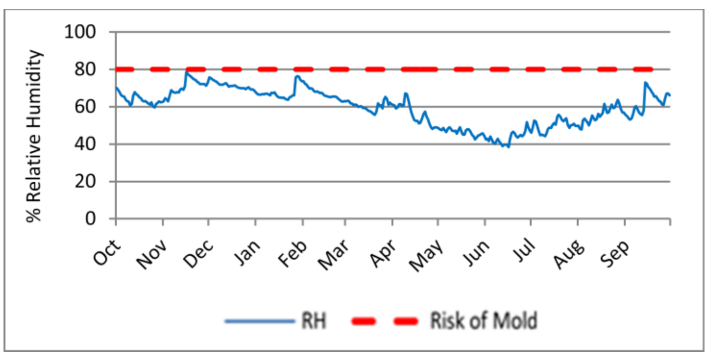


Figure C-3 Relative Humidity Inboard of Sheathing

Outward vapour drive does not cause problems for this wall at the inboard surface of the sheathing. Relative humidities remain below 80% consistently throughout the year, thereby not contribution to elevated moisture conditions due to vapour passing through the polyethylene toward the exterior.

Inward Vapour Drive Outboar

RH Risk of Mold

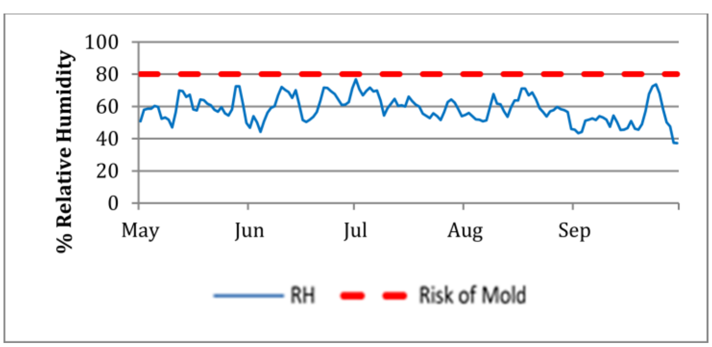


Figure C-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure C-5. This envelope design requires careful air barrier detailing.

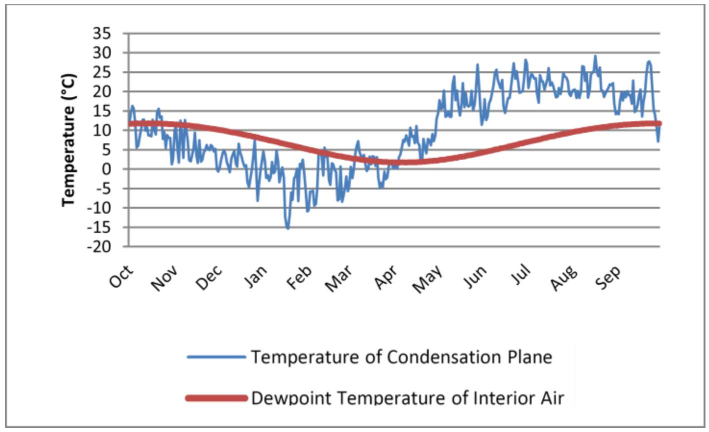


Figure C-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis

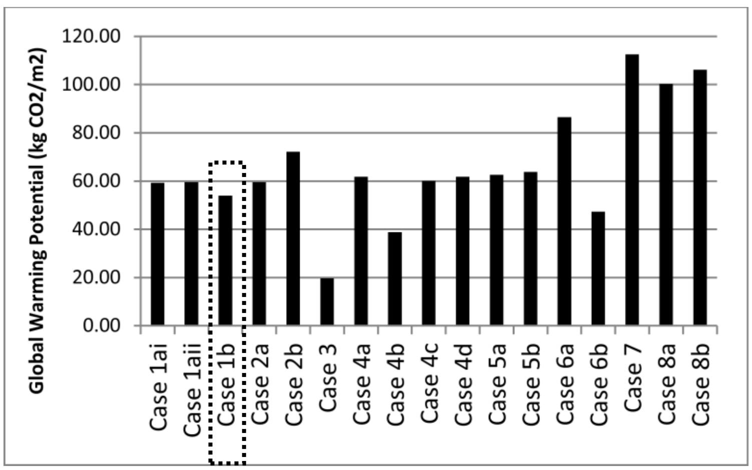


Figure C-6 Global Warming Potential per Square Meter

The use of vinyl siding reduces Case 1b's global warming potential because it avoids the use of brick. Advanced framing improves the result as well due to reduced material inputs. Glass fibre insulation has a relatively low impact in comparison with mineral wool and foam insulations.

Cost Analysis

At a cost of $165.85, Case 1b is one of the least costly walls that were considered. The combination of lower cost vinyl siding, and reduced material costs due to advanced framing contribute to its low cost per square meter.

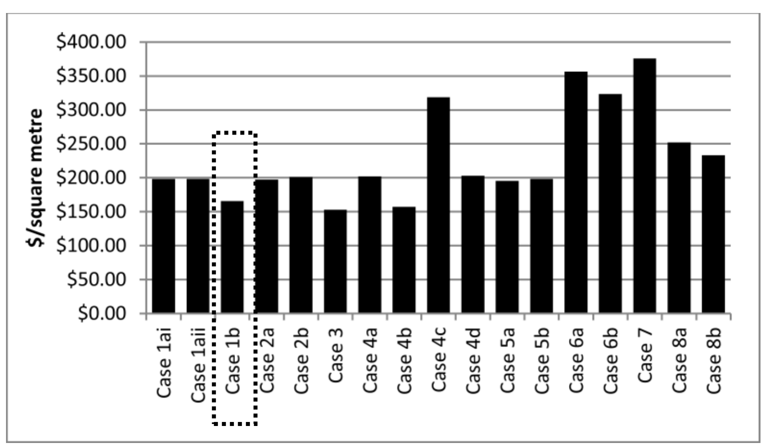


Figure C-7 Costs of Wall Assemblies per Square Meter

Appendix D - Case 2a

Case 2a, as shown in Figure D-1, is similar to the standard wall in that it uses brick cladding, and glass fibre insulation, but differs in that it the insulation is of a higher density and OSB sheathing is replaced by fibreboard insulated sheathing. With an nominal RSI value of 4.22, this wall complies with compliance packages I, J and K.

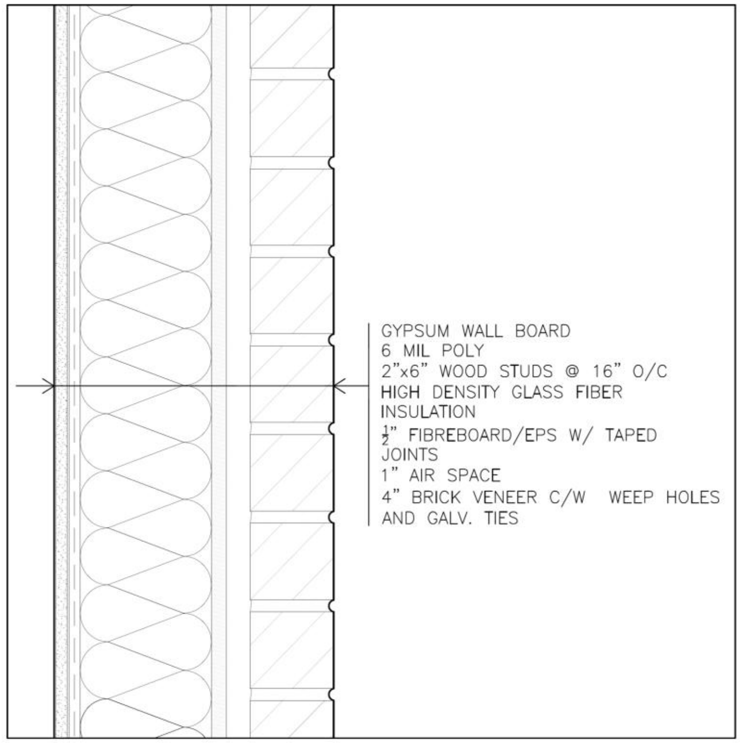


Figure D-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table D-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	2	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	3	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	2.81	
		Rim joist section	2.84	
		Top plate	2.49	
		Whole-wall	2.78	
	Nominal RSI		4.22	
	Whole Wall RSI Deviation from nominal RSI		-34%	
Env. Impact	Kg CO2 eq./sq. Meter		59.51	
Cost	$/sq.meter		**$197.59**	

Heat Transfer

Highlighted in the black dotted line in Figure D-2, Case 2a performs at the lower mid range of the walls considered. Although the use of insulated fibreboard does increase its whole wall and nominal RSI values over the reference case, thermal bridging is still a major concern as seen by its deviation from nominal RSI of 34%.

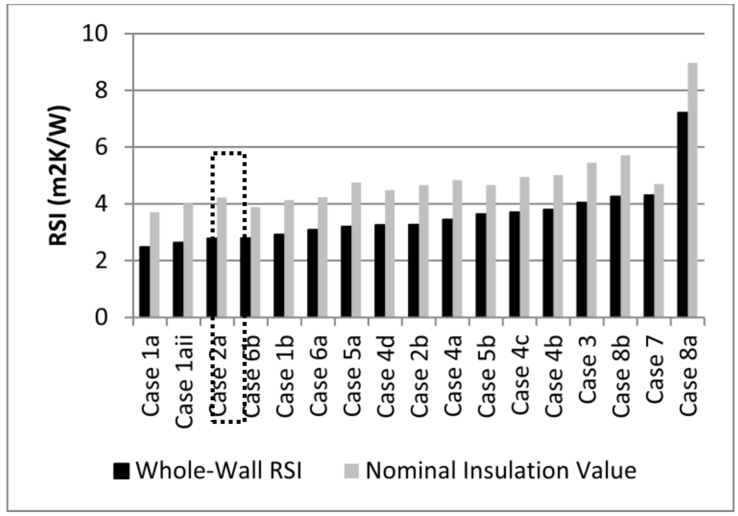


Figure D-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

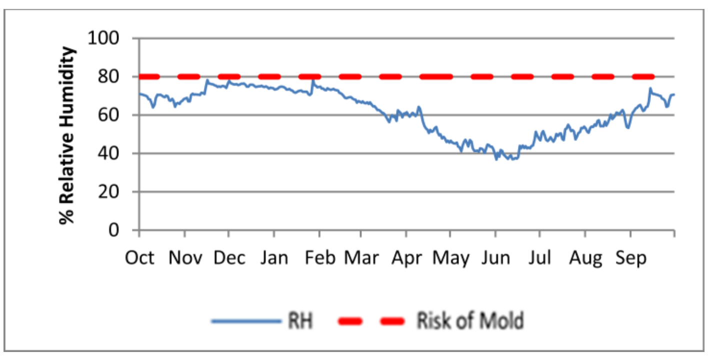
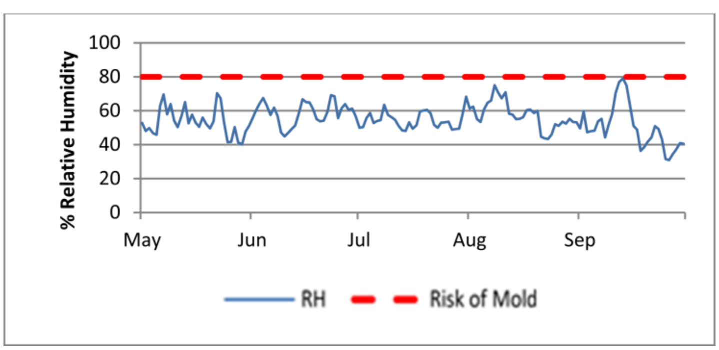


Figure D-3 Relative Humidity Inboard of Sheathing

Outward vapour drive does not cause problems for this wall at the inboard surface of the sheathing. Relative humidities remain below 80% consistently throughout the year, thereby not contribution to elevated moisture conditions due to vapour passing through the polyethylene toward the exterior.

Inward Vapour Drive Outboard of Vapour Retarder



FigureD-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure D-5. This envelope design requires careful air barrier detailing.

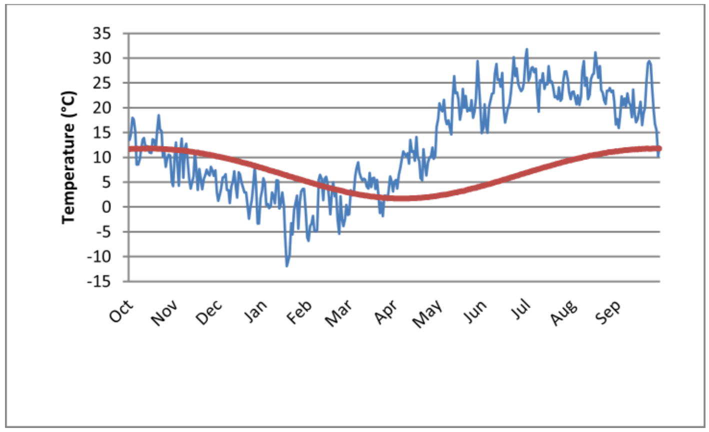


Figure D-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis

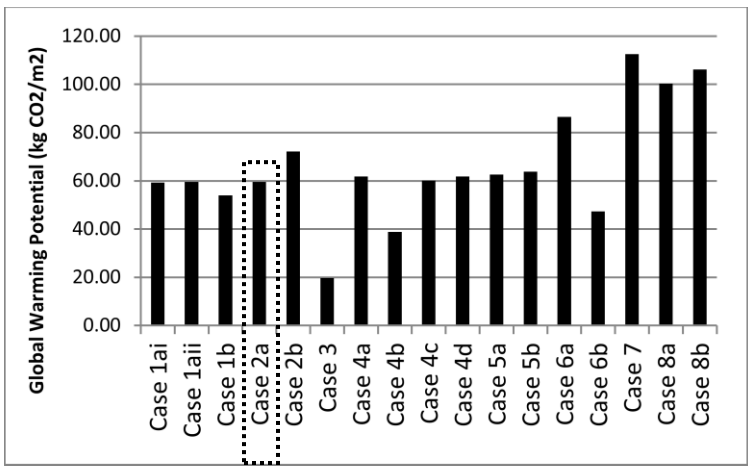


Figure D-6 Global Warming Potential per Square Meter

Case 2a's global warming potential is modeled at 59.51 kg CO2 eq./m^2. With the use of brick cladding, which is the largest GWP contributor out of any of the assembly components, Case 2a is modeled at only slightly above the GHG contribution of the reference case.

Cost Analysis

At a cost of $197.59 per square meter, Case 2b is an average performer in terms of cost. Brick cladding accounts for much of its costs. Savings could be found by using advanced framing technique.

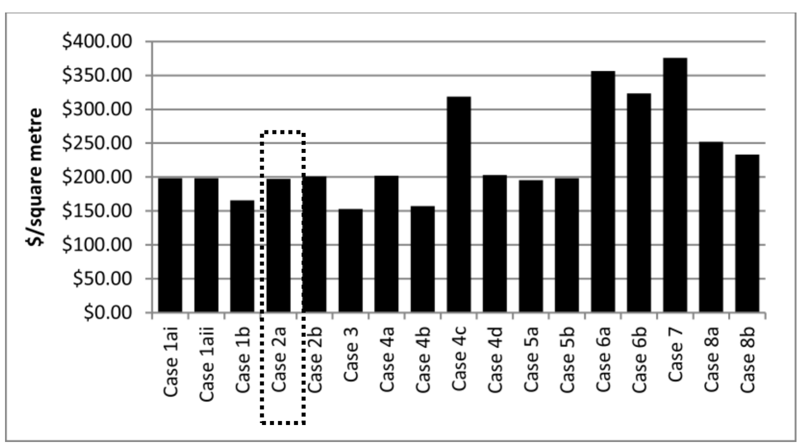


Figure D-7 Costs of Wall Assemblies per Square Meter

Appendix E - Case 2b

Case 2b's principal difference from the reference wall, as shown in Figure E-1, is in its use of mineral wool insulation and composite fibreboard/EPS insulated sheathing. Its nominal insulation value, owing in part to the insulated sheathing and to the mineral wool insulation, achieves an RSI value of 4.66, and complies with compliance packages A, D, E, F, G and H.

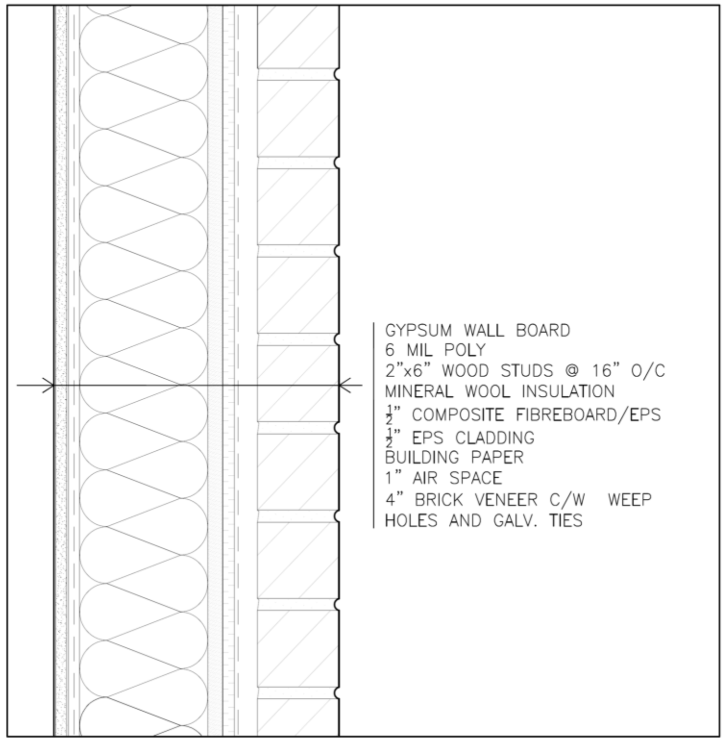


Figure E-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table E-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	1	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	2	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.34	
		Rim joist section	3.33	
		Top plate	2.75	
		Whole-wall	3.27	
	Nominal RSI		4.66	
	Whole Wall RSI Deviation from nominal RSI		-30%	
Env. Impact	Kg CO2 eq./sq. Meter		72.20	
Cost	$/sq.meter		**$201.26**	

Heat Transfer

Highlighted in the black dotted line in Figure E-2, Case 2b performs at the middle range of the walls considered with a whole-wall RSI value of 3.27, which deviates from the nominal RSI value by 30%. The lower deviation compared to the reference case is due to the higher thermal resistance of the composite fibreboard/EPS insulated sheathing.

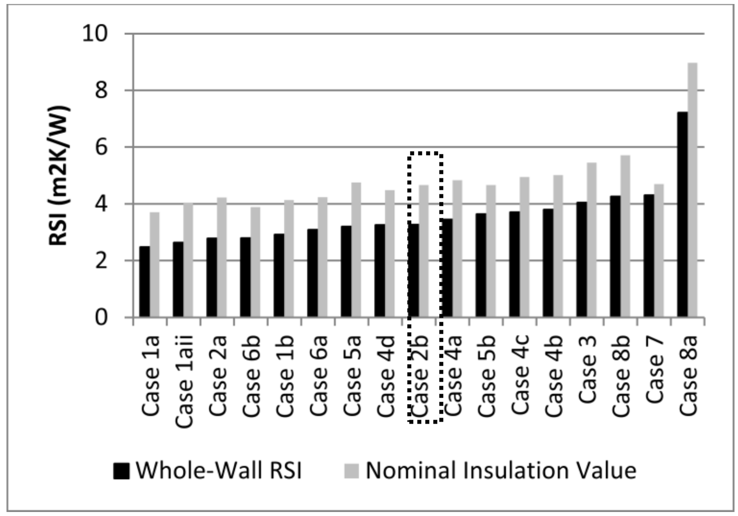


Figure E-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

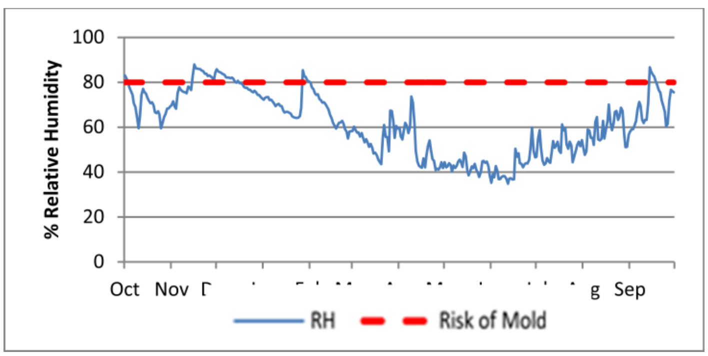


Figure E-3 Relative Humidity Inboard of Sheathing

Outward vapour drive causes some spikes over 80% relative humidity at the inboard face of the sheathing. This is due to the resistance to vapour diffusion of the composite insulated sheathing. These spikes are of short duration and do not present significant risk of moisture damage.

Inward Vapour Drive Outboard of Vapour Retarder

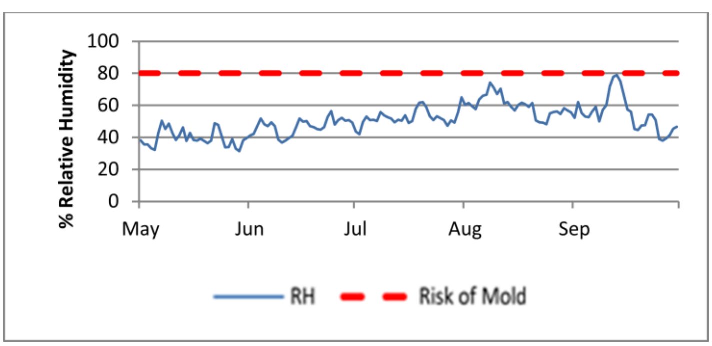


Figure E-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophilic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure E-5. This envelope design requires careful air barrier detailing.

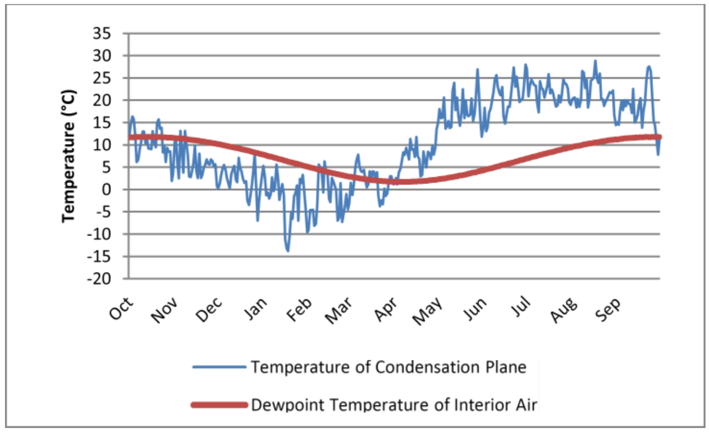
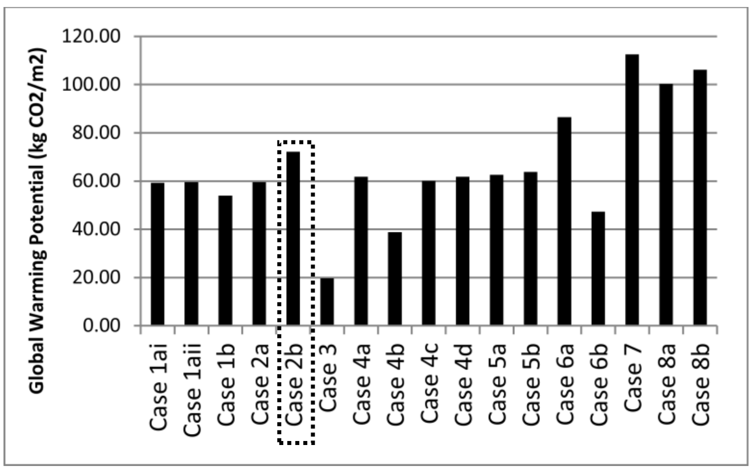


Figure E-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Case 2b's global warming potential is modeled at 72.20 kg CO2 eq./m^2. This significant increase over the reference case is due to the mineral wool insulation and EPS component of the composite sheathing.

Figure E-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $201.26, Case 2b is an average performer in terms of cost. Brick cladding accounts for much of its costs. Savings could be found by using advanced framing technique, which also contributes to lower RSI and environmental impact.

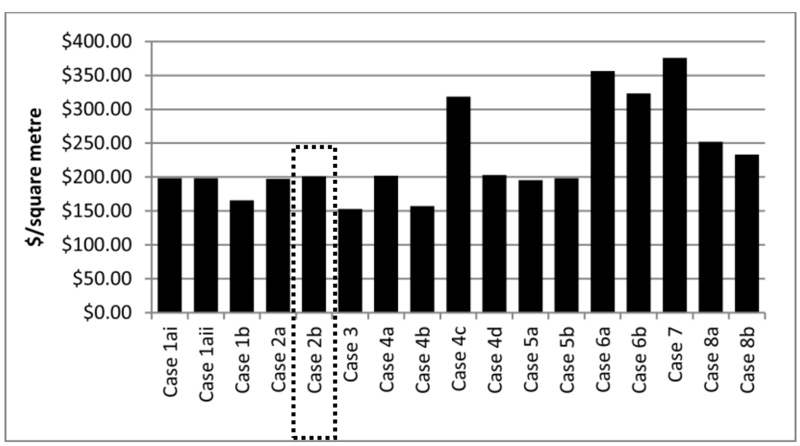


Figure E-7 Costs of Wall Assemblies per Square Meter

Appendix F - Case 3

Case 3, as shown in Figure F-1, with an exterior insulation and finish system (EIFS) construction, uses a significant amount of exterior insulation outboard of the structural OSB sheathing. Its nominal RSI value is 5.45 and complies with compliance packages B and C.

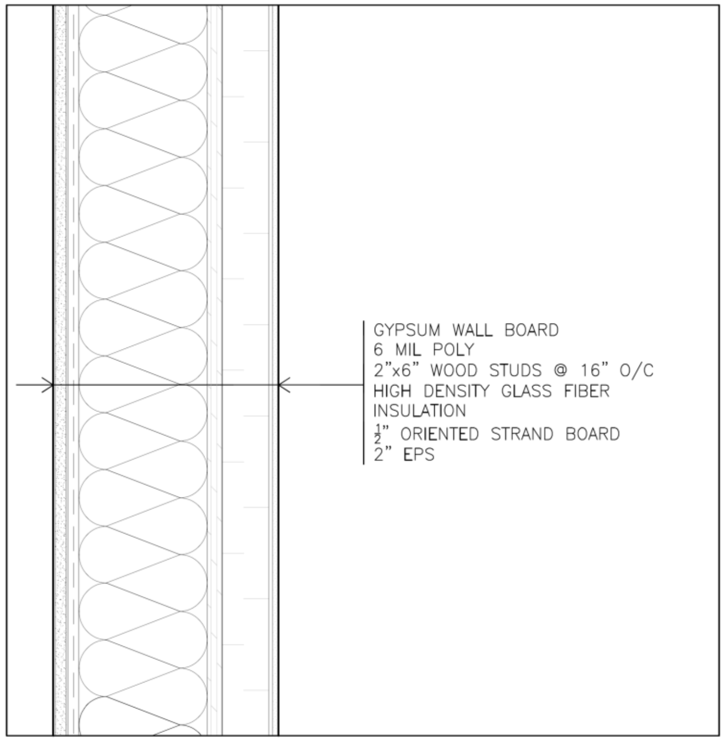


Figure F-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table F-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	9	F
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	4	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	4.08	
		Rim joist section	4.06	
		Top plate	3.77	
		Whole-wall	4.04	
	Nominal RSI		5.45	
	Whole Wall RSI Deviation from nominal RSI		-26%	
Env. Impact	Kg CO2 eq./sq. Meter		19.65	
Cost	$/sq.meter		**$153.12**	

Heat Transfer

Highlighted in the black dotted line in Figure F-2, Case 3 performs relatively well, with a whole-wall RSI value of 4.04. The combined high density cavity insulation and 51mm of EPS insulated sheathing contribute to a nominal RSI value of 5.45.

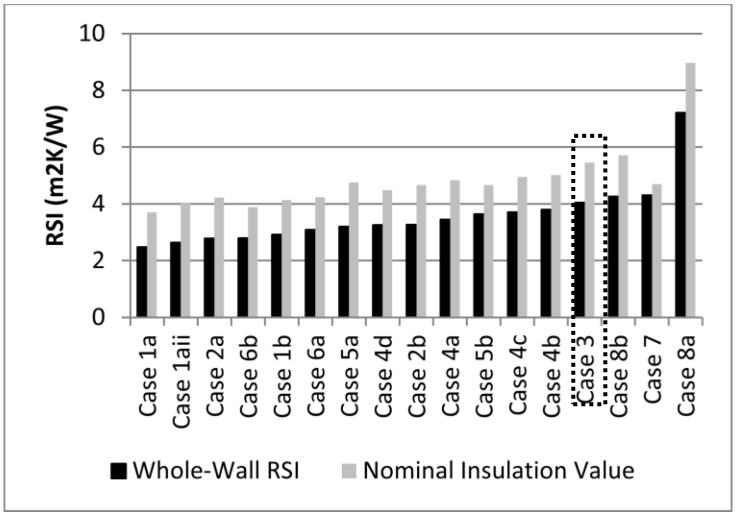


Figure F-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

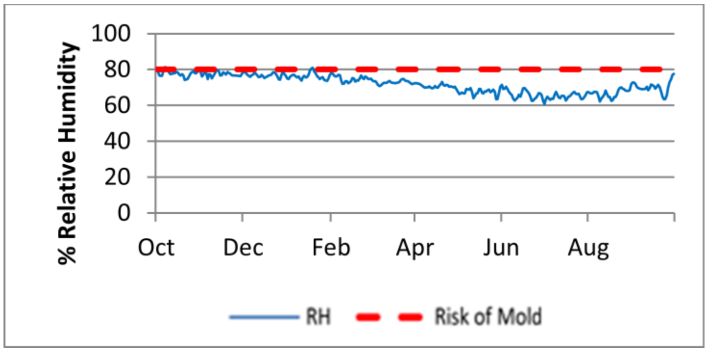


Figure F-3 Relative Humidity Inboard of Sheathing

Outward vapour drive typically does not cause problems for this wall at the inboard surface of the sheathing although it failed the ASHRAE 160P test due to elevated initial moisture content in the materials. Otherwise, it is consistently below 80% RH at the sheathing.

Inward Vapour Drive Outboard of Vapour Retarder

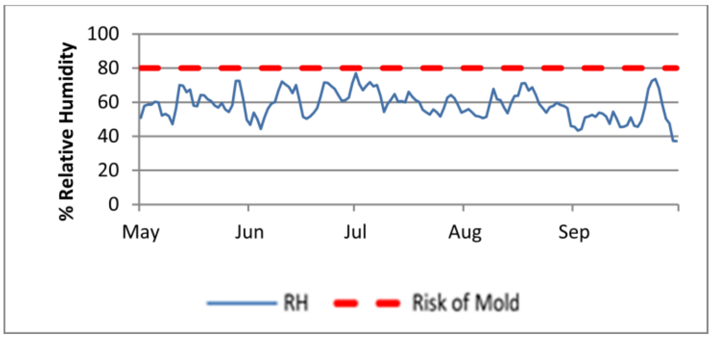


Figure F-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure F-5. This envelope design requires careful air barrier detailing.

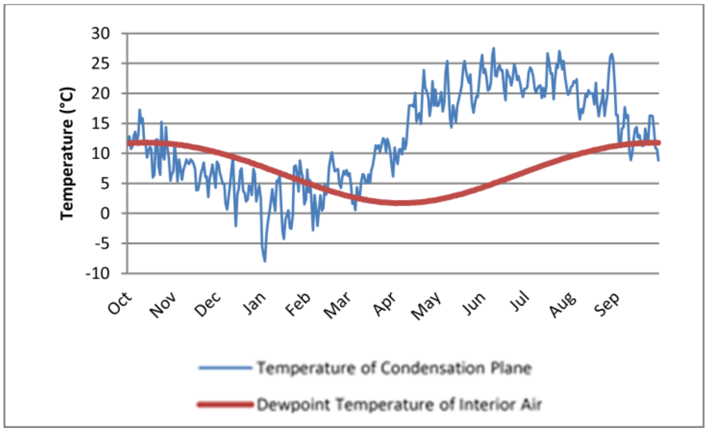
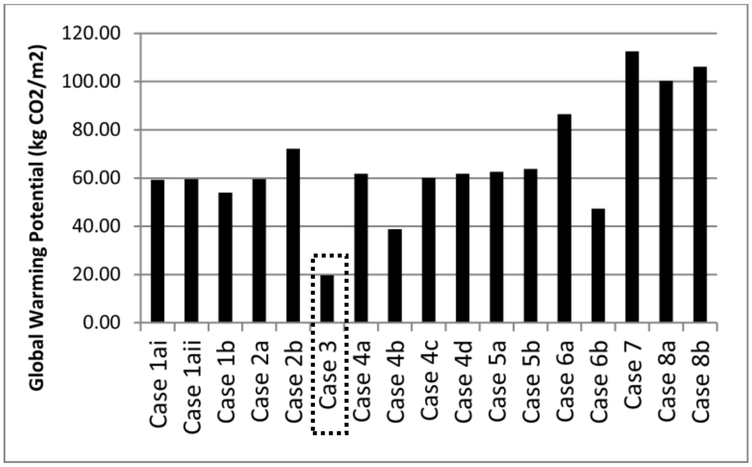


Figure F-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Case 3 has the lowest global warming potential out of the walls considered with 19.65 kg CO_2 eq./m^2. This is mainly due to the use of non-brick cladding and avoiding the use of sprayed polyurethane cavity insulation.

Figure F-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $153.12, Case 3 performs best in terms of cost. Avoiding brick cladding accounts for much of the cost savings.

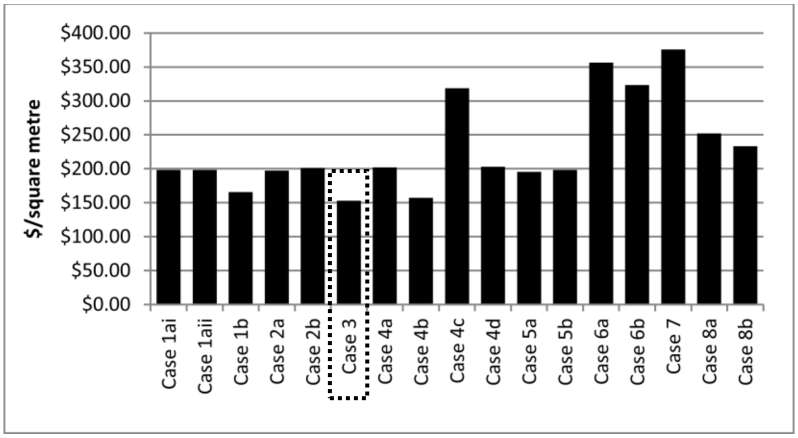


Figure F-7 Costs of Wall Assemblies per Square Meter

Appendix G - Case 4a

The principle features of Case 4a, as shown in Figure G-1, is the use of high density glass fibre insulation, standard framing, and 25mm of extruded polystyrene insulated sheathing. With whole wall RSI value of 4.83 and a nominal RSI value of 4.83, this wall experiences a 29% deviation from nominal and complies with compliance packages B and C.

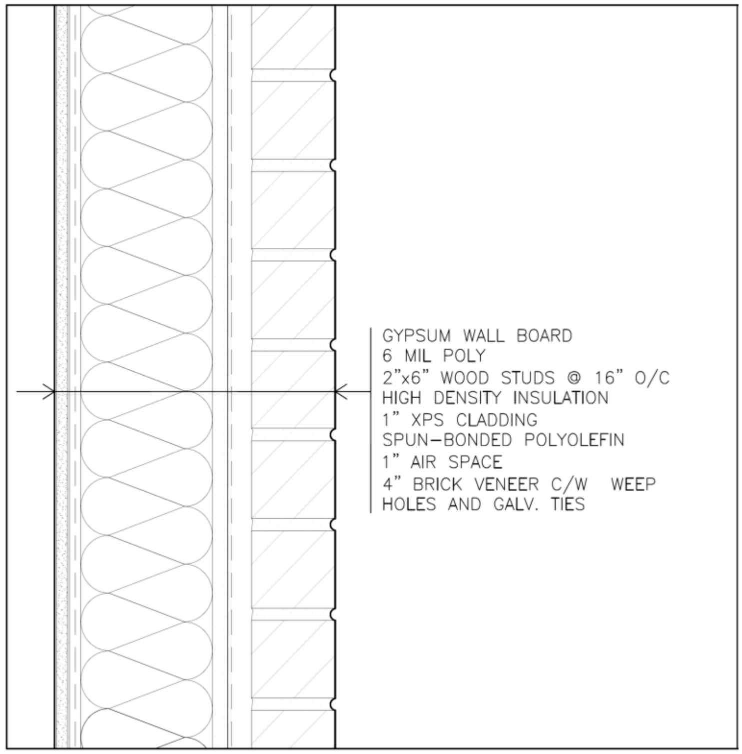


Figure G-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table G-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	16	F
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	0	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.47	
		Rim joist section	3.51	
		Top plate	3.20	
		Whole-wall	3.45	
	Nominal RSI		4.83	
	Whole Wall RSI Deviation from nominal RSI		-29%	
Env. Impact	Kg CO2 eq./sq. Meter		61.74	
Cost	$/sq.meter		**$201.85**	

Heat Transfer

Highlighted in the black dotted line in Figure G-2, Case 4a performs slightly better than the average of the walls considered. The 25mm of extruded polystyrene helped to reduce its deviation from nominal RSI value to 29%. Its whole wall RSI value is modeled at 3.45.

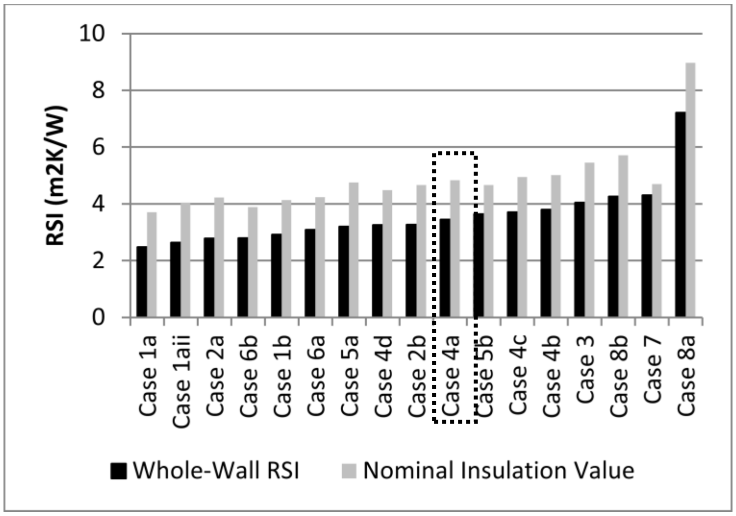


Figure G-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

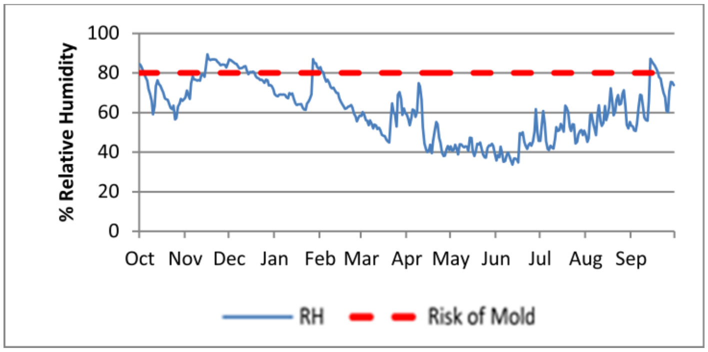


Figure G-3 Relative Humidity Inboard of Sheathing

Outward vapour drive causes some spikes over 80% relative humidity at the inboard face of the sheathing. This is due to the resistance to vapour diffusion of the composite insulated sheathing. These spikes are of short duration and do not present significant risk of moisture damage.

Inward Vapour Drive Outboard of Vapour Retarder

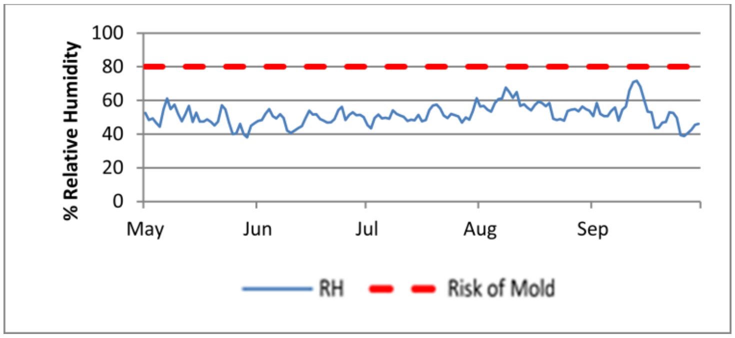


Figure G-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure G-5. This envelope design requires careful air barrier detailing.

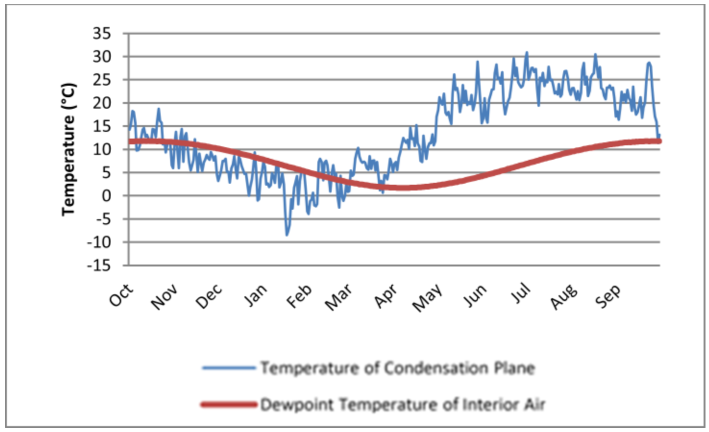


Figure G-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis

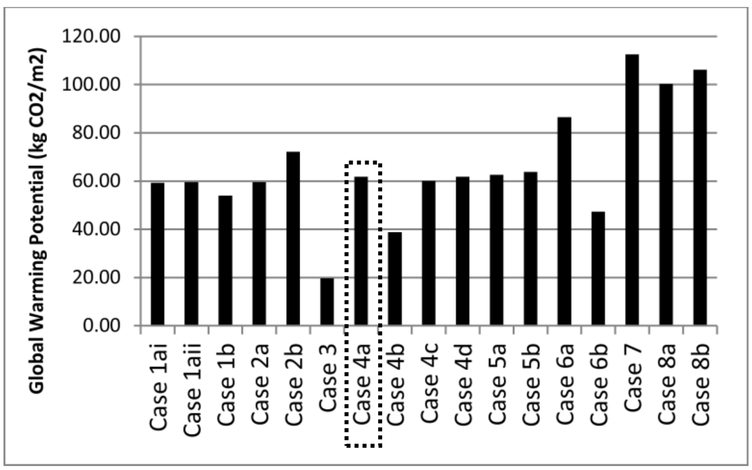


Figure G-6 Global Warming Potential per Square Meter

Case 4a is an average performer in terms of environmental impact. The use of brick cladding and extruded polystyrene contribute most to its global warming potential. Improvements could be found by using advanced framing and considering an alternative cladding material.

Cost Analysis

At a cost of $201.85, Case 4a is an average performer in terms of cost. Brick cladding accounts for much of its costs. Savings could be found by using advanced framing technique, which also contributes to lower RSI and environmental impact.

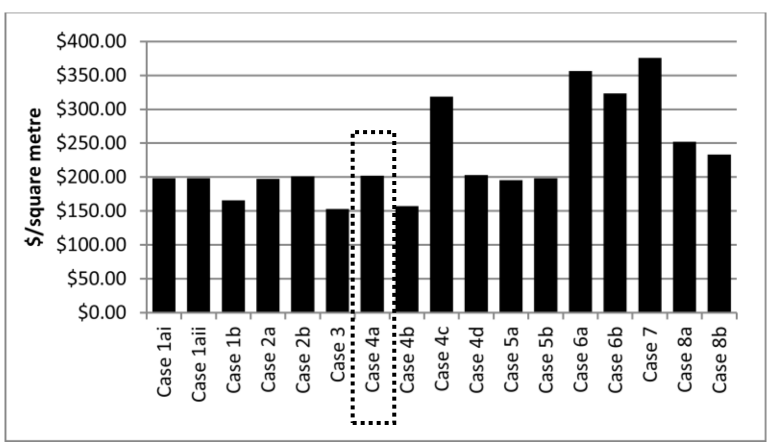


Figure G-7 Costs of Wall Assemblies per Square Meter

Appendix H - Case 4b

The principal features of this wall assembly is the use of standard framing, blown in glass fibre insulation, 25mm of XPS insulated sheathing and vinyl siding. This wall complies with code packages B and C.

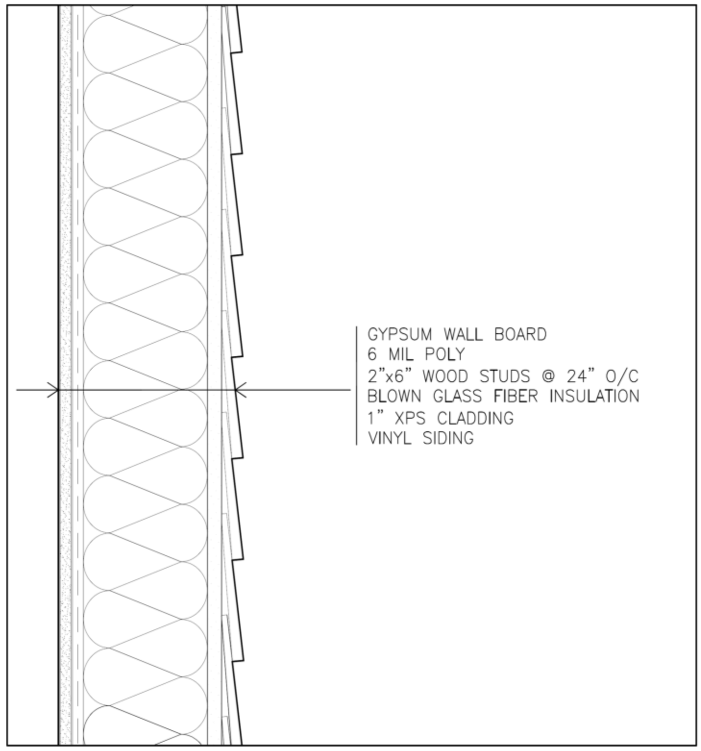


Figure H-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table H-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	15	F
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	0	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	4.00	
		Rim joist section	3.59	
		Top plate	3.25	
		Whole-wall	3.8	
	Nominal RSI		5.01	
	Whole Wall RSI Deviation from nominal RSI		-24%	
Env. Impact	Kg CO2 eq./sq. Meter		38.83	
Cost	$/sq.meter		**$157.28**	

Heat Transfer

Highlighted in the black dotted line in Figure H-2, Case 4b well in terms of heat transfer characteristics. With a nominal RSI value of 5.01 and a whole wall RSI value of 3.8, this wall experiences a deviation from nominal values by 24%.

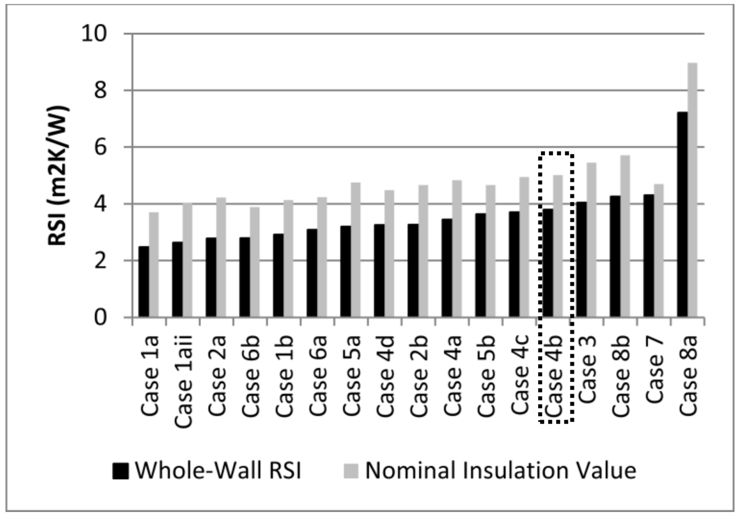


Figure H-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

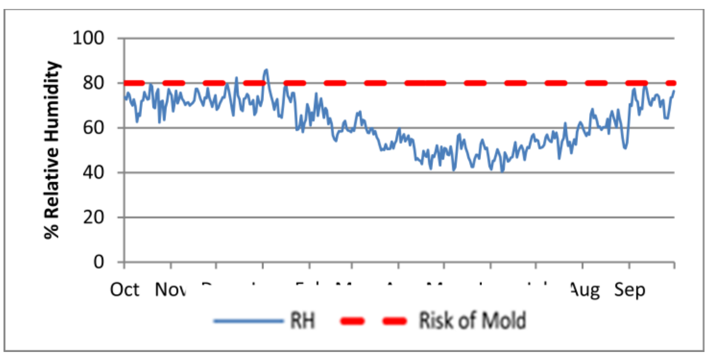


Figure H-3 Relative Humidity Inboard of Sheathing

Outward vapour drive does not cause problems for this wall at the inboard surface of the sheathing. The brief spike in relative humidity in January is of little concern due to the period of time over below 80% relative humidity.

Inward Vapour Drive Outboard of Vapour Retarder

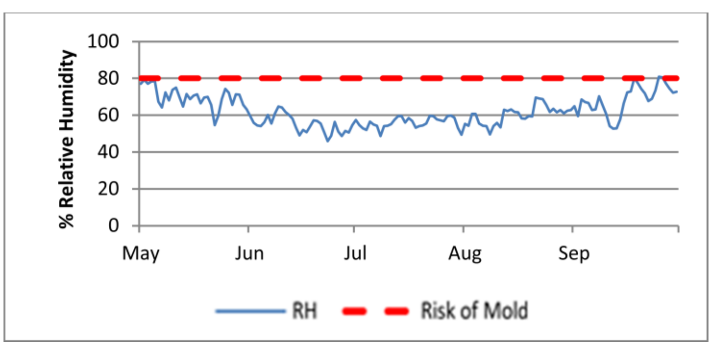


Figure H-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80%.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure H-5. This envelope design requires careful air barrier detailing.

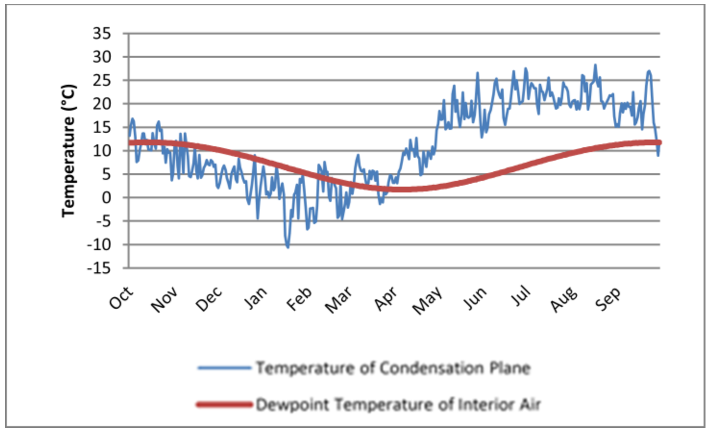
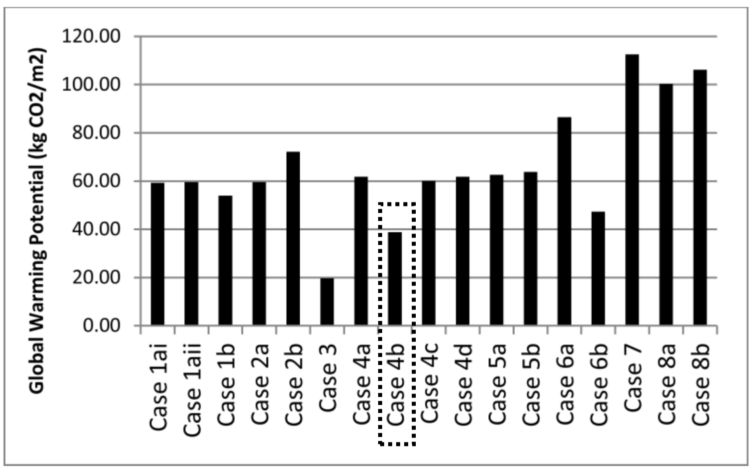


Figure H-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Case 4b's global warming potential is modeled at 61.74 kg CO2 eq./m^2, and performs toward the best of the walls considered. This positive result is due primarily to the use of vinyl siding instead of the use of brick cladding as well as the use of advanced framing.

Figure H-7 Global Warming Potential per Square Meter

Cost Analysis

As one of the least expensive walls in this study, Case 4b saves costs by reducing materials inputs due to advanced framing as well as the use of lower cost vinyl cladding.

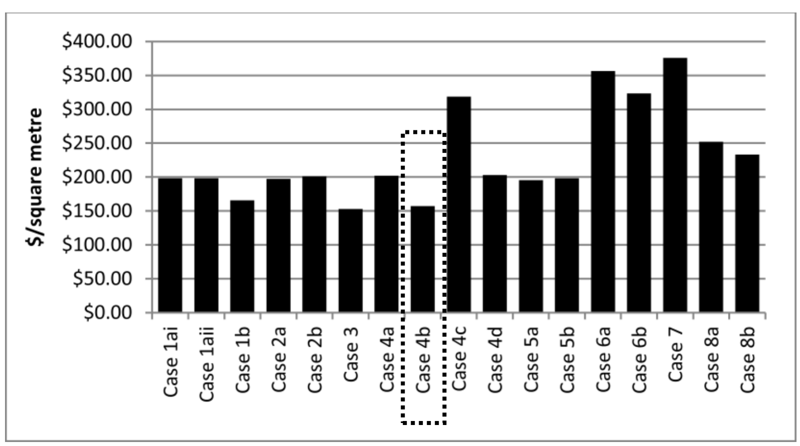


Figure H-6 Costs of Wall Assemblies per Square Meter

Appendix I - Case 4c

As shown in Figure I-1, Case 4c uses spray polyurethane foam, 36mm of extruded polystyrene insulated sheathing and brick cladding.

With a nominal RSI value of 4.94, this wall complies with compliance packages B and C.

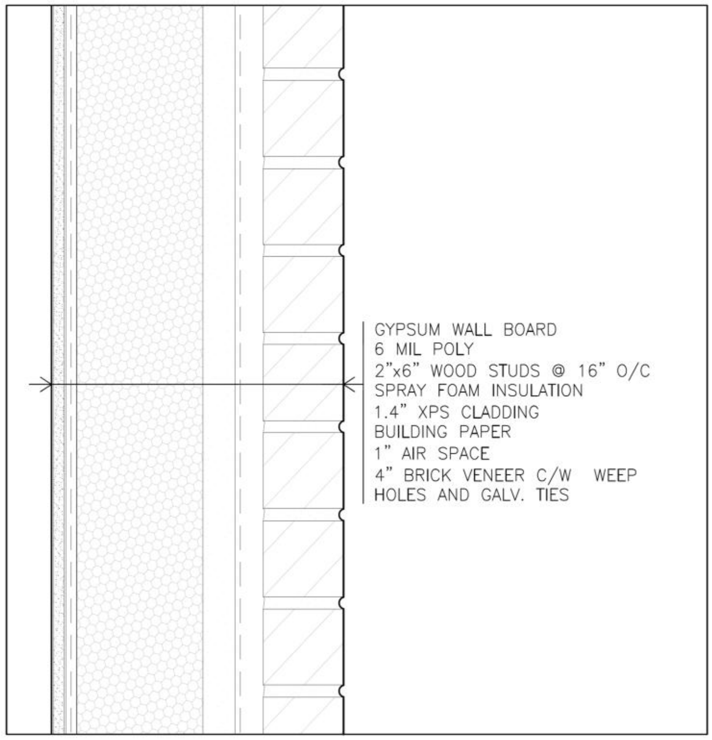


Figure I -1 Wall Assembly Cross-Section (Twiddy, 2011)

Table I-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	2	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	3	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.70	
		Rim joist section	3.84	
		Top plate	3.43	
		Whole-wall	3.7	
	Nominal RSI		4.94	
	Whole Wall RSI Deviation from nominal RSI		-25%	
Env. Impact	Kg CO2 eq./sq. Meter		58.00	
Cost	$/sq.meter		**$318.68**	

Heat Transfer

Highlighted in the black dotted line in Figure I-2, Case 4c performs well, with a whole-wall RSI value of 3.7 and a nominal RSI value of 4.94. Although there is a significant amount of exterior insulation used, the deviation from nominal RSI value is at 25%. This could be reduced by using advanced framing.

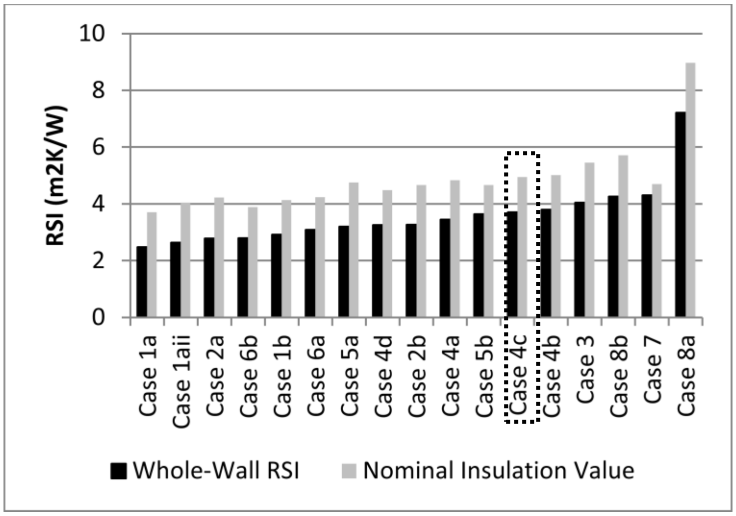


Figure I-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

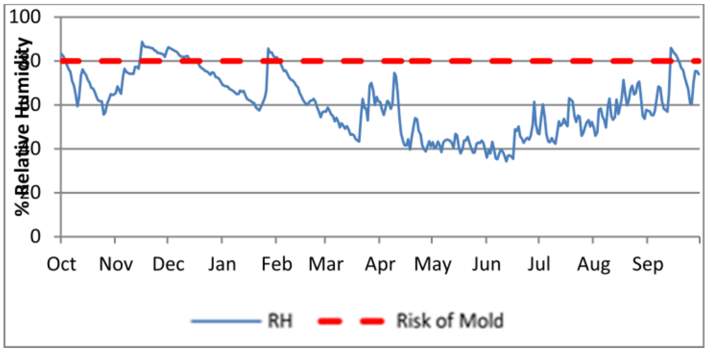


Figure I-3 Relative Humidity Inboard of Sheathing

Outward vapour drive causes some spikes over 80% relative humidity at the inboard face of the sheathing. This is due to the resistance to vapour diffusion of the composite insulated sheathing. These spikes are of short duration and do not present significant risk of moisture damage.

Inward Vapour Drive Outboard of Vapour Retarder

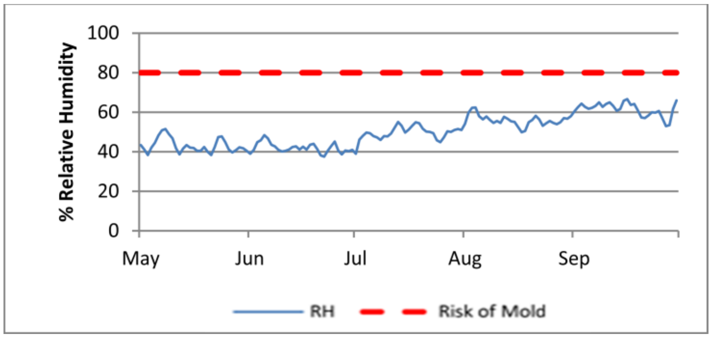


Figure I-4 Relative Humidity Outboard of Polyethylene

Case 4c performs well in the case of inward vapour drive. The combined resistance to vapour diffusion of the extruded polystyrene and the spray foam polyurethane reduces the RH levels outboard of the polyethylene.

Temperature of Condensation Plane

This wall performs exceptionally well in terms of reduced risk of exfiltration related condensation within the wall assembly. This is due to the use of spray foam insulation that acts as a continuous air barrier.

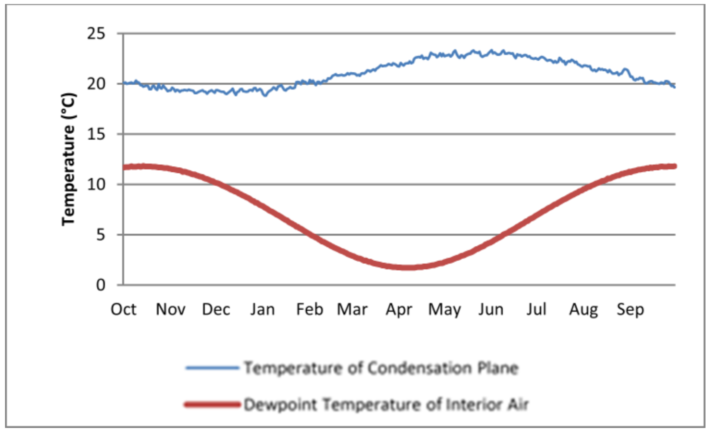
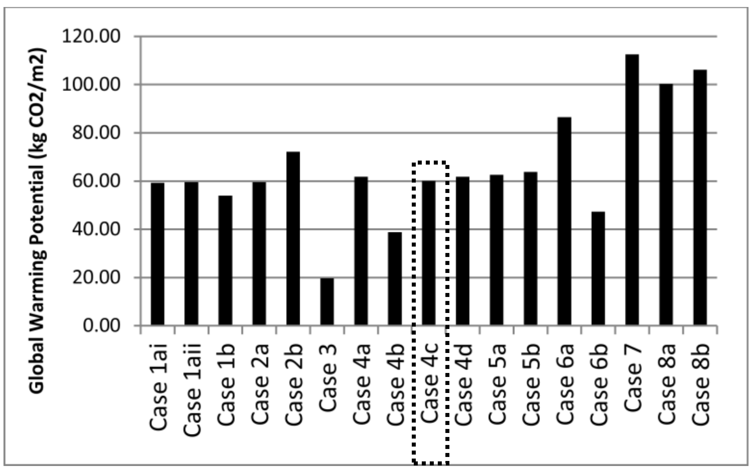


Figure I-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



This wall's global warming potential was modeled at 58 kg CO_2 eq./m^2. The use of brick cladding is the primary contributor to the environmental impact of the wall, but is also increased by the use of XPS and spray foam insulations.

Figure I-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of \$318.68/m^2, Case 4c is one of the higher costing wall assemblies. Brick cladding and spray foam insulation account for much of its high costs.

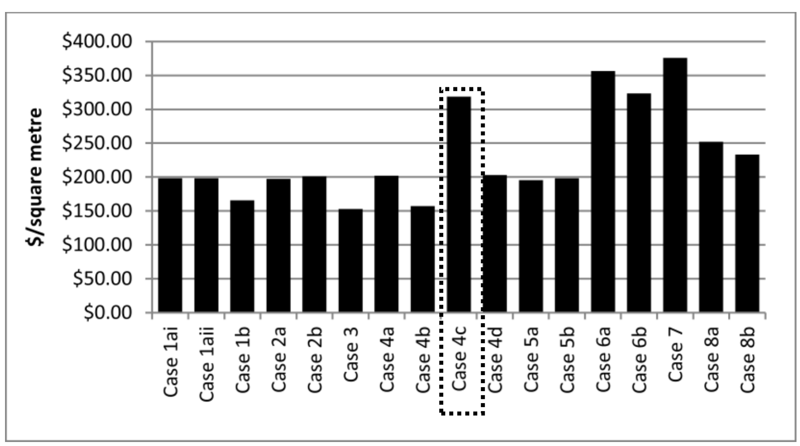


Figure I-7 Costs of Wall Assemblies per Square Meter

Appendix J - Case 4d

As shown in Figure J-1, Case 4d uses low density glass fibre insulation, 25mm of extruded polystyrene insulated sheathing and brick cladding. With a nominal RSI value of 4.48, this wall complies with compliance packages A, D, E, F, G and H.

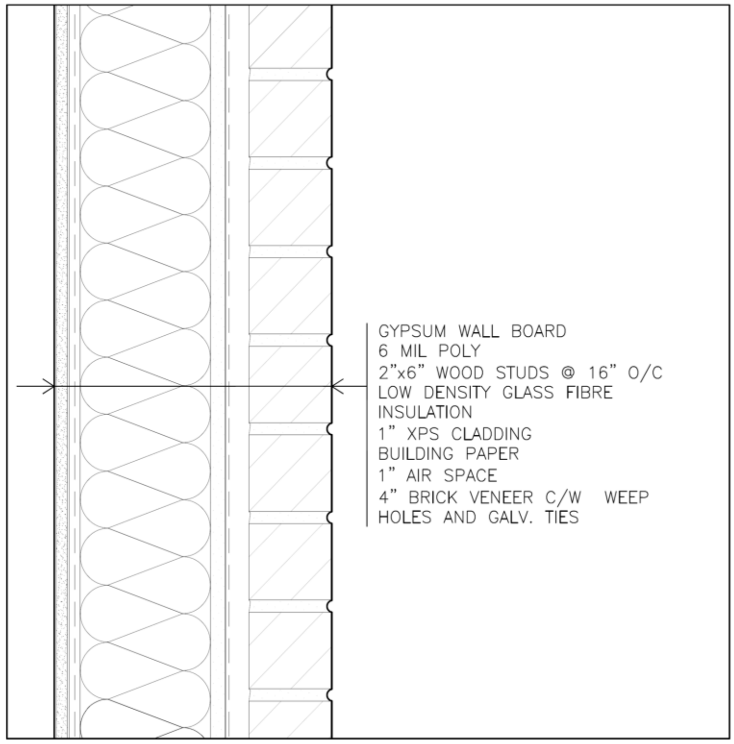


Figure J-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table J-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	1	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	5	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.26	
		Rim joist section	3.32	
		Top plate	3.03	
		Whole-wall	3.25	
	Nominal RSI		4.48	
	Whole Wall RSI Deviation from nominal RSI		-27%	
Env. Impact	Kg CO2 eq./sq. Meter		61.74	
Cost	$/sq.meter		**$202.97**	

Heat Transfer

Highlighted in the black dotted line in Figure J-2, Case 4d is an average performer both in nominal RSI and whole-wall RSI values. The deviation from nominal RSI values is 27% owing to its standard framing and low density fiberglass insulation.

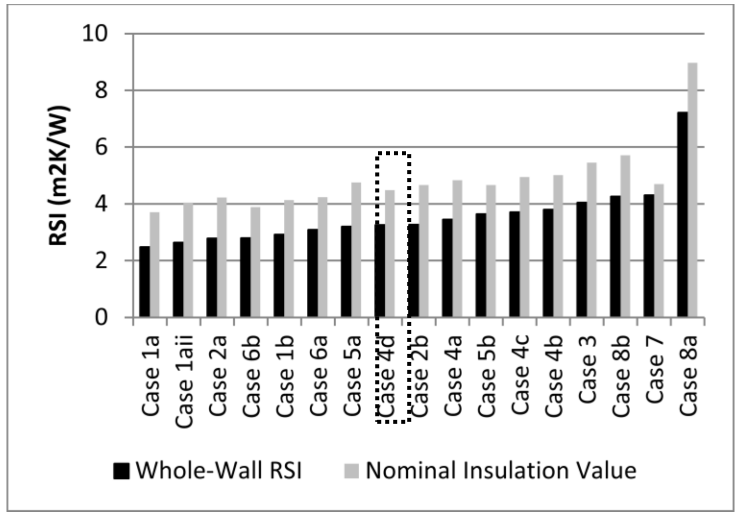


Figure J-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

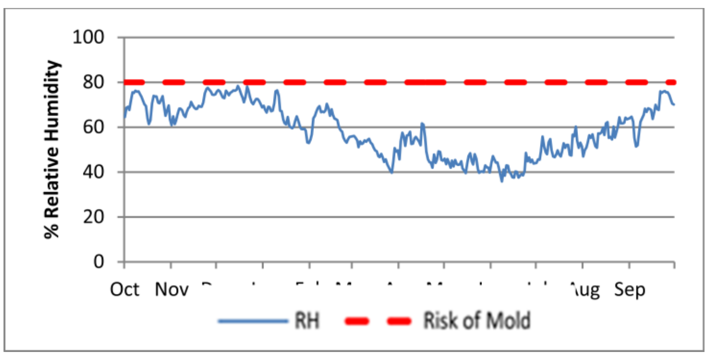


Figure J-3 Relative Humidity Inboard of Sheathing

Outward vapour drive does not cause problems for this wall at the inboard surface of the sheathing. Relative humidities remain below 80% consistently throughout the year, thereby not contribution to elevated moisture conditions due to vapour passing through the ployethylene toward the exterior.

Inward Vapour Drive Outboard of Vapour Retarder

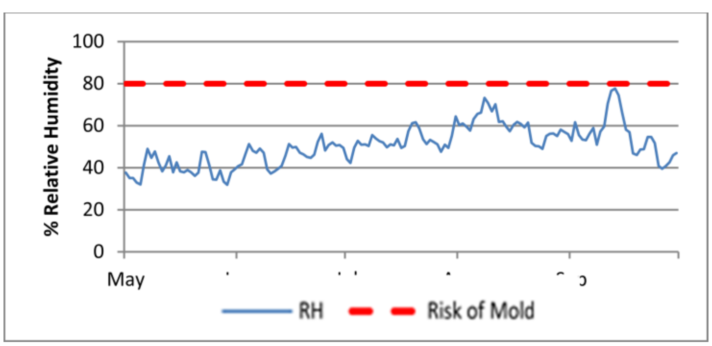


Figure J-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophylic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure J-5. This envelope design requires careful air barrier detailing.

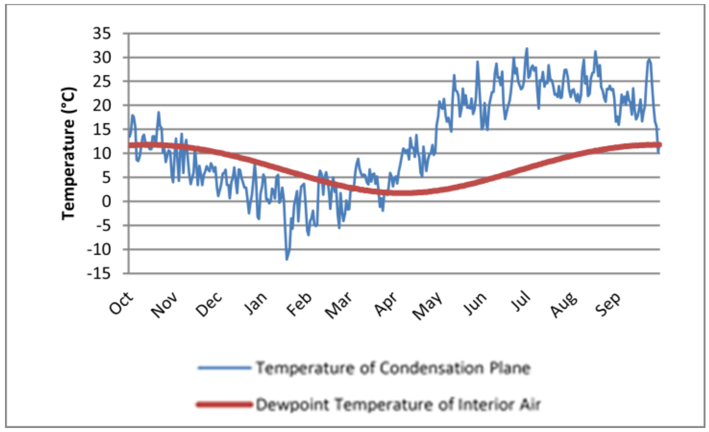
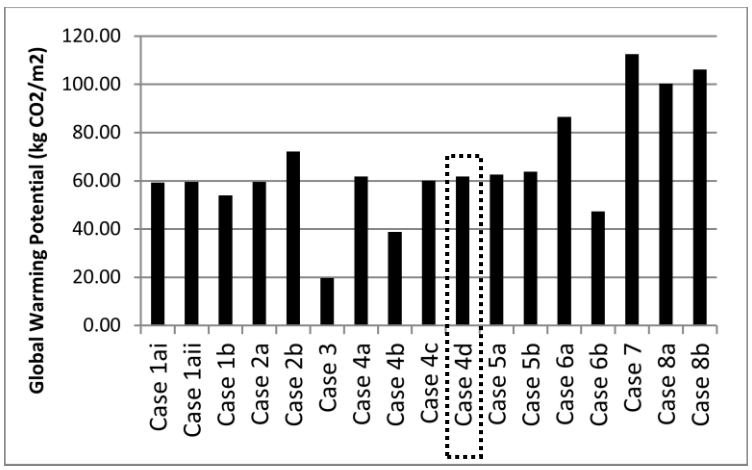


Figure J-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



This wall assembly's global warming potential was modeled at 61.74 kg CO2 eq./m^2. Results could be lowered by using a non-brick cladding and advanced framing technique.

Figure J-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $202.97, Case 4d is an average performer in terms of cost. Brick cladding accounts for much of its costs. Savings could be found by using advanced framing technique, which also contributes to lower RSI and GWP.

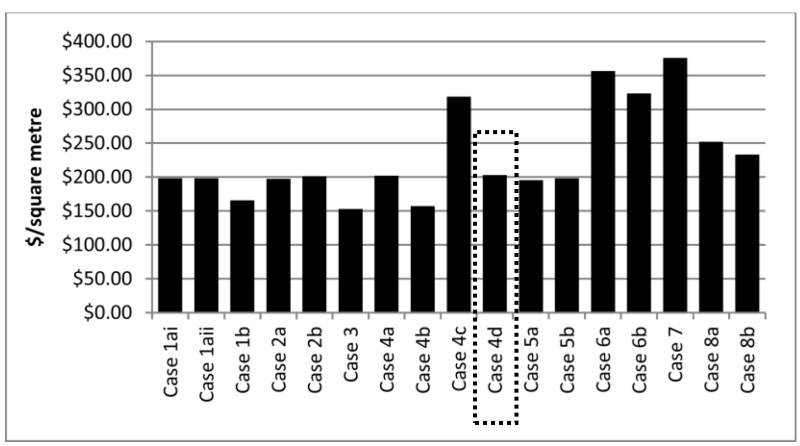


Figure J-7 Costs of Wall Assemblies per Square Meter

Appendix K - Case 5a

The principle features of Case 5a are the use of standard framing, high density glass fibre insulation, 19mm of foil faced polyisocyanurate and brick cladding. With a nominal RSI value of 4.75, this wall complies with compliance packages B and C.

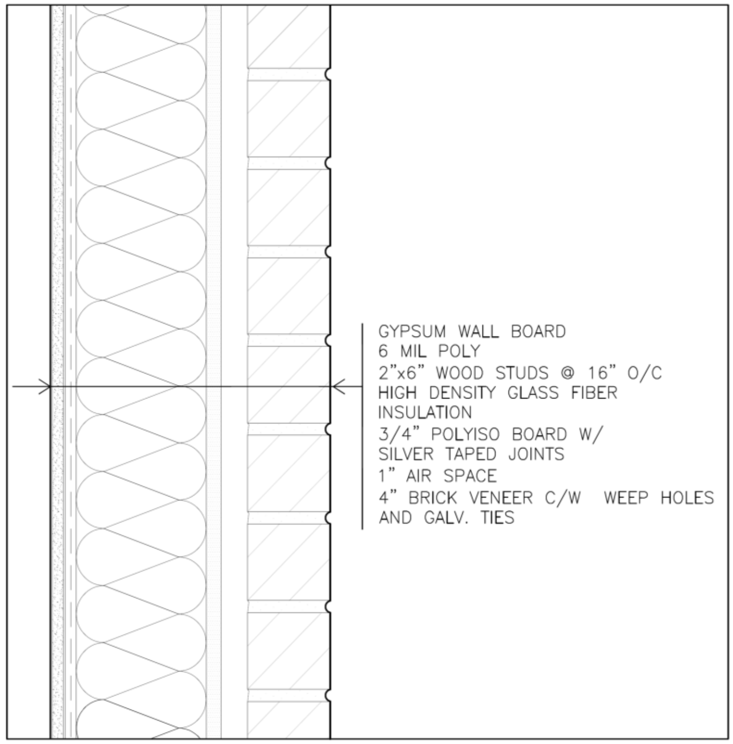


Figure K-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table K-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	45	F
		>98%	10	F
		>100%	0	P
	Inward vapour drive	>80%	9	F
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.18	
		Rim joist section	3.35	
		Top plate	3.02	
		Whole-wall	3.2	
	Nominal RSI		4.75	
	Whole Wall RSI Deviation from nominal RSI		-33%	
Env. Impact	Kg CO2 eq./sq. Meter		62.60	
Cost	$/sq.meter		**$195.69**	

Heat Transfer

Highlighted in the black dotted line in Figure K-2, Case 5a is slightly below average, with a whole-wall RSI value of 3.2. In comparison to the nominal RSI value, this wall experiences a deviation of 33%.

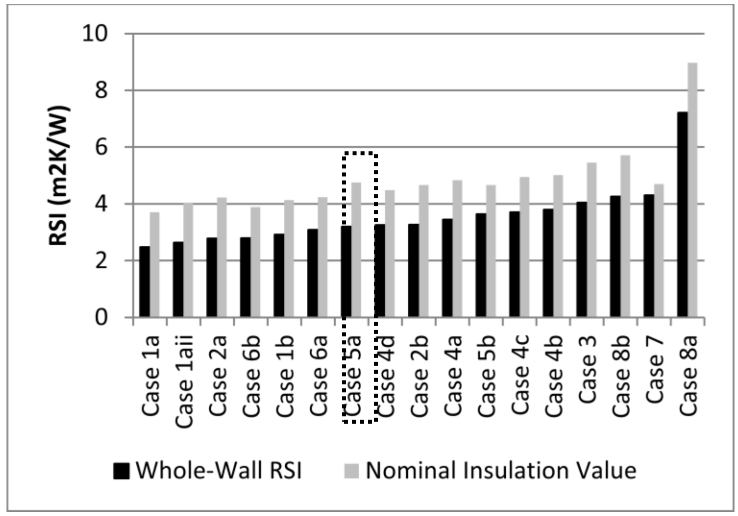


Figure K-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

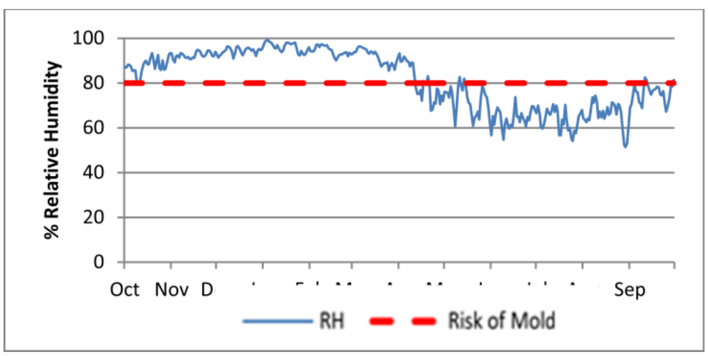


Figure K-3 Relative Humidity Inboard of Sheathing

Due to the trapped vapour between the polyethylene vapour retarder and the foil faced polyisocyanurate, relative humidity levels are elevated to high levels and for long durations throughout the heating season. This is cause for significant concern, as there is reduced drying potential in this type of construction.

Inward Vapour Drive Outboard of Vapour Retarder

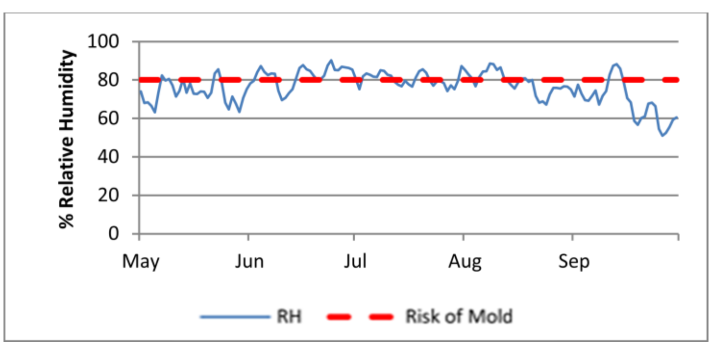


Figure K-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive also raises relative humidity levels above 80% frequently throughout the summer season. This is caused by the trapped moisture within the wall assembly. This approaches questionable moisture safety, caution is recommended.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure K-5. This envelope design requires careful air barrier detailing.

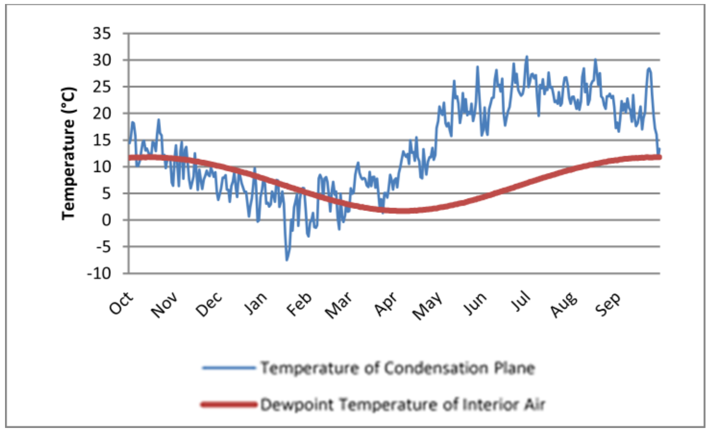
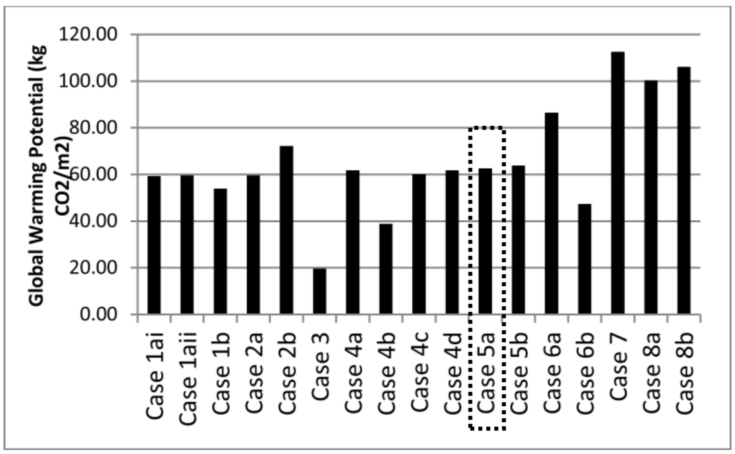


Figure K-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Case 5a's global warming potential is modeled at 62.60 kg CO2 eq./m^2, which is the near the average for the walls considered. Results could be lowered by using a non-brick cladding and the advanced framing technique.

Figure K-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $195.69, Case 5a is an average performer in terms of cost. Brick cladding accounts for much of its costs, although some savings are found in taping the polyisocyanurate rather than using an additional weather barrier.

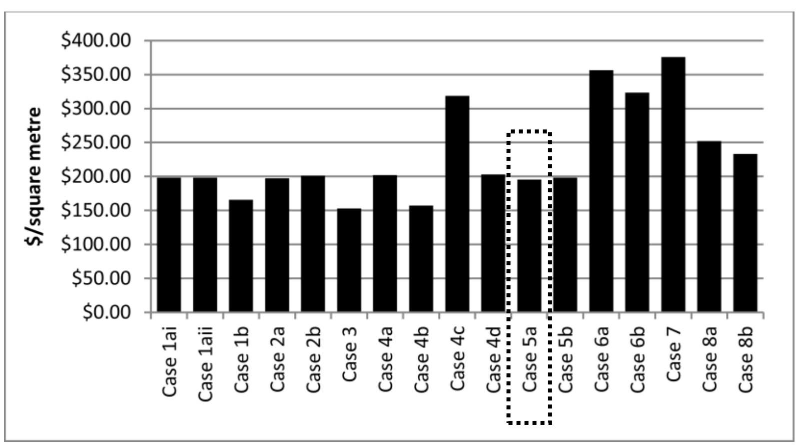


Figure K-7 Costs of Wall Assemblies per Square Meter

Appendix L - Case 5b

The principle features of Case 5b are the use of advanced framing, low density glass fibre insulation, 25mm of foil faced polyisocyanurate and brick cladding. This wall complies with compliance packages B and C.

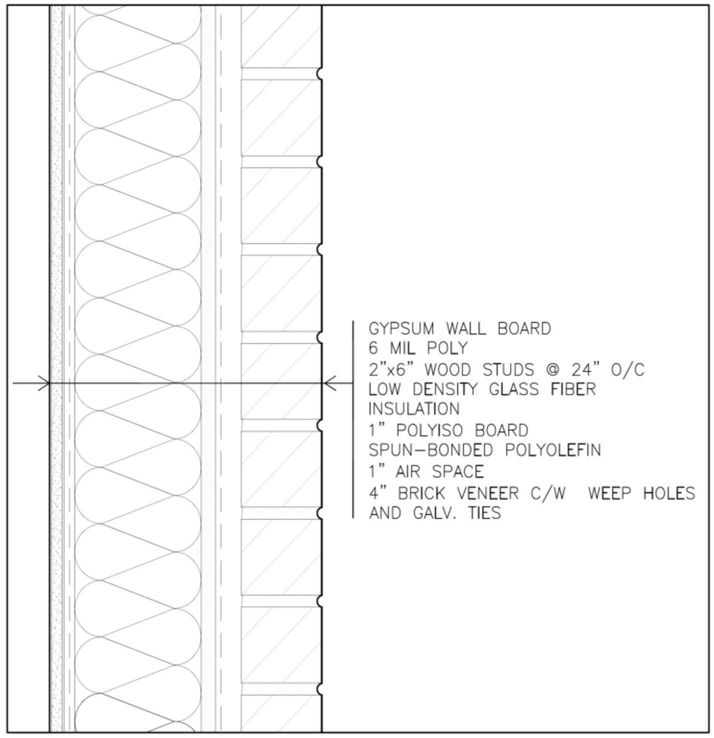


Figure L-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table L-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	45	F
		>98%	4	P
		>100%	0	P
	Inward vapour drive	>80%	2	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.77	
		Rim joist section	3.51	
		Top plate	3.23	
		Whole-wall	3.64	
	Nominal RSI		4.66	
	Whole Wall RSI Deviation from nominal RSI		-22%	
Env. Impact	Kg CO2 eq./sq. Meter		63.81	
Cost	$/sq.meter		**$198.29**	

Heat Transfer

Highlighted in the black dotted line in Figure L-2, Case 5b performs at a level above average, out of the walls considered. The whole-wall RSI value of 3.64 represents a 22% deviation from its nominal RSI value of 4.66. The use of advanced framing and 25mm thickness of polyisocyanurate contribute to these results.

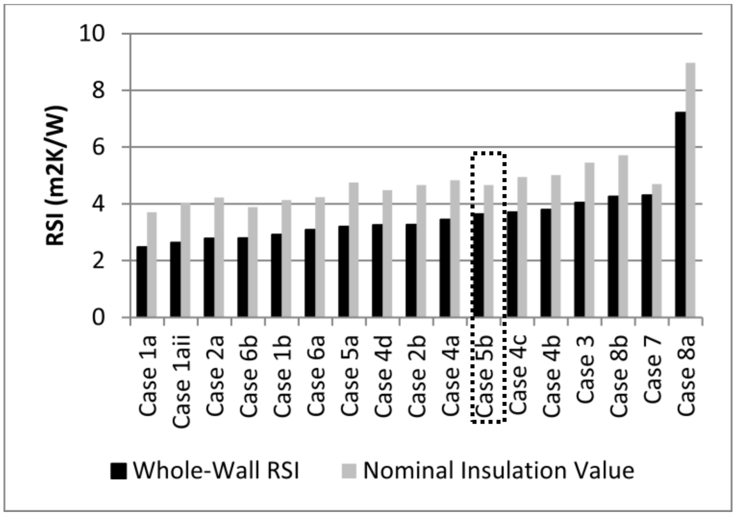


Figure L-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

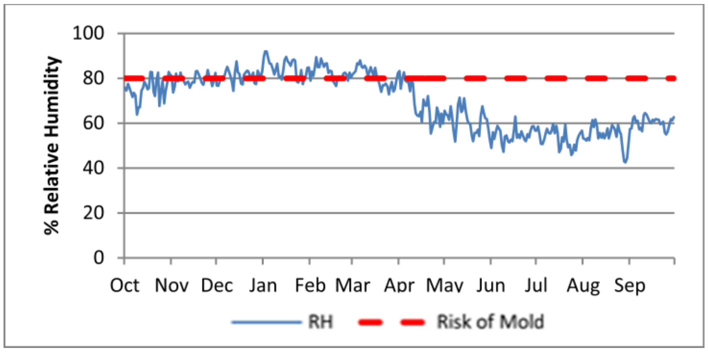


Figure L-3 Relative Humidity Inboard of Sheathing

Due to the trapped vapour between the polyethylene vapour retarder and the foil faced polyisocyanurate, relative humidity levels are elevated to high levels and for long durations. This is cause for significant concern, as there is reduced drying potential in this type of construction.

Inward Vapour Drive Outboard of Vapour Retarder

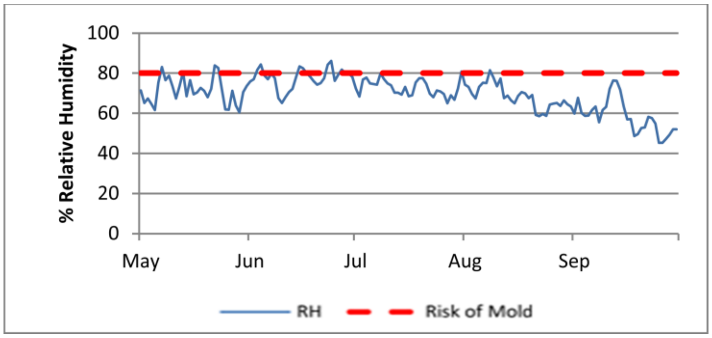


Figure L-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive also raises relative humidity levels above 80% frequently throughout the summer season. This is caused by the trapped moisture within the wall assembly. This approaches questionable moisture safety, caution is recommended.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure L-5. This envelope design requires careful air barrier detailing.

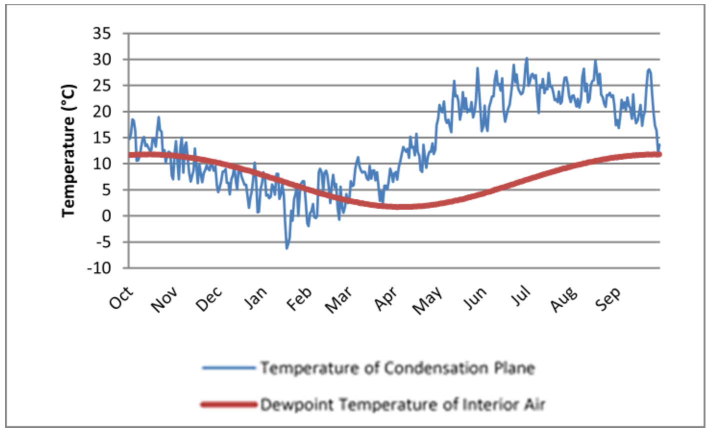
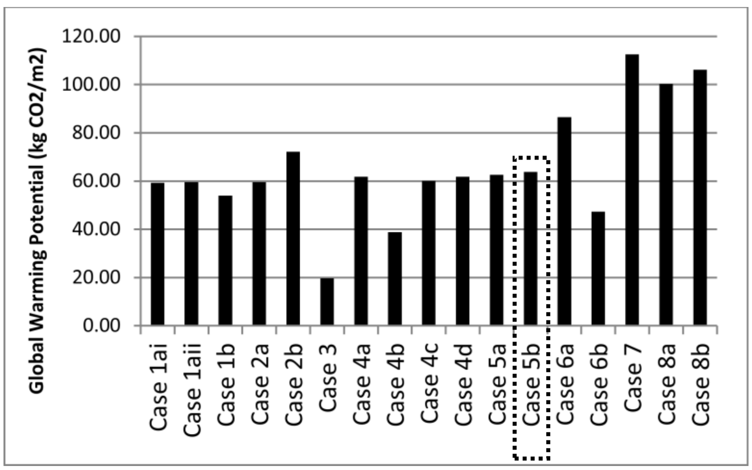


Figure L-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Case 5b's global warming potential is modeled at 63.81kg CO2 eq./m^2, which is the near the average for the walls considered. Results could be lowered by using a non-brick cladding and omitting the spun-bonded polyolefin in favour of taping the polyisocyanurate.

Figure L-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $198.29, Case 5b is an average performer in terms of cost. Brick cladding accounts for much of its costs, although some savings are found in advanced framing.

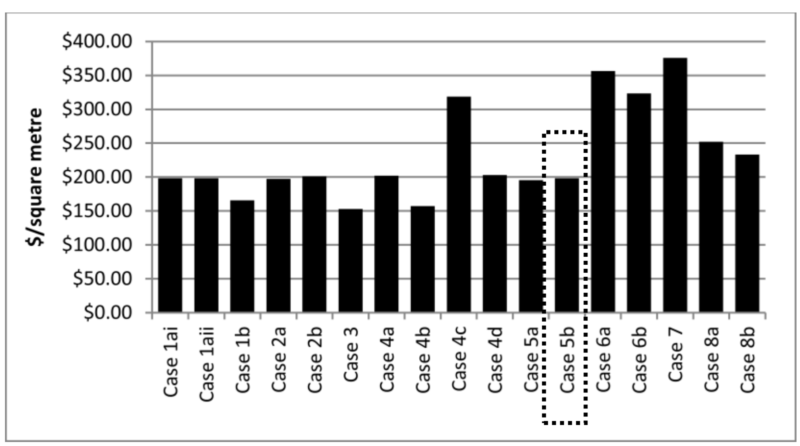


Figure L-7 Costs of Wall Assemblies per Square Meter

Appendix M - Case 6a

The principal features of Case 6a, as shown in Figure M-1, are the use of light-weight steel framing, spray polyurethane foam cavity insulation, 51mm of extruded polystyrene insulated sheathing and brick cladding. The nominal RSI value of wall is 4.23, which satisfies compliance packages A, D, E, F, G and H.

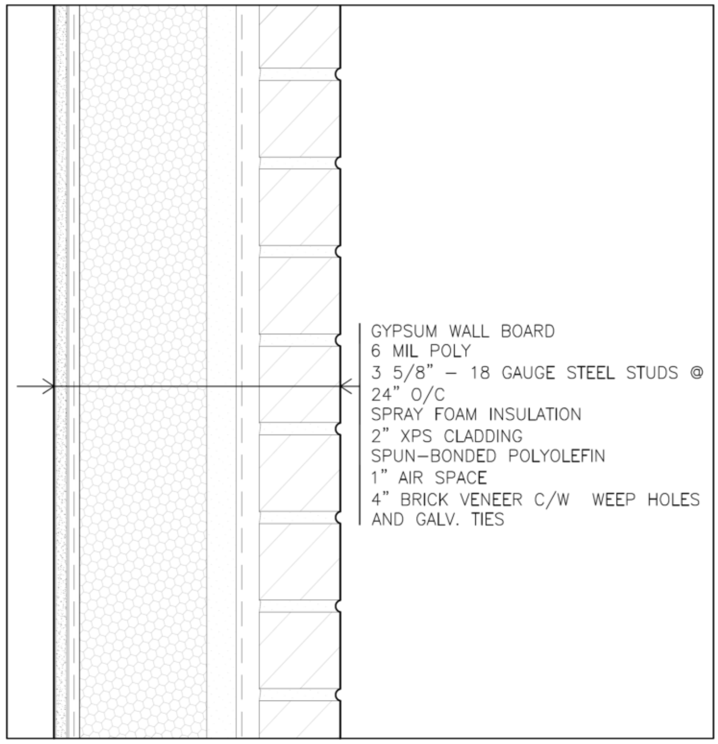


Figure M-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table M-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	2	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	3	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	3.16	
		Rim joist section	2.79	
		Top plate	3.31	
		Whole-wall	3.09	
	Nominal RSI		4.23	
	Whole Wall RSI Deviation from nominal RSI		-27%	
Env. Impact	Kg CO2 eq./sq. Meter		86.50	
Cost	$/sq. meter		**$356.57**	

Heat Transfer

Highlighted in the black dotted line in Figure M-2, Case 6a has a whole-wall RSI of 3.09, which represents a deviation of 27% from the nominal RSI value. Without the thick layer of polystyrene, the steel studs would contribute toward much higher deviations from nominal RSI values.

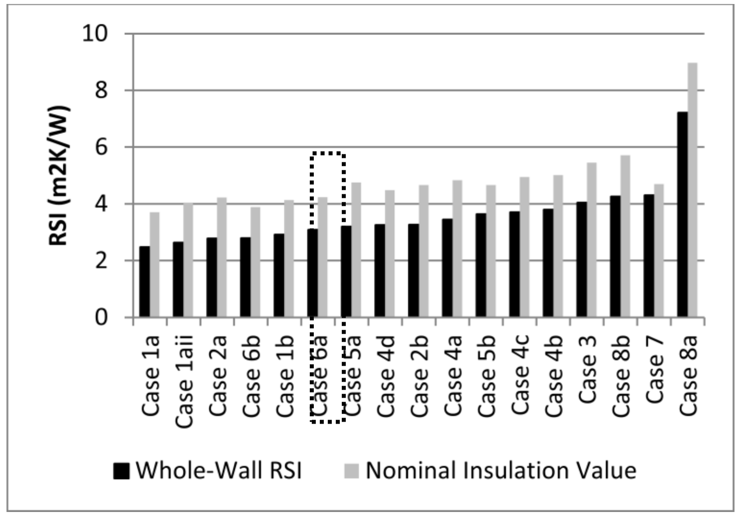


Figure M-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

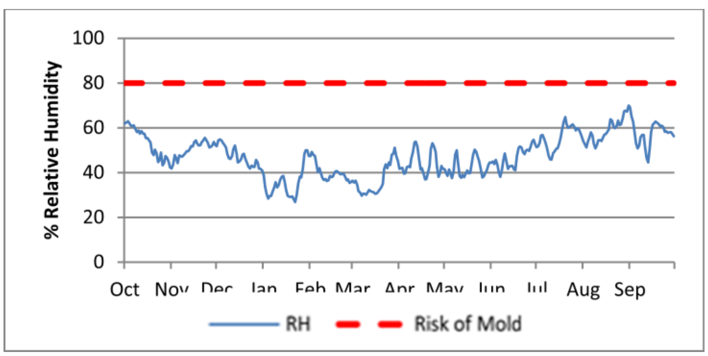


Figure M-3 Relative Humidity Inboard of Sheathing

This wall assembly performs very well in terms of managing outward moisture drive. Due to the vapour diffusion resistance of the spray polyurethane, the RH levels are consistently below 65% RH throughout the year.

Inward Vapour Drive Outboard of Vapour Retarder

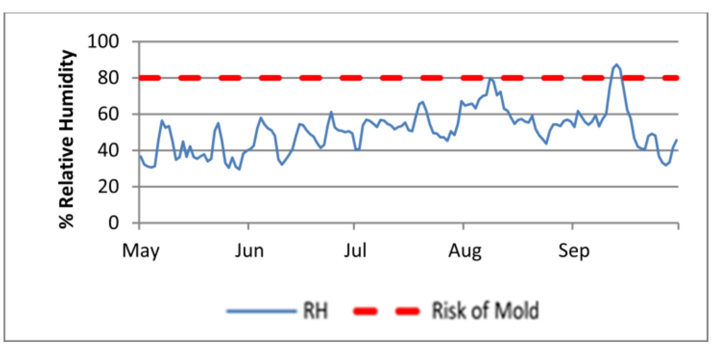


Figure M-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Although there is a small spike in September, the relative humidity levels are below 80% for most of the year.

Temperature of Condensation Plane

There is little risk of air leakage related condensation against the inboard surface of the sheathing because the temperature of the sheathing is consistently higher than the interior dew point temperature.

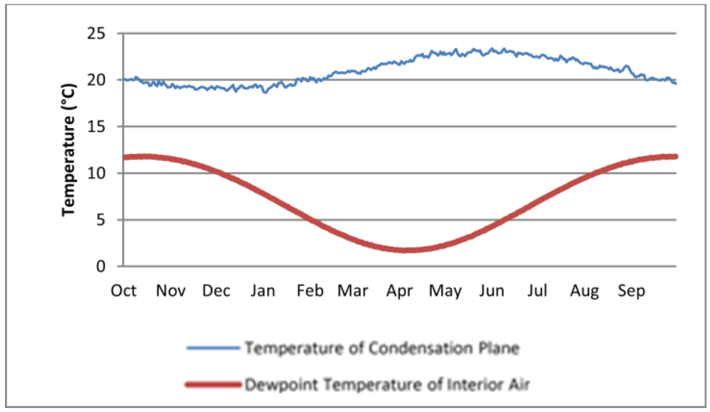
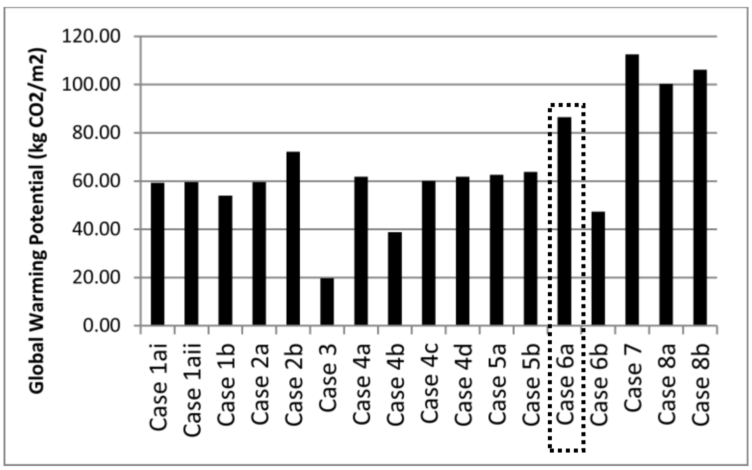


Figure M-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



The combination of spray foam cavity insulation and the use of steel studs, the global warming of this wall assembly is markedly above average at 86.5 kg CO2 eq./m^2.

Figure M-7 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $356.57, Case 6a is the most expensive wall assembly considered in this research. The combination of expensive materials such as brick cladding, spray foam insulation and steel framing accounts for much of its costs.

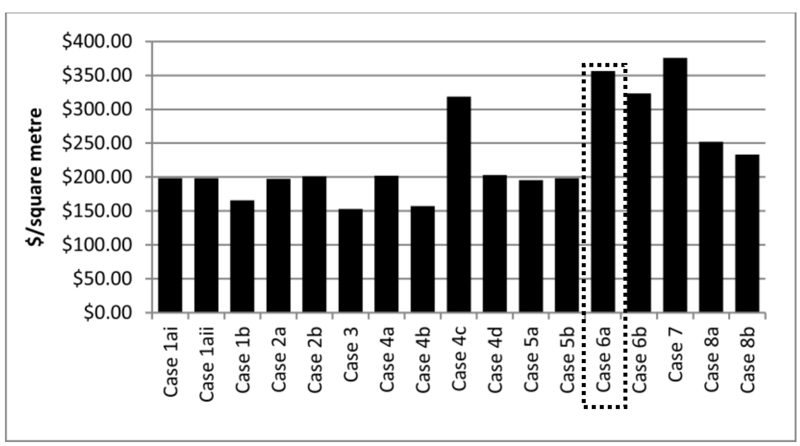


Figure M-6 Costs of Wall Assemblies per Square Meter

Appendix N - Case 6b

The principal features of Case 6b, as shown in Figure N-1, are the use of light-weight steel framing, spray polyurethane foam cavity insulation, 51mm of expanded polystyrene insulated sheathing with EIFS construction. The nominal RSI value of wall is 3.88, which satisfies compliance packages I, J and K.

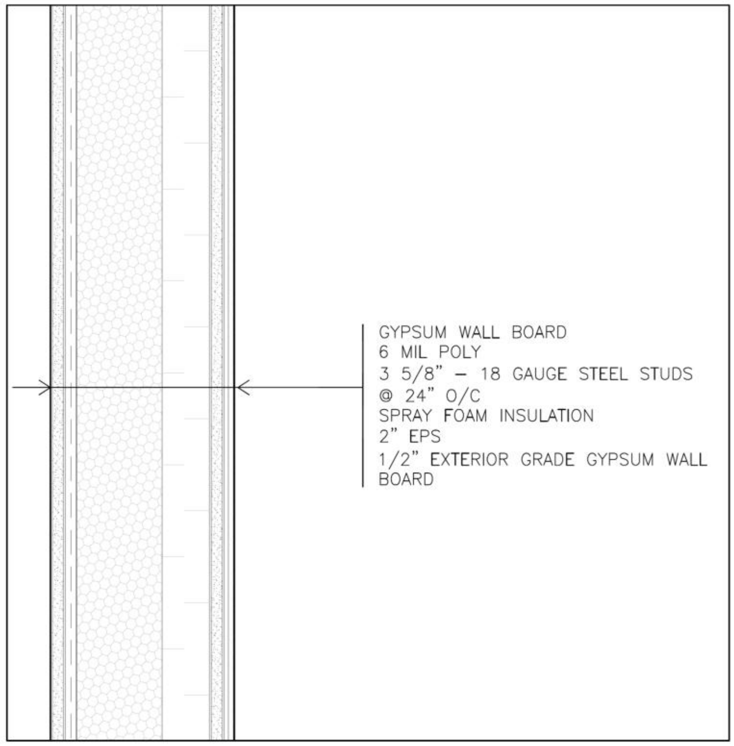


Figure N-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table N-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	3	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	0	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	2.90	
		Rim joist section	2.42	
		Top plate	2.92	
		Whole-wall	2.79	
	Nominal RSI		3.88	
	Whole Wall RSI Deviation from nominal RSI		-28%	
Env. Impact	Kg CO2 eq./sq. Meter		47.33	
Cost	$/sq.meter		**$323.46**	

Heat Transfer

Highlighted in the black dotted line in Figure N-2, Case 6b has a whole-wall RSI of 2.79, which represents a deviation of 28% from the nominal RSI value. Without the thick layer of polystyrene, the steel studs would contribute toward much higher deviations from nominal RSI values.

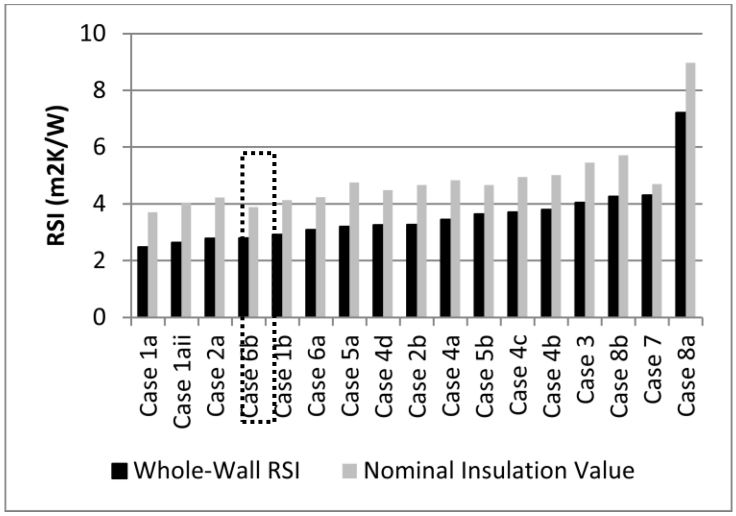
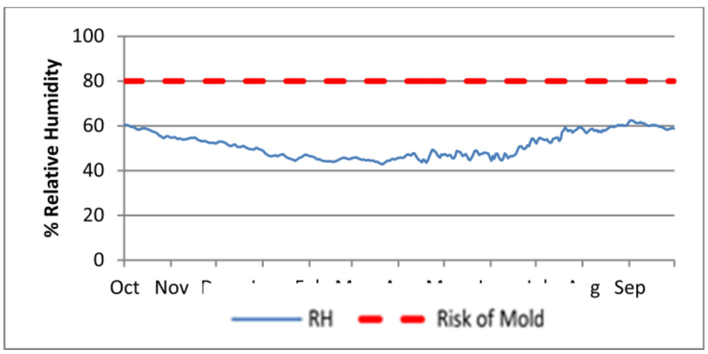


Figure N-2 Whole-Wall and Nominal RSI Values

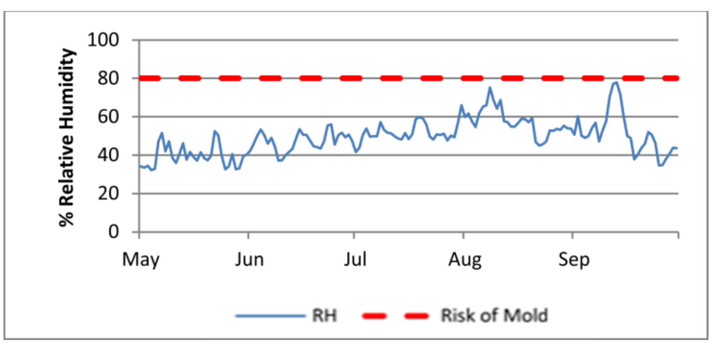
Outward Vapour Drive (All Year)



This wall assembly performs very well in terms of managing outward moisture drive. Due to the vapour diffusion resistance of the spray polyurethane, the RH levels are consistently below 65% RH throughout the year.

Figure N-3 Relative Humidity Inboard of Sheathing

Inward Vapour Drive Outboard of Vapour Retarder



Warm weather inward vapour drive is not an issue with this wall assembly configuration. Although there is a small spike in September, the relative humidity levels are below 80% throughout the year.

Figure N-4 Relative Humidity Outboard of Polyethylene

Temperature of Condensation Plane

There is little risk of air leakage related condensation against the inboard surface of the sheathing because the temperature of the sheathing is consistently higher than the interior dew point temperature.

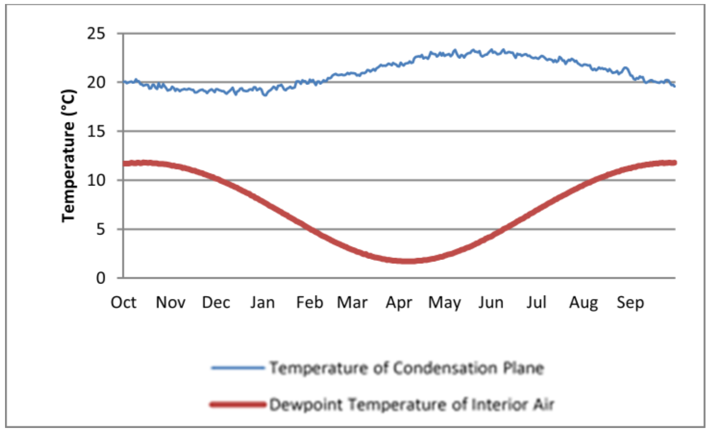
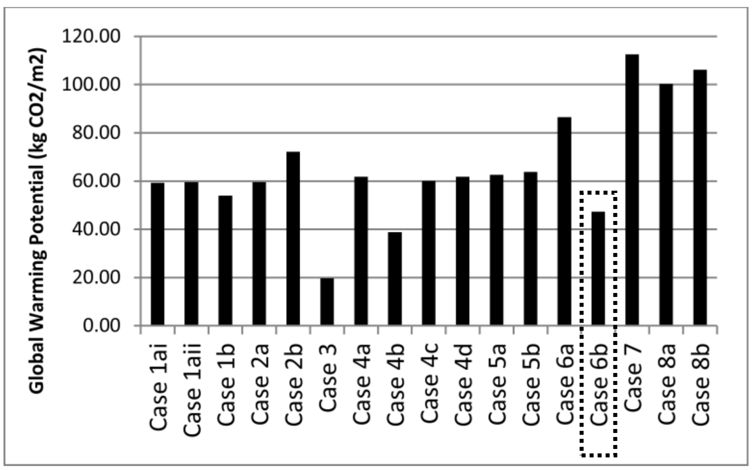


Figure N-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



The combination of spray foam cavity insulation and the use of steel studs is significant in the global warming potential of this wall assembly, although avoiding the use of brick cladding, the GWP of this wall is at 47.33 kg CO_2 eq./m^2 which is far below average.

Figure N-7 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $323.46, Case 6b is one of the more expensive wall assemblies considered in this research. The combination of expensive materials such as spray foam insulation and steel framing accounts for much of its costs.

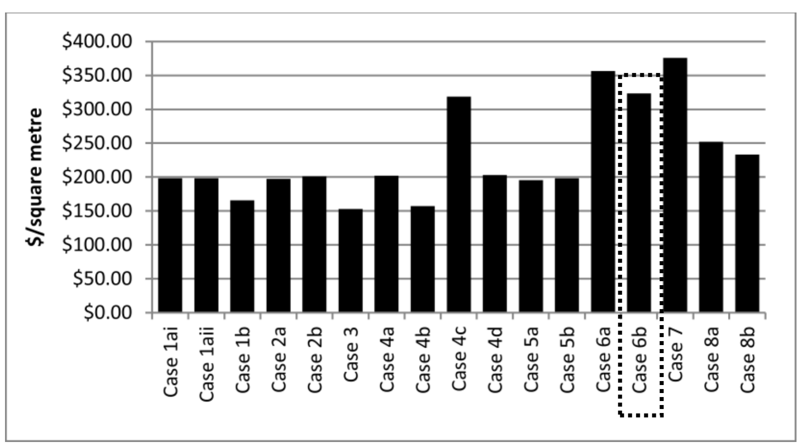


Figure N-6 Costs of Wall Assemblies per Square Meter

Appendix O - Case 7

The principle feature of Case 7, as shown in Figure O-1, are the use of brick cladding over an insulated concrete form construction. The 67mm of expanded polystyrene on both sides of the concrete structure provide a nominal RSI value of 4.7, which satisfies the compliance packages B and C.

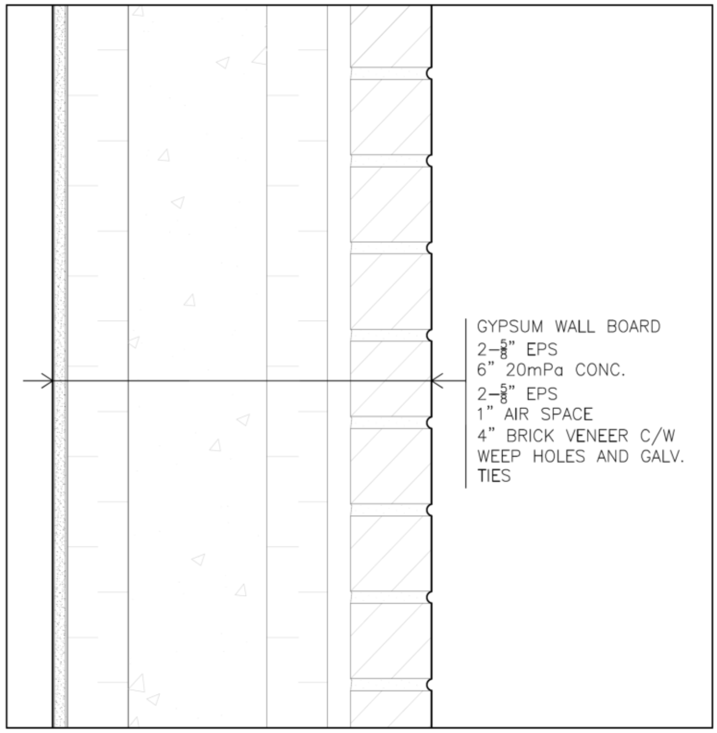


Figure O-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table 0-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	0	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	0	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		Low	
Heat Transfer	Whole Wall RSI Analysis	Wall section	4.70	
		Rim joist section	2.84	
		Top plate	3.78	
		Whole-wall	4.3	
	Nominal RSI		4.7	
	Whole Wall RSI Deviation from nominal RSI		-9%	
Env. Impact	Kg CO2 eq./sq. Meter		112.60	
Cost	$/sq.meter		**$375.80**	

Heat Transfer

Highlighted in the black dotted line in Figure O-2, Case 7 is the highest performer in terms of whole wall RSI value deviation from nominal RSI value at 10%. This is due to the virtually non-existent thermal bridging, with the exception of the steel floor joist inserts.

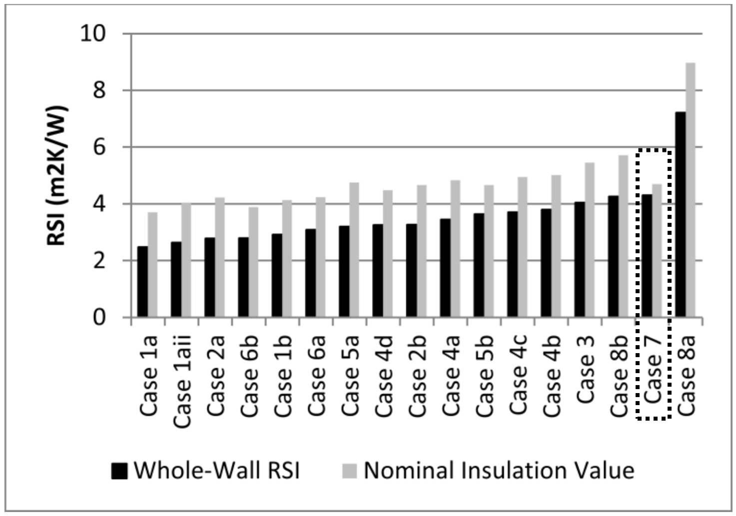


Figure 0-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

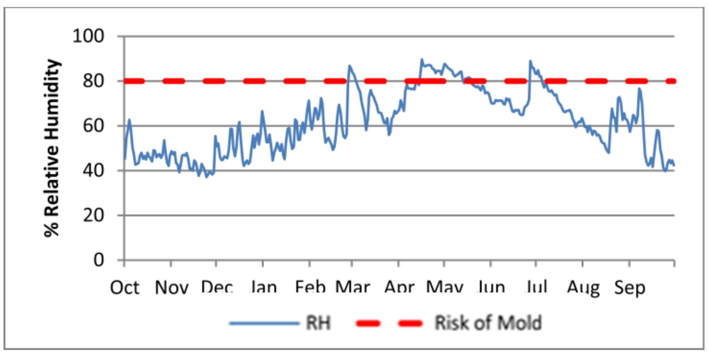


Figure 0-3 Relative Humidity Inboard of Sheathing

Outward vapour drive causes some spikes over 80% relative humidity at the inboard face of the outer EPS part of the ICF form. This is due to the resistance to vapour diffusion of the expanded polystyrene on inboard side of the concrete. These spikes are of short duration and do not present significant risk of moisture damage.

Inward Vapour Drive Outboard of Vapour Retarder

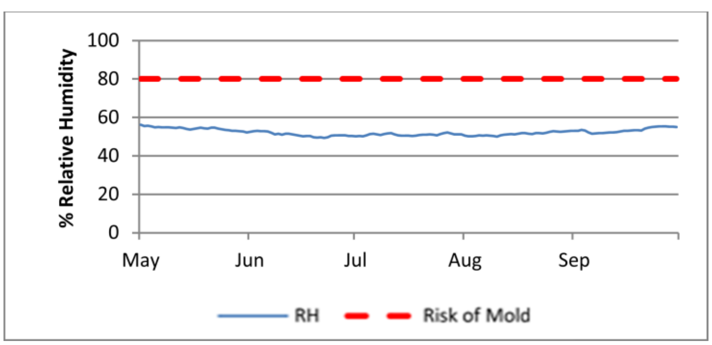


Figure 0-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. The relative humidity levels are below 60% for most of the year.

Temperature of Condensation Plane

There is little risk of air leakage related condensation against the inboard surface of the sheathing because the temperature of the sheathing is consistently higher than the interior dew point temperature.

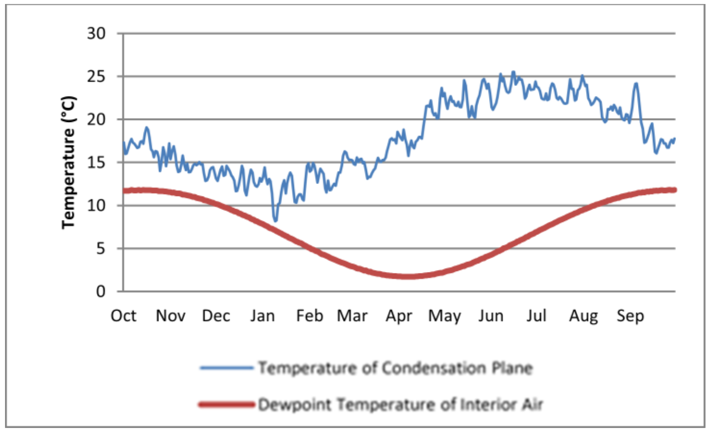


Figure 0-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis

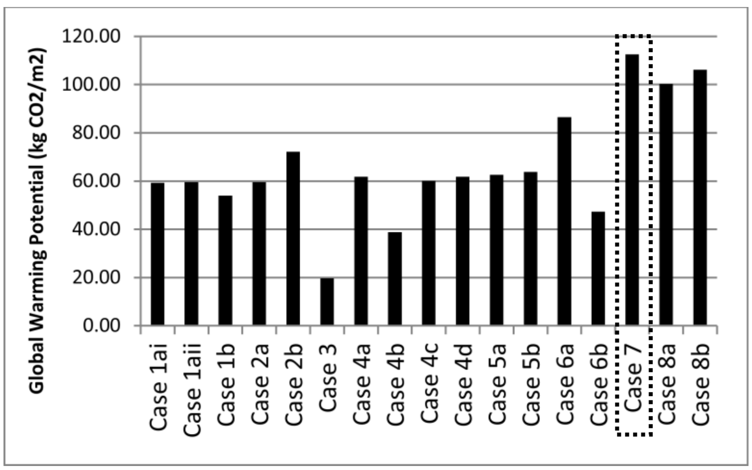


Figure 0-6 Global Warming Potential per Square Meter

Case 7 is modeled at 112.6 kg CO_2 eq./m^2 which is the highest global warming potential value for any of the wall assemblies considered. This is due to the use of large amounts of concrete, which is a highly energy intensive process, as well as an accumulated 134mm of expanded polystyrene.

Cost Analysis

At a cost of $375.80, Case 7 is one of the most costly wall assemblies considered. This is due to the use of expensive concrete, ICF forms and the use of brick cladding.

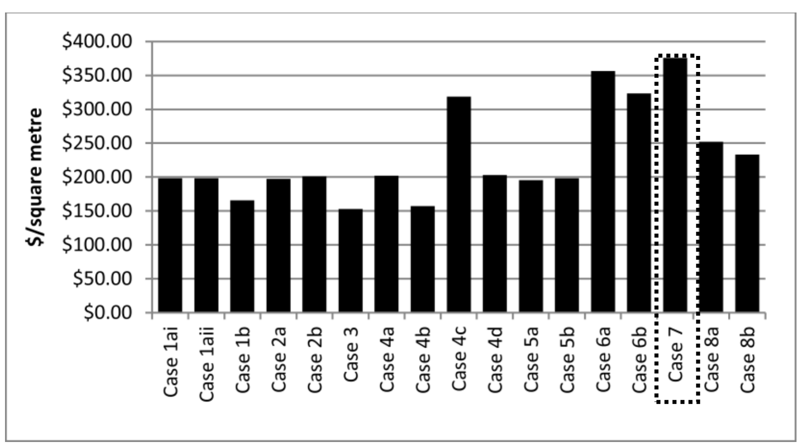


Figure 0-7 Costs of Wall Assemblies per Square Meter

Appendix P - Case 8a

The principle features of Case 8a, as shown in Figure P-1, are double stud construction with expanded polystyrene spacers, mineral wool insulation, OSB sheathing, foil-faced polyisocyanurate insulated sheathing and wood siding. The nominal RSI value of this wall is 8.97, which far exceeds the demands of compliance packages B and C.

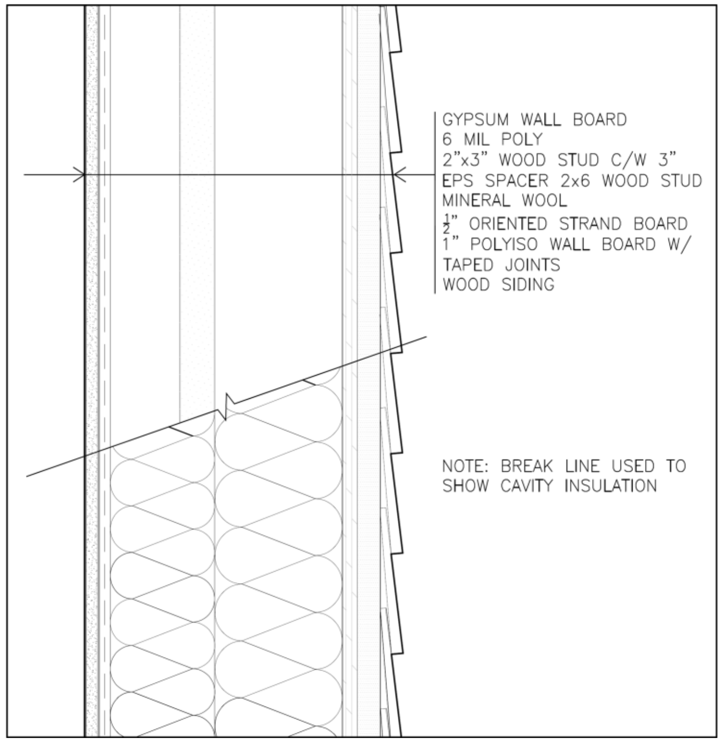


Figure P-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table P-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	42	F
Moisture Safety	RH outboard of sheathing	>98%	0	P
Moisture Safety	RH outboard of sheathing	>100%	0	P
Moisture Safety	Inward vapour drive	>80%	70	F
Moisture Safety	Inward vapour drive	>98%	0	P
Moisture Safety	Inward vapour drive	>100%	0	P
Moisture Safety	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	7.89	
Heat Transfer	Whole Wall RSI Analysis	Rim joist section	5.32	
Heat Transfer	Whole Wall RSI Analysis	Top plate	7.84	
Heat Transfer	Whole Wall RSI Analysis	Whole-wall	7.21	
Heat Transfer	Nominal RSI		8.97	
Heat Transfer	Whole Wall RSI Deviation from nominal RSI		-20%	
Env. Impact	Kg CO2 eq./sq. Meter		100.36	
Cost	$/sq.meter		**$252.08**	

Heat Transfer

Highlighted in the black dotted line in Figure P-2, Case 8a has the highest nominal and whole-wall RSI values of any wall considered. The double stud construction, with advanced framing, 280mm of mineral wool insulation resulted in a deviation of 20% from its nominal value.

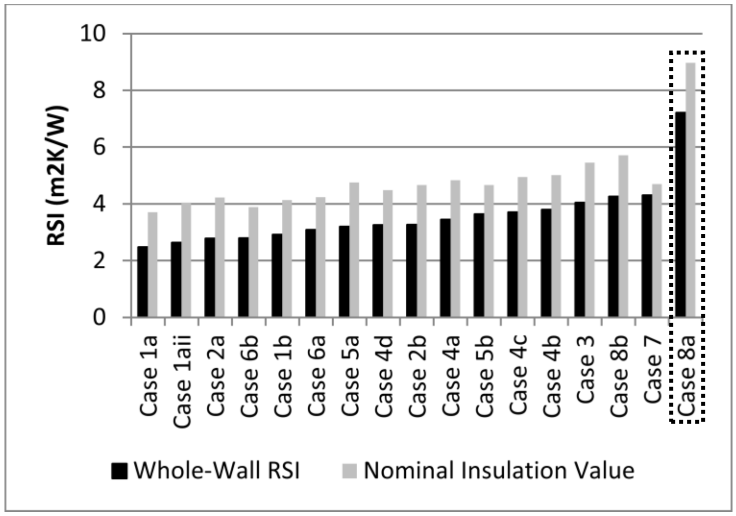


Figure P-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

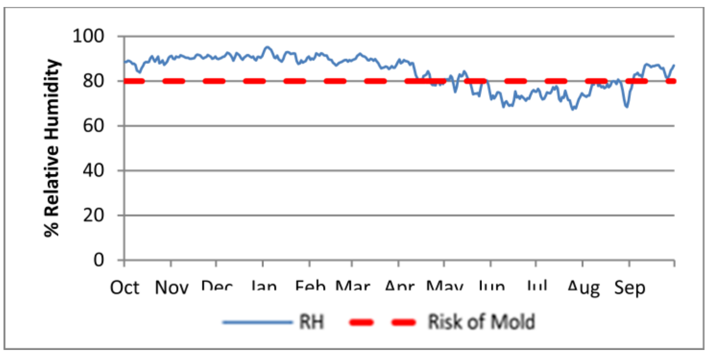


Figure P-3 Relative Humidity Inboard of Sheathing

Due to the use of foil-faced polyisocyanurate to the exterior and polyethylene to the interior, this wall traps moisture, which leads to extended periods at high relative humidity levels. Builders are cautioned against this type of construction.

Inward Vapour Drive Outboard of Vapour Retarder

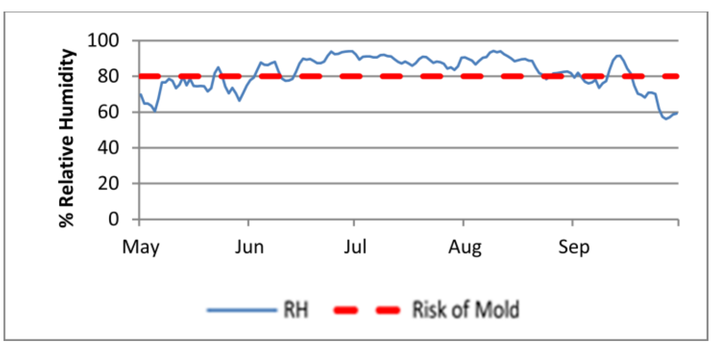


Figure P-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive also raises relative humidity levels above 80% frequently throughout the summer season. This is caused by the trapped moisture within the wall assembly. This approaches questionable moisture safety, caution is recommended.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure P-5. This envelope design requires careful air barrier detailing.

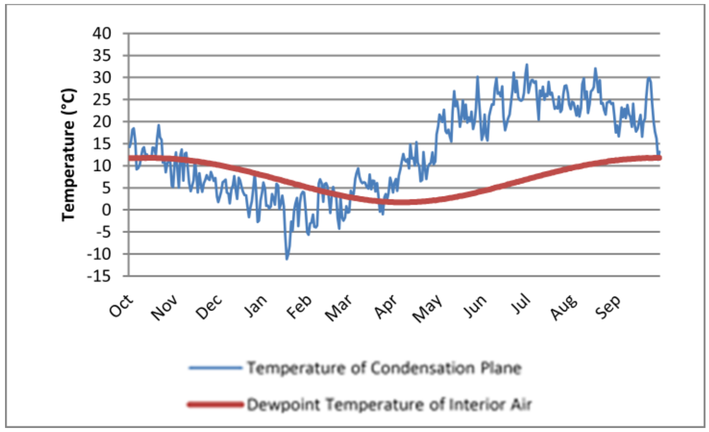


Figure P-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis

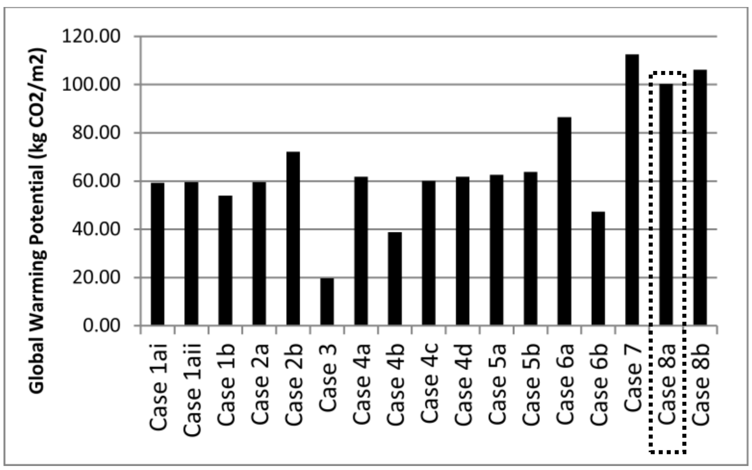


Figure P-1 Global Warming Potential per Square Meter

With large amounts of mineral wool insulation, case 8a's global warming potential is modeled at 100.36 kg CO_2 eq./m^2. Although wood siding is used, avoiding the use of brick, the volume of mineral wool insulation dwarfs the effects of the other contributing assembly components in terms of global warming potential.

Cost Analysis

At a cost of $252.08, Case 8a has an upper-mid range cost per square meter. Double stud framing and large amounts of insulation contribute to the high costs.

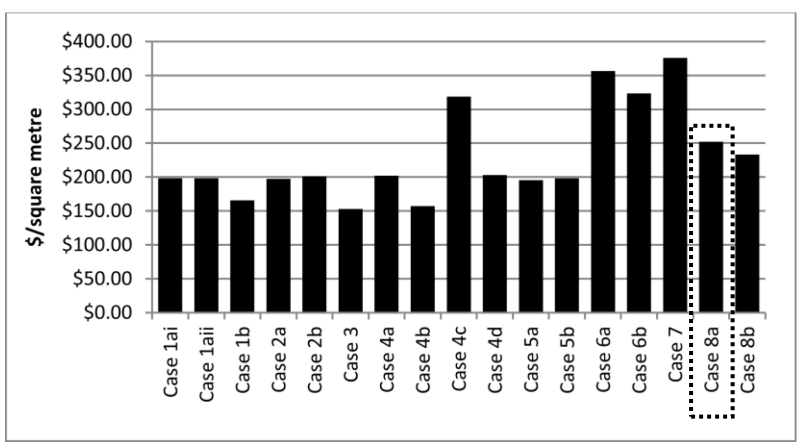


Figure P-7 Costs of Wall Assemblies per Square Meter

Appendix Q - Case 8b

The principle features of Case 8a, as shown in Figure Q-1, are double stud construction with expanded polystyrene spacers, mineral wool insulation, OSB sheathing, foil-faced polyisocyanurate insulated sheathing and wood siding. The nominal RSI value of this wall is 5.71, which exceeds the demands of compliance packages B and C.

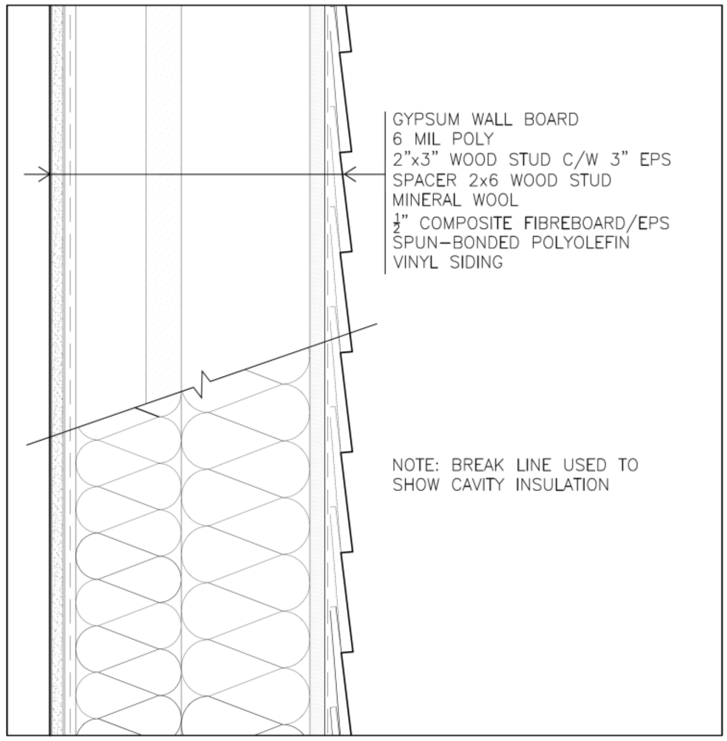


Figure Q-1 Wall Assembly Cross-Section (Twiddy, 2011)

Table Q-1 Summary of Results

Analysis Description			Days over RH%	ASHRAE pass/fail
Moisture Safety	RH outboard of sheathing	>80%	2	P
		>98%	0	P
		>100%	0	P
	Inward vapour drive	>80%	0	P
		>98%	0	P
		>100%	0	P
	Condensation plane - Risk of condensation		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	4.39	
		Rim joist section	3.80	
		Top plate	4.56	
		Whole-wall	4.26	
	Nominal RSI		5.71	
	Whole Wall RSI Deviation from nominal RSI		-25%	
Env. Impact	Kg CO2 eq./sq. Meter		106.14	
Cost	$/sq.meter		**$233.32**	

Heat Transfer

Highlighted in the black dotted line in Figure Q-2, Case 8b is an upper mid-range performer in terms of RSI values. The double stud construction, and composite fibreboard/EPS insulated sheathing reduce the thermal bridging effect, resulting in a deviation of 25% from its nominal value.

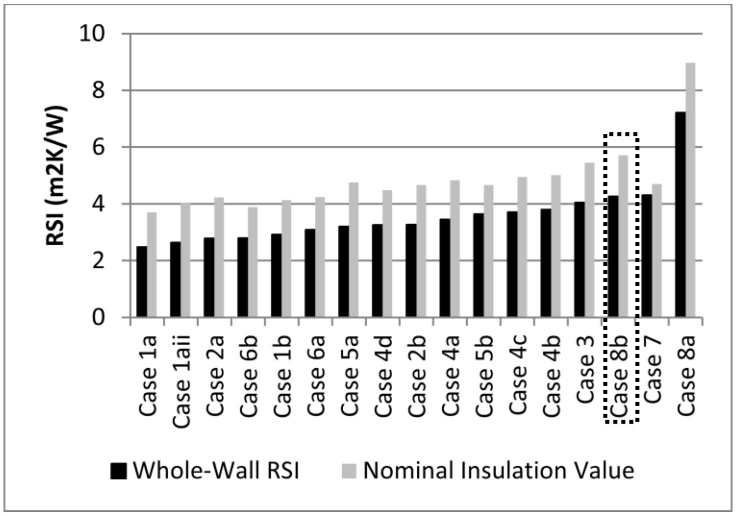


Figure Q-2 Whole-Wall and Nominal RSI Values

Outward Vapour Drive (All Year)

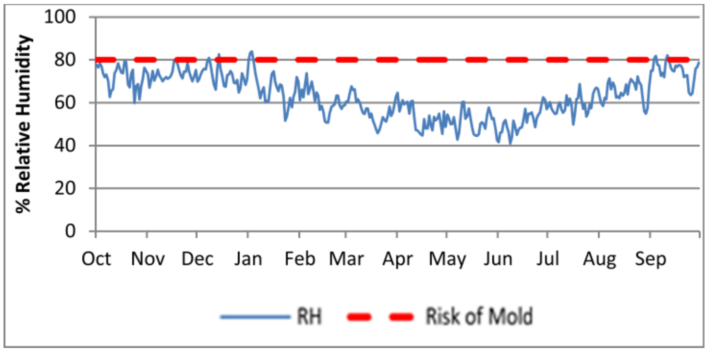


Figure Q-3 Relative Humidity Inboard of Sheathing

Outward vapour drive causes some spikes over 80% relative humidity at the inboard face of the sheathing. This is due to the resistance to vapour diffusion of the composite insulated sheathing. These spikes are of short duration and do not present significant risk of moisture damage.

Inward Vapour Drive Outboard of Vapour Retarder

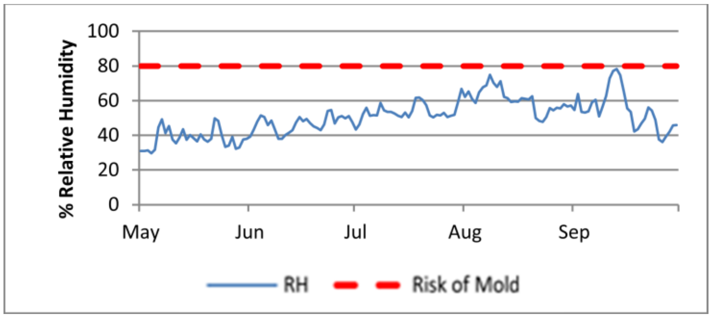


Figure Q-4 Relative Humidity Outboard of Polyethylene

Warm weather inward vapour drive is not an issue with this wall assembly configuration. Relative humidity levels are consistently below 80% and no evidence exists of hygrophilic cladding generating extreme inward vapour drive.

Temperature of Condensation Plane

The condensing plane temperatures are clearly below interior air dew point temperatures during winter months, as is evident in Figure Q-5. This envelope design requires careful air barrier detailing.

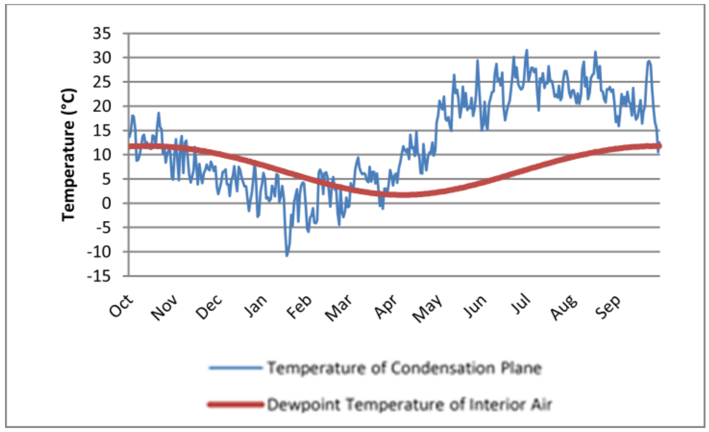
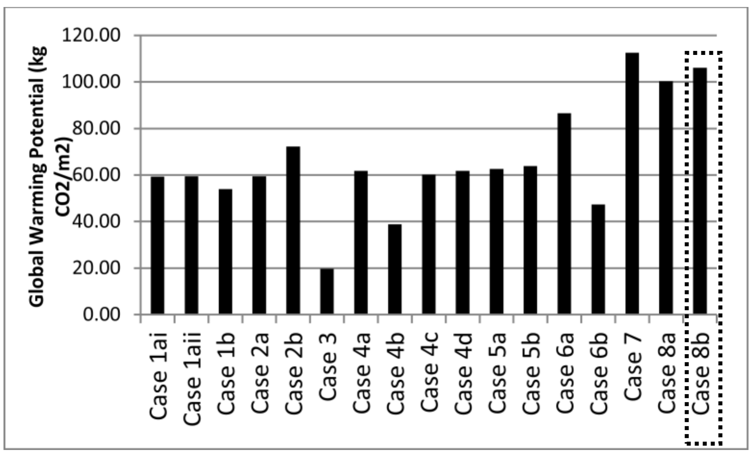


Figure Q-5 Dew Point and Sheathing Surface Temperature

Global Warming Potential Analysis



Having one of the heaviest environmental burden, Case 8b's global warming potential is modeled at 106.14 kg CO2 eq./m^2. The standard framing, use of mineral wool and expanded polystyrene contribute to the high GWP results.

Figure Q-6 Global Warming Potential per Square Meter

Cost Analysis

At a cost of $233.32, Case 8b has a mid-range cost per square meter. Large amounts of insulation and standard framing account for these results.

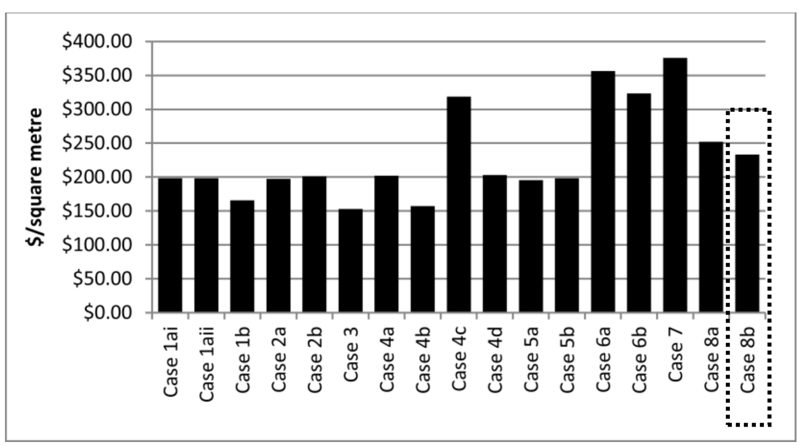


Figure Q-7 Costs of Wall Assemblies per Square Meter

Appendix R - Research Summary Data

Table R-1 Summary of Research Data

			Wall Assembly Summary																																		
			1ai		1aii		Case 1b		Case 2a		Case 2b		Case 3		Case 4a		Case 4b		Case 4c		Case 4d		Case 5a		Case 5b		Case 6a		Case 6b		Case 7		Case 8a		Case 8b	
Criterion	Analysis Description	Case #	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE	Daily Avg	ASHRAE
Hygrothermal	RH outboard of sheathing	<80%	6	P	2	P	1	P	2	P	1	P	9	F	16	F	15	F	2	P	1	P	**45**	**F**	**45**	**F**	2	P	3	3	0	P	**42**	**F**	2	P
		<98%	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	10	F	4	F	0	P	0	0	0	P	0	P	0	P
		<100%	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	0	0	P	0	P	0	P
	Inward vapour drive	<80%	9	F	0	P	2	P	3	P	2	P	4	P	0	P	0	P	3	P	5	P	9	F	2	P	3	P	0	0	0	P	70	F	0	P
		<98%	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	0	0	P	0	P	0	P
		<100%	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	P	0	0	0	P	0	P	0	P
	Risk of condensation		High		High		High		High		High		High		High		High		High		High		High		High		High		High		Low		High		High	
Heat Transfer	Whole Wall RSI Analysis	Wall section	2.48		2.66		3.12		2.81		3.34		4.08		3.47		4.00		3.70		3.26		3.18		3.77		3.16		2.90		4.70		7.89		4.39	
		Rim joist section	2.61		2.70		2.73		2.84		3.33		4.06		3.51		3.59		3.84		3.32		3.35		3.51		2.79		2.42		2.84		5.32		3.80	
		Top plate	2.20		2.31		2.31		2.49		2.75		3.77		3.20		3.25		3.43		3.03		3.02		3.23		3.31		2.92		3.78		7.84		4.56	
		Whole-wall	2.48		2.63		2.92		2.78		3.27		4.04		3.45		3.8		3.7		3.25		3.2		3.64		3.09		2.79		4.3		7.21		4.26	
	Nominal RSI		3.71		4.04		4.13		4.22		4.66		5.45		4.83		5.01		4.94		4.48		4.75		4.66		4.23		3.88		4.7		8.97		5.71	
	Deviation from nominal RSI		-33%		-35%		-29%		-34%		-30%		-26%		-29%		-24%		-25%		-27%		-33%		-22%		-27%		-28%		-9%		-20%		-25%	
Environmental Impact	Kg CO2 eq./sq. Meter		59.29		59.51		53.95		59.51		72.20		19.647536		61.74		38.83		58.00		61.74		62.60		63.81		86.5		47.33		112.60		100.36		106.14	
Cost	$/sq.meter		$198.40		$198.15		165.85		$197.59		$219.77		$153.12		$201.85		$157.28		$305.32		$202.97		$182.34		202.13		$343.22		$302.33		$305.95		$252.08		$233.32	
Overall Normalized Score			N/A		**0.16**		**0.31**		**0.18**		**0.24**		**1.00**		**0.23**		**0.57**		**0.14**		**0.26**		**0.07**		**0.10**		**0.00**		**0.07**		**0.09**		**0.00**		**0.20**	

Appendix S - Vapour Diffusion Resistance Factor Calculations

Table S-1 Vapour Diffusion Resistance Factor Calculations

Product	Perms	Permeance (SI)	Thickness	VDRF
6 mil poly	0.06		0.001	54666.67
Foil facing	0.06		0.001	54666.67
Roxul	6.00	1895.00	0.14	3.90
Icynene	2.00		0.14	11.71
Comp BP	3.50	200.00	0.03	32.77
1" cladmate	3.50		0.03	36.90
7/16" aspenite	7.00	105.00	0.01	42.17
Excel II	5.00	856.00	0.01	51.65
Type II EPS (1")	5.25	200.00	0.03	24.60
BP Airgard	350.00	6.10	0.00	9.37
Building paper	3.70	230.00	0.00	886.49
Brick	3.50	191.00	0.09	10.53
Codebord	0.85	45.00	0.03	151.92
Durock Vapour Block	0.26	15.00	0.00	7851.34
Durock Finish Coat	2.98	170.00	0.00	274.94
Dens Glass	23.00		0.01	11.41
Durex Stonetex	14.65	835.00	0.00	149.27
Durock Adhesive Plus	5.61	320.00	0.00	368.03
Cement Bear	3.35	191.00	0.00	489.42
prepcoat	5.61	320.00	0.00	292.13
fringe	2.98	170.00	0.00	549.88
airless paint	2.98	170.00	0.00	549.88

Appendix T - Nominal Thermal Resistance Calculations

Table T-1 Nominal Thermal Conductivity Calculations

Name	Stud Size	Gypsum R	Stud Insulation	Ext Ins	Other R	Total R	Total RSI
Saugeen	2X3+3"+2X6	Gypsum	2x R22 Roxul	1" Polyiso board	7/16" OSB		
Case 8a		0.45	44	6	0.51	50.96	8.974991
Habitat Keswick	2x3+1"+2x4	Gypsum	R28 Roxul	Comp BP R4 (BP Canada)			0
Case 8b		0.45	28	4		32.45	5.715041
Sean Mason (next gen)	2x6 24"	Gypsum	BIB	1" codeboard			0
Case 4b		0.45	23	5		28.45	5.010567
Sean Mason (now)	2x6 24"	Gypsum	BIB	5/16 osb			0
Case 1bii		0.45	23	0		23.45	4.129975
Marshall	2x6	Gypsum	R22 Fibreglass	Excel II (BP Canada)			0
Case 2a		0.45	22	1.5		23.95	4.218035
Empire	2x6	Gypsum	R22 Roxul	Comp BP R4 (BP Canada)			0
Case 2b		0.45	22	4		26.45	4.65833
Garden Homes	2x6	Gypsum	R22 Fibreglass	3/4" Polyiso (R4.5)			0
Case 5a		0.45	22	4.5		26.95	4.74639
Geertsma ES	2x6 24"	Gypsum	R20 fibreglass	1" Energy Shield			0
Case 5b		0.45	20	6		26.45	4.65833
Rodeo	2x6	Gypsum	5.5" @ R3.75/inch	1.4" Cladmate			0
Case 4c		0.45	20.625	7		28.075	4.944523
Royal Pine	2x6	Gypsum	R19 Fibreglass	1" Cladmate			0
Case 4d		0.45	20	5		25.45	4.482212
Helicon	2x6	Gypsum	equivalent R14	1" codeboard			0
Case 4a		0.45	22	5		27.45	4.834449
FastForm	N/A	Gypsum	6" 20mPa Concrete	2x 2-5/8" EPS			0
Case 7		0.45		26.25		26.7	4.70236
Geertsma OSB	2x6 24"	Gypsum	R20 fibreglass	7/16 OSB			0
Case 1bi		0.45	20	0.51		20.96	3.691441
Dalerose	2x6	Gypsum	R22 fibreglass	7/16" OSB			0
Case 1aii		0.45	22	0.51		22.96	4.043677
Fifthshire 1.5" Clad	18 gauge steel	Gypsum	1/2lb foam	1.5" cladmate			0
Case 6a		0.45	13.59375	7.5		21.54375	3.79425
Fifthshire 2"Clad	18 gauge steel	Gypsum	1/2lb foam	2" CLAD			0
Case 6b		0.45	13.59375	10		24.04375	4.234546
Fifthshire EIFS	18 gauge steel	Gypsum	1/2lb foam	2" EPS			0

Case 6c		0.45	13.59375	8		22.04375	3.882309
Royal Park	2x6	Gypsum	R22 Fibreglass	7/16" aspenite	2" EPS		0
Case 3		0.45	22	0.51	8	30.96	5.452624
Standard		Gypsum		1/2" OSB			0
Case 1ai		0.45	20	0.62		21.07	3.710814

Appendix U - Thermal Conductivity Calculations

Table U-1 Thermal Conductivity Calculations

Name	Thickness	RSI	R-Value	mm	RSI/25mm	R/Inch	C-value	RSI	k-value	k-value
Gypsum Board	12.5								0.160	
Studs									0.120	
Steel									43.000	
Icynene	0.14				0.65			3.58	0.039	
Low density fibreglass	0.14							3.52	0.040	
High density fibreglass	0.14							3.87	0.036	
Blow in blanket	5.5		23	0.13				4.05		0.034
Roxul batt	0.14				0.74			4.07	0.034	
Excel II	0.0127							0.26	0.049	
Comp BP	0.0286		4	28.6				0.70	0.041	
Cladmate	0.0254		5					0.88	0.029	
Codebord	0.0254		5					0.88	0.029	
EPS			3.71	0.0254				0.65	0.039	
Energy Shield	0.0254		6					1.05	0.024	
OSB									.08-.11	
Plywood									.09-.12	

Appendix V - Therm Modeling Images

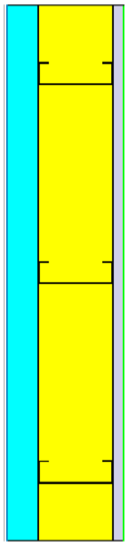


Figure V-1 Steel Framing Case 6a

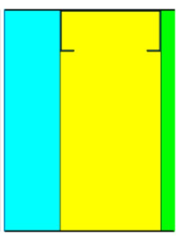


Figure V-2 Steel Framing Top Plate Section Case 6a

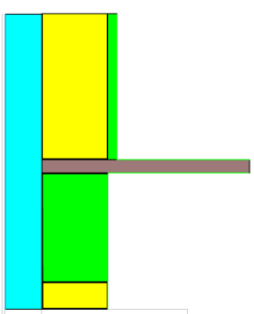


Figure V-3 Steel Framing Rim Joist Section Case 6a

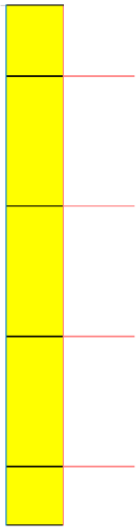


Figure V-4 Steel Framing Floor Joist Plan Case 6a

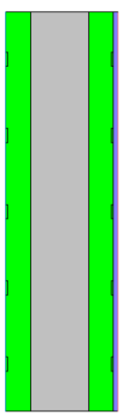


Figure V-5 ICF Wall Section Case 7

Figure V-6 ICF Top Plate Section Case 7

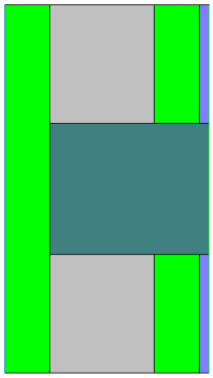


Figure V-7 ICF Rim Joist Section Case 7

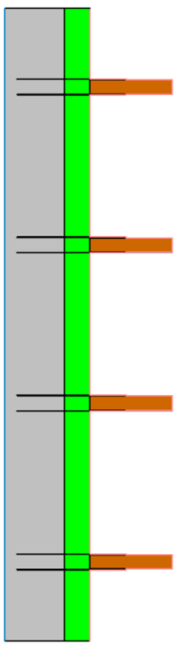


Figure V-8 ICF Floor Joist Plan Case 7

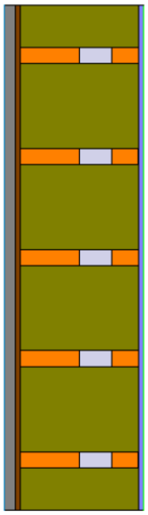


Figure V-9 Double Stud Wall Section Case 8a

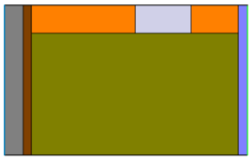


Figure V-10 Double Stud Wall Top Plate Section Case 8a

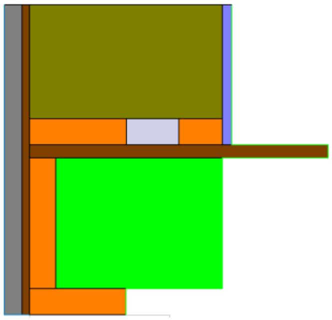


Figure V-11 Double Stud Wall Rim Joist Section Case 8a

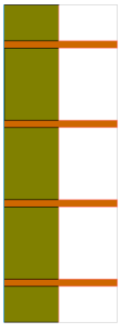


Figure V-12 Double Stud Wall Floor Joist Plan Case 8a

Appendix W - Athena Modeling Comparisons

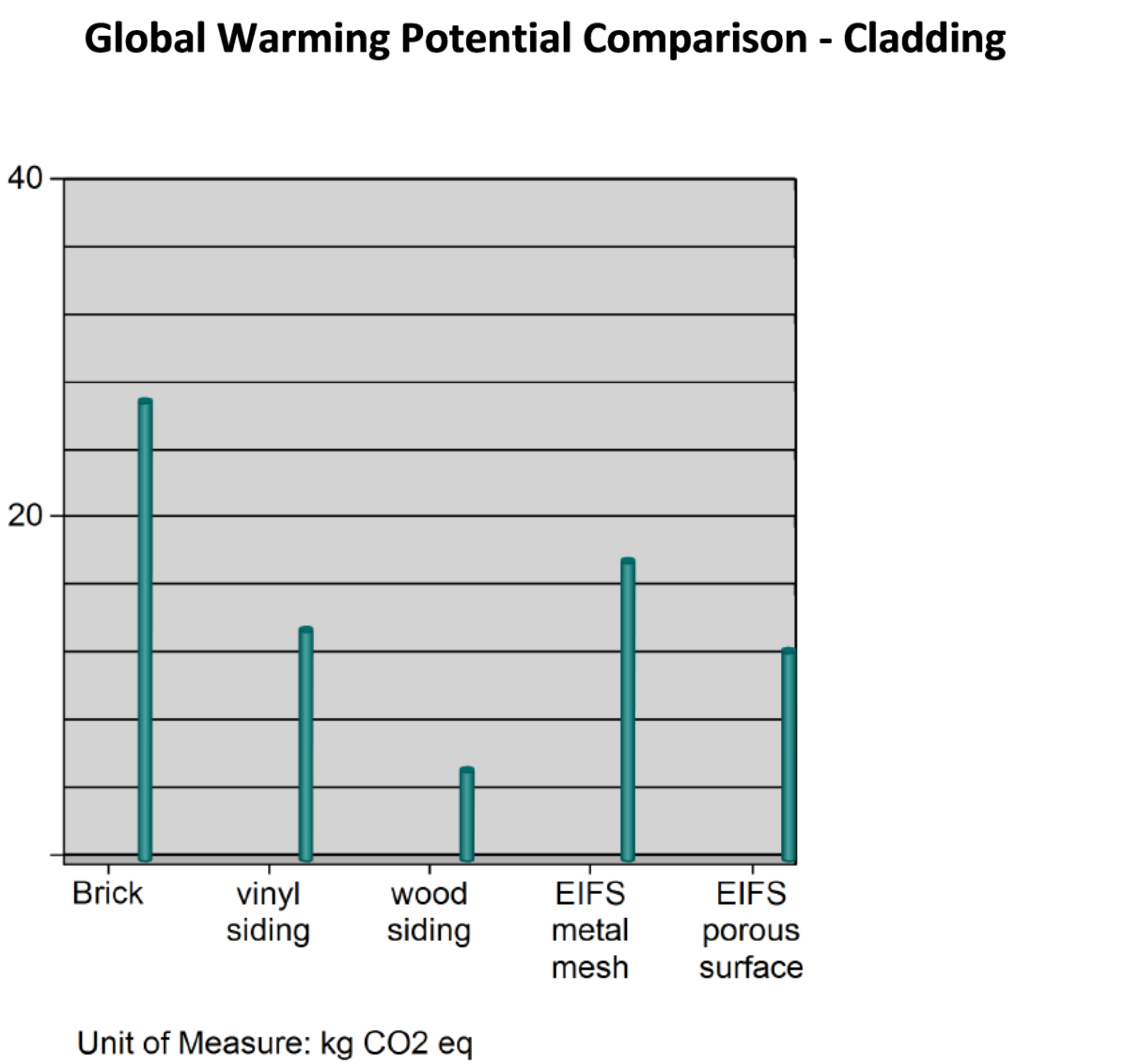


Figure W-1 Athena - Cladding Comparison GWP

Global Warming Potential Comparison - Insulation

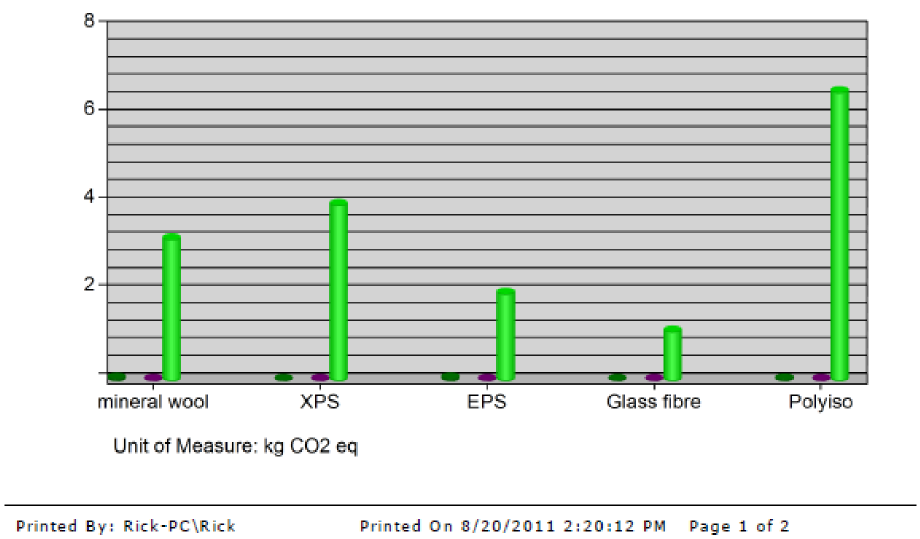


Figure W-2 Athena - Insulation Comparison GWP

Appendix X - RS Means Costing Data

Table X-1 Case 1ai

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 1AI							
Div. 070000 Thermal and Moisture Protection							
1. Vapour Retarder							
.1) 6mil Poly				**2314**	**sf**		**$44.47**
2. Blanket Insulation							
.1) Batt Insulation R19				**1733**	**sf**		**$1,611.69**
3. Weather Barrier							
.1) House Wrap Spun bound				**2314**	**sf**		**$624.78**
Div. 060000 Wood Plastics and Composites							
1. Plates; sp#2 ***- included in 2. Studs***							
.1) Exterior; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				**0.37**	**mbfm**		**$666.98**
061600 Sheathing							
4. Sheating							
.1) 7/16" Aspenite				**2314**	**sf**		**$2,290.86**
Div. 040000 Masonry							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
040523-Accessories							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				**259**	**f**		**$752.67**
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				**115**	**f**		**$2,163.30**
090000 Finishes							
1. Drywall							
.1) GWB Finish				**2314**	**sf**		**2871.21**
SUBTOTAL							**$42,654.95**
PER SF TOTAL (SUBTOTAL / 2314 SF)							**$18.43**
PER SM TOTAL (SUBTOTAL / 215 SM)							**$198.40**

Case 1aii

Table X-2

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 1AII							
Div. 070000 Thermal and Moisture Protection							
1. Vapour Retarder							
.1) 6mil Poly				**2314**	**sf**		**$44.47**
2. Blanket Insulation							
.1) Batt Insulation R22				**1733**	**sf**		**$1,559.70**
3. Weather Barrier							
.1) House Wrap Spun bound				**2314**	**sf**		**$624.78**
Div. 060000 Wood Plastics and Composites							
1. Plates; sp#2 ***- included in 2. Studs***							
.1) Exterior; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				**0.37**	**mbfm**		**$666.98**
061600 Sheathing							
4. Sheating							
.1) 7/16" Aspenite				**2314**	**sf**		**$2,290.86**
Div. 040000 Masonry							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
040523-Accessories							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				**259**	**f**		**$752.67**
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				**115**	**f**		**$2,163.30**
090000 Finishes							
1. Drywall							
.1) GWB Finish				**2314**	**sf**		**2871.21**
SUBTOTAL							**$42,602.96**
PER SF TOTAL (SUBTOTAL / 2314 SF)							**$18.41**
PER SM TOTAL (SUBTOTAL / 215 SM)							**$198.15**

Case 1b

Table X-3

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 1B							
Div. 070000 Thermal and Moisture Protection							
1. Vapour Retarder							
.1) 6mil Poly				**2314**	**sf**		**$44.47**
2. Insulation							
.1) Blown Insulation				**1733**	**sf**		**$2,596.94**
3. Weather Barrier							
.1) House Wrap Spun bound				**2314**	**sf**		**$624.78**
Div. 060000 Wood Plastics and Composites							
1. Plates; sp#2 ***- included in 2. Studs***							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				**270**	**lf**		**$9,296.25**
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				**0.23**	**mbfm**		**$666.98**
061600 Sheathing							
4. Sheating							
.1) 5/8" OSB				**2314**	**sf**		**$4,304.04**
074633 Plastic Siding							
4. Plastic siding							
.1) Vynil Siding				**2314**	**sf**		**$15,253.66**
090000 Finishes							
1. Drywall							
.1) GWB Finish				**2314**	**sf**		**2871.21**
SUBTOTAL							**$35,658.33**
PER SF TOTAL (SUBTOTAL / 2314 SF)							**$15.41**
PER SM TOTAL (SUBTOTAL / 215 SM)							**$165.85**

Case 2a

TableX-4

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 2A									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Blanket Insulation									
.1) Batt Insulation R22						**1733**	**sf**		**$1,559.70**
3. Weather Barrier									
.1) Tuck tape						**7.5**	**ea**		**$106.78**
Div. 060000 Wood Plastics and Composites									
1. Plates; sp#2 ***- included in 2. Studs***									
.1) Exteriror; 38x140 (2"x6")									
2. Studs; sp#2									
.1) Exterior; 38x140 (2"x6")						**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2									
.1) 38x235x3660mm (2"x12"x12')						**0.23**	**mbfm**		**$666.98**
061600 Sheathing									
4. Sheating									
.1) BP Comp R4						**2314**	**sf**		**$2,687.71**
Div. 040000 Masonry									
040519-M. Anchorage and Reinf.									
1. Ties									
.1) Galv.Brick Ties									
2. Lintels									
.1) 90x90x6 Steel Lintels									
.2) 100x90x6 Steel Lintels									
040523-Accessories									
3. Accessories									
.1) Weep Holes									
.2) Galvanized Iron Flashing						**259**	**f**		**$752.67**
042100-Clay Unit Masonry									
.1) 90mm Brick Veneer						**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties									
lintels)									
044000-Stone Assemblies									
.1) Concrete Sills (100mm x 150mm)						**115**	**f**		**$2,163.30**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**2871.21**
SUBTOTAL									**$42,481.81**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$18.36**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$197.59**

Case 2b

Table X-5

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 2B							
Div. 070000 Thermal and Moisture Protection							
1. Vapour Retarder							
.1) 6mil Poly				**2314**	**sf**		**$44.47**
2. Blanket Insulation							
.1) Batt Insulation Roxul R22				**1733**	**sf**		**$1,830.05**
3. Weather Barrier							
.1) House Wrap Spun bound				**2314**	**sf**		**$624.78**
Div. 060000 Wood Plastics and Composites							
1. Plates; sp#2 ***- included in 2. Studs***							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				**0.37**	**mbfm**		**$666.98**
061600 Sheathing							
4. Sheating							
.1) BP Comp R4				**2314**	**sf**		**$2,687.71**
Div. 040000 Masonry							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
040523-Accessories							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				**259**	**f**		**$752.67**
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				**115**	**f**		**$2,163.30**
090000 Finishes							
1. Drywall							
.1) GWB Finish				**2314**	**sf**		**2871.21**
SUBTOTAL							**$43,270.16**
PER SF TOTAL (SUBTOTAL / 2314 SF)							**$18.70**
PER SM TOTAL (SUBTOTAL / 215 SM)							**$201.26**

Case 3

Table X-6

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 3							
<u>Div. 070000 Thermal and Moisture Protection</u>							
1. Vapour Retarder							
.1) 6mil Poly				**2314**	**sf**		**$44.47**
2. Blanket Insulation							
.1) Batt Insulation R22				**1733**	**sf**		**$1,559.70**
<u>Div. 060000 Wood Plastics and Composites</u>							
1. Plates; sp#2 ***- included in 2. Studs***							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				**0.23**	**mbfm**		**$666.98**
<u>061600 Sheathing</u>							
4. Sheating							
.1) 7/16" Aspenite				**2314**	**sf**		**$2,290.86**
.2) 2" EPS				**2314**	**sf**		**$3,980.08**
<u>090000 Finishes</u>							
1. Drywall							
.1) GWB Finish				**2314**	**sf**		**2871.21**
2.) Vapour block							
.1) Troweled				**2314**	**sf**		**$932.08**
3.) Exterior							
.1) Fibre mesh w/ finish coat				**357**	**sy**		**$18,073.40**
SUBTOTAL							**$36,593.77**
PER SF TOTAL (SUBTOTAL / 2314 SF)							**$15.81**
PER SM TOTAL (SUBTOTAL / 215 SM)							**$170.20**

Case 4a

Table X-7

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 4A									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Blanket Insulation									
.1) Batt Insulation R22						**1733**	**sf**		**$1,559.70**
3. Weather Barrier									
.1) House Wrap Spun bound						**2314**	**sf**		**$624.78**
Div. 060000 Wood Plastics and Composites									
1. Plates; sp#2 ***- included in 2. Studs***									
.1) Exterior; 38x140 (2"x6")									
2. Studs; sp#2									
.1) Exterior; 38x140 (2"x6")						**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2									
.1) 38x235x3660mm (2"x12"x12')						**0.37**	**mbfm**		**$666.98**
061600 Sheathing									
4. Sheating									
.1) 25mm XPS						**2314**	**sf**		**$3,085.02**
Div. 040000 Masonry									
040519-M. Anchorage and Reinf.									
1. Ties									
.1) Galv.Brick Ties									
2. Lintels									
.1) 90x90x6 Steel Lintels									
.2) 100x90x6 Steel Lintels									
040523-Accessories									
3. Accessories									
.1) Weep Holes									
.2) Galvanized Iron Flashing						**259**	**f**		**$752.67**
042100-Clay Unit Masonry									
.1) 90mm Brick Veneer						**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties									
lintels)									
044000-Stone Assemblies									
.1) Concrete Sills (100mm x 150mm)						**115**	**f**		**$2,163.30**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**2871.21**
SUBTOTAL									**$43,397.12**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$18.75**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$201.85**

Case 4b

Table X-8

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 4B							
Div. 070000 Thermal and Moisture Protection							
1. Vapour Retarder							
.1) 6mil Poly				2314	sf		$44.47
2. Insulation							
.1) Blown Insulation				1733	sf		$2,596.94
Div. 060000 Wood Plastics and Composites							
1. Plates; sp#2 *- included in 2. Studs*							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				270	lf		$9,296.25
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				0.23	mbfm		$666.98
061600 Sheathing							
4. Sheating							
.1) 25mm XPS				2314	sf		$3,085.02
074633 Plastic Siding							
4. Plastic siding							
.1) Vynil Siding				2314	sf		$15,253.66
090000 Finishes							
1. Drywall							
.1) GWB Finish				2314	sf		2871.21
SUBTOTAL							$33,814.53
PER SF TOTAL (SUBTOTAL / 2314 SF)							$14.61
PER SM TOTAL (SUBTOTAL / 215 SM)							$157.28

Case 4c

Table X-9

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 4C							
<u>Div. 070000 Thermal and Moisture Protection</u>							
1. Vapour Retarder							
.1) 6mil Poly				2314	sf		$44.47
2. Spray Insulation							
.1) 5.5" @ R3.75/inch R 21				1733	sf		$25,876.98
3. Weather Barrier							
.1) Bldg paper				2314	sf		$439.66
<u>Div. 060000 Wood Plastics and Composites</u>							
1. Plates; sp#2 *- included in 2. Studs*							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				3.18	mbfm		$6,174.99
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				0.23	mbfm		$666.98
<u>061600 Sheathing</u>							
4. Sheating							
.1) 1.4" Clademate				2314	sf		$4,071.48
<u>Div. 040000 Masonry</u>							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
<u>040523-Accessories</u>							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				259	f		$752.67
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				2314	sf		$25,454.00
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				115	f		$2,163.30
<u>090000 Finishes</u>							
1. Drywall							
.1) GWB Finish				2314	sf		2871.21
SUBTOTAL							$68,515.74
PER SF TOTAL (SUBTOTAL / 2314 SF)							$29.61
PER SM TOTAL (SUBTOTAL / 215 SM)							$318.68

Case 4d

Table X-10

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 4D									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Blanket Insulation									
.1) Batt Insulation R19						**1733**	**sf**		**$1,611.69**
3. Weather Barrier									
.1) Bldg paper						**2314**	**sf**		**$439.66**
Div. 060000 Wood Plastics and Composites									
1. Plates; sp#2 ***- included in 2. Studs***									
.1) Exteriror; 38x140 (2"x6")									
2. Studs; sp#2									
.1) Exterior; 38x140 (2"x6")						**3.18**	**mbfm**		**$6,174.99**
3. Lintels; sp#2									
.1) 38x235x3660mm (2"x12"x12')						**0.37**	**mbfm**		**$666.98**
061600 Sheathing									
4. Sheating									
.1) 1" Clademate						**2314**	**sf**		**$3,459.43**
Div. 040000 Masonry									
040519-M. Anchorage and Reinf.									
1. Ties									
.1) Galv.Brick Ties									
2. Lintels									
.1) 90x90x6 Steel Lintels									
.2) 100x90x6 Steel Lintels									
040523-Accessories									
3. Accessories									
.1) Weep Holes									
.2) Galvanized Iron Flashing						**259**	**f**		**$752.67**
042100-Clay Unit Masonry									
.1) 90mm Brick Veneer						**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties									
lintels)									
044000-Stone Assemblies									
.1) Concrete Sills (100mm x 150mm)						**115**	**f**		**$2,163.30**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**2871.21**
SUBTOTAL									**$43,638.40**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$18.86**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$202.97**

Case 5a

Table X-11

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 5A							
<u>Div. 070000 Thermal and Moisture Protection</u>							
1. Vapour Retarder							
.1) 6mil Poly				2314	sf		$44.47
2. Blanket Insulation							
.1) Batt Insulation R22				1733	sf		$1,559.70
3. Weather Barrier							
.1) Silver Tape				20.85	ea		$118.64
<u>Div. 060000 Wood Plastics and Composites</u>							
1. Plates; sp#2 *- included in 2. Studs*							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				3.18	mbfm		$6,174.99
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				0.23	mbfm		$666.98
<u>061600 Sheathing</u>							
4. Sheating							
.1) 3/4" Polyiso (R4.5)				2314	sf		$2,267.72
<u>Div. 040000 Masonry</u>							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
<u>040523-Accessories</u>							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				259	f		$752.67
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				2314	sf		$25,454.00
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				115	f		$2,163.30
<u>090000 Finishes</u>							
1. Drywall							
.1) GWB Finish				2314	sf		2871.21
SUBTOTAL							$42,073.68
PER SF TOTAL (SUBTOTAL / 2314 SF)							$18.18
PER SM TOTAL (SUBTOTAL / 215 SM)							$195.69

Case 5b

Table X-12

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 5B							
Div. 070000 Thermal and Moisture Protection							
1. Vapour Retarder							
.1) 6mil Poly				2314	sf		$44.47
2. Blanket Insulation							
.1) Batt Insulation R19				1733	sf		$1,611.69
3. Weather Barrier							
.1) House Wrap Spun bound				2314	sf		$624.78
Div. 060000 Wood Plastics and Composites							
1. Plates; sp#2 *- included in 2. Studs*							
.1) Exteriror; 38x140 (2"x6")							
2. Studs; sp#2							
.1) Exterior; 38x140 (2"x6")				3.18	mbfm		$6,174.99
3. Lintels; sp#2							
.1) 38x235x3660mm (2"x12"x12')				0.37	mbfm		$666.98
061600 Sheathing							
4. Sheating							
.1) 1" Polyiso (R4.5)				2314	sf		$2,267.72
Div. 040000 Masonry							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
040523-Accessories							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				259	f		$752.67
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				2314	sf		$25,454.00
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				115	f		$2,163.30
090000 Finishes							
1. Drywall							
.1) GWB Finish				2314	sf		2871.21
SUBTOTAL							$42,631.81
PER SF TOTAL (SUBTOTAL / 2314 SF)							$18.42
PER SM TOTAL (SUBTOTAL / 215 SM)							$198.29

Case 6a

Table X-13

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 6A									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Spray Insulation									
.1) 3 5/8" @ R3.75/inch R 14						**1733**	**sf**		**$11,386.85**
3. Weather Barrier									
.1) House Wrap Spun bound						**2314**	**sf**		**$624.78**
Div. 050000 Metals									
.1) 18 guage Struct. Studs						**270.2**	**lf**		**$27,195.63**
061600 Sheathing									
4. Sheating									
.1) 50mm XPS						**2314**	**sf**		**$6,170.04**
Div. 040000 Masonry									
040519-M. Anchorage and Reinf.									
1. Ties									
.1) Galv.Brick Ties									
2. Lintels									
.1) 90x90x6 Steel Lintels									
.2) 100x90x6 Steel Lintels									
040523-Accessories									
3. Accessories									
.1) Weep Holes									
.2) Galvanized Iron Flashing						**259**	**f**		**$752.67**
042100-Clay Unit Masonry									
.1) 90mm Brick Veneer						**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties									
lintels)									
044000-Stone Assemblies									
.1) Concrete Sills (100mm x 150mm)						**115**	**f**		**$2,163.30**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**2871.21**
SUBTOTAL									**$76,662.95**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$33.13**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$356.57**

Case 6b

Table X-14

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 6B									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Spray Insulation									
.1) 3 5/8" @ R3.75/inch R 14						**1733**	**sf**		**$11,386.85**
Div. 050000 Metals									
.1) 18 guage Struct. Studs						**270.2**	**lf**		**$27,195.63**
061600 Sheathing									
4. Sheating									
.1) Densglass						**2314**	**sf**		**$2,871.21**
.2) 50mm XPS						**2314**	**sf**		**$6,170.04**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**$2,871.21**
2.) Vapour block									
.1) Troweled						**2314**	**sf**		**$932.08**
3.) Exterior									
.1) Fibre mesh w/ finish coat						**357**	**sy**		**$18,073.40**
SUBTOTAL									**$69,544.89**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$30.05**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$323.46**

Case 7

Table X-15

Description	No.	Dimensions	Extensions	Quantity	Unit	Unit Price	Cost ($)
			Brought Forward from Page:				
CASE 7							
Div. 030000 Concrete							
1.) 6"- 20mPa Conc				**75**	**cm**		**$38,403.49**
061600 Sheathing							
4. Sheating							
.1) 2-5/8" EPS x2				**2314**	**sf**		**$11,107.20**
1. Vapour Retarder							
.1) 6mil Poly				**2314**	**sf**		**$44.47**
Div. 040000 Masonry							
040519-M. Anchorage and Reinf.							
1. Ties							
.1) Galv.Brick Ties							
2. Lintels							
.1) 90x90x6 Steel Lintels							
.2) 100x90x6 Steel Lintels							
040523-Accessories							
3. Accessories							
.1) Weep Holes							
.2) Galvanized Iron Flashing				**259**	**f**		**$752.67**
042100-Clay Unit Masonry							
.1) 90mm Brick Veneer				**2314**	**sf**		**$25,454.00**
(inc. Mortar & Waste Factors, Ties							
lintels)							
044000-Stone Assemblies							
.1) Concrete Sills (100mm x 150mm)				**115**	**f**		**$2,163.30**
090000 Finishes							
1. Drywall							
.1) GWB Finish				**2314**	**sf**		**2871.21**
SUBTOTAL							**$80,796.34**
PER SF TOTAL (SUBTOTAL / 2314 SF)							**$34.92**
PER SM TOTAL (SUBTOTAL / 215 SM)							**$375.80**

Case 8a

Table X-16

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 8A									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Blanket Insulation									
.1) Batt Insulation Roxul R22						**1733**	**sf**		**$1,830.05**
3. Weather Barrier									
.1) Tuck tape						**7.5**	**ea**		**$106.78**
4. Sheating									
.1) BP Comp R4					**x3**	**2314**	**sf**		**$8,063.13**
Div. 060000 Wood Plastics and Composites									
1. Plates; sp#2 ***- included in 2. Studs***									
.1) Exteriror; 38x140 (2"x6")									
2. Studs; sp#2									
.1) Exterior; 38x140 (2"x6")						**3.18**	**mbfm**		**$6,174.99**
3. Studs; sp#2									
.1) Partition; 38x100 (2"x4") Inc. Plates						**270.20**	**lf**		**5466.16**
4. Lintels; sp#2									
.1) 38x235x3660mm (2"x12"x12')						**0.23**	**mbfm**		**$666.98**
061600 Sheathing									
4. Sheating									
.1) 7/16" Aspenite						**2314**	**sf**		**$2,290.86**
.2) 1" Polyiso						**2314**	**sf**		**$2,429.70**
4. Ext. Finish									
.1) Wood fibre board (siding)						**2314**	**sf**		**24252.11**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**2871.21**
SUBTOTAL									**$54,196.44**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$23.42**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$252.08**

Case 8b

Table X-17

Description	No.	Dimensions			Extensions	Quantity	Unit	Unit Price	Cost ($)
					Brought Forward from Page:				
CASE 8B									
Div. 070000 Thermal and Moisture Protection									
1. Vapour Retarder									
.1) 6mil Poly						**2314**	**sf**		**$44.47**
2. Blanket Insulation									
.1) Batt Insulation Roxul R28						**1733**	**sf**		**$1,830.05**
3. Weather Barrier									
.1) House Wrap Spun bound						**2314**	**sf**		**$624.78**
Div. 060000 Wood Plastics and Composites									
3. Studs; sp#2									
.1) Part.& Struct.;38x100 (2"x4") Inc. Plates						**540.40**	**lf**		**$10,932.32**
3. Lintels; sp#2									
.1) 38x235x3660mm (2"x12"x12')						**0.23**	**mbfm**		**$666.98**
061600 Sheathing									
4. Sheating									
.1) BP Comp R4						**2314**	**sf**		**$2,687.71**
4. Ext. Finish									
.1) Wood fibre board						**2314**	**sf**		**$15,253.66**
074633 Plastic Siding									
4. Plastic siding									
.1) Vynil Siding						**2314**	**sf**		**$15,253.66**
090000 Finishes									
1. Drywall									
.1) GWB Finish						**2314**	**sf**		**2871.21**
SUBTOTAL									**$50,164.84**
PER SF TOTAL (SUBTOTAL / 2314 SF)									**$21.68**
PER SM TOTAL (SUBTOTAL / 215 SM)									**$233.32**

Appendix Y - Normalized Score Calculations

Table Y-1 Normalized Score Figures

Normalized U-Values	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	RSI	2.63	2.92	2.78	3.27	4.04	3.45	3.8	3.7	3.25	3.2	3.64	3.09	2.79	4.3	7.21	4.26
	U-Value	0.3802281	0.3424658	0.3597122	0.3058104	0.2475248	0.2898551	0.2631579	0.2702703	0.3076923	0.3125	0.2747253	0.3236246	0.3584229	0.2325581	0.1386963	0.2347418
	Score	1.00	0.84	0.92	0.69	0.45	0.63	0.52	0.54	0.70	0.72	0.56	0.77	0.91	0.39	0.00	0.40
Normalized GWP	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	GWP	59.51	53.95	59.51	72.20	19.65	61.74	38.83	60.11	61.74	62.60	63.81	86.50	47.33	112.60	100.36	106.14
	Score	0.43	0.37	0.43	0.57	0.00	0.45	0.21	0.44	0.45	0.46	0.48	0.72	0.30	1.00	0.87	0.93
Normalized Costs	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	Cost	$198.15	165.85	$197.59	$201.00	$153.12	$201.85	$157.28	$305.32	$202.97	$182.34	202.13	$343.22	$302.33	$305.95	$252.08	$233.32
	Score	0.24	0.07	0.23	0.25	0.00	0.26	0.02	0.80	0.26	0.15	0.26	1.00	0.78	0.80	0.52	0.42
Normalized Days over 80% RH	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	Outward	2	1	2	1	9	16	15	2	1	45	45	2	3	0	42	2
	Inward	1	2	3	2	4	0	0	3	5	9	2	3	0	0	70	0
	Norm. Out	0.04	0.02	0.04	0.02	0.20	0.36	0.33	0.04	0.02	1.00	1.00	0.04	0.07	0.00	0.93	0.04
	Norm. In	0.01	0.03	0.04	0.03	0.06	0.00	0.00	0.04	0.07	0.13	0.03	0.04	0.00	0.00	1.00	0.00
	Average Out/In	0.03	0.03	0.04	0.03	0.13	0.18	0.17	0.04	0.05	0.56	0.51	0.04	0.03	0.00	0.97	0.02
	Overall Days over 80%	0.03	0.03	0.05	0.03	0.13	0.18	0.17	0.05	0.05	0.58	0.53	0.05	0.03	0.00	1.00	0.02
Overall Normalized Score	Normalized scores with weighting	6.6646	5.1656	6.3525	5.7611	2.603	5.8994	3.7717	6.8059	5.6005	7.8644	7.351	9.3469	7.8826	7.6145	9.2421	6.1698
	Inversed weighted scores	0.15	0.1936	0.1574	0.1736	0.3842	0.1695	0.2651	0.1469	0.1786	0.1272	0.136	0.107	0.1269	0.1313	0.1082	0.1621
	Overall Scores	**0.16**	**0.31**	**0.18**	**0.24**	**1.00**	**0.23**	**0.57**	**0.14**	**0.26**	**0.07**	**0.10**	**0.00**	**0.07**	**0.09**	**0.00**	**0.20**

Appendix Z - Builder's Questionnaire

Ryerson University Best Wall Study in Association with John Godden from Clearsphere

By filling out this form, you will be helping to ensure the best quality data for the analysis in this project.

What is your name and company affiliation?
i.e. Jim Smith; Excellent Homes Inc.

What is your contact information?
i.e. Jjsmith@excellenhomes; (647) 354-1324

Please describe the cladding used in your wall assembly
Please include product name

Please indicate if you use housewrap or building paper as a weather barrier
If other, please indicate the product name and if this is a combined barrier system i.e. weather/air barrier

Please describe the sheathing, insulated sheathing or exterior insulation used in your wall assembly
please include product name and R-value

Please describe the framing used in your exterior wall assembly

Please describe the cavity insulation used in your exterior wall assembly
please include product name and R-value

Please describe the interior finish used in your exterior wall assembly

Please indicate the cost per square foot of cladding used in the wall described above
Where possible, break down the price in terms of labour, material and other costs

Please indicate the cost per square foot of housewrap or building paper used in the wall described above
Where possible, break down the price in terms of labour, material and other costs

Please indicate the cost per square foot of sheathing, insulated sheathing or exterior insulation used in the wall described above
Where possible, break down the price in terms of labour, material and other costs

Appendix Z – Category Weighting Questionnaire

Please indicate the cost per square foot of the framing used in the wall described above
Where possible, break down the price in terms of labour, material and other costs

Please indicate the cost per square foot of the cavity insulation used in the wall described above
Where possible, break down the price in terms of labour, material and other costs

Please indicate the cost per square foot of the 6 mil poly used in the wall described above
Where possible, break down the price in terms of labour, material and other costs

Please indicate from 1 to 5, your opinion of how cost should be weighted in determining th 'best wall'
1 is of low priority; 5 is highest priority

1

Please indicate from 1 to 5, your opinion of how moisture safety should be weighted in determining the 'best wall'
1 is of low priority; 5 is highest priority

1

Please indicate from 1 to 5, your opinion of how thermal efficiency should be weighted in determining the 'best wall'

Please indicate from 1 to 5, your opinion of how thermal efficiency should be weighted in determining the 'best wall'

1 is of low priority; 5 is highest priority

1

Please indicate from 1 to 5, your opinion of how environmental impact should be weighted in determining the 'best wall'

1 is of low priority; 5 is highest priority

1

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Figure Z-1 Builder's Questionnaire

Appendix AA – Overall Normalizing Scoring Results

Table AA-1 Overall Normalized Scoring Results

Normalized U-Values	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	RSI	2.63	2.92	2.78	3.27	4.04	3.45	3.8	3.7	3.25	3.2	3.64	3.09	2.79	4.3	7.21	4.26
	U-Value	0.380228	0.342466	0.359712	0.30581	0.247525	0.289855	0.263158	0.27027	0.307692	0.3125	0.274725	0.323625	0.358423	0.232558	0.138696	0.234742
	Score	**1.00**	**0.84**	**0.92**	**0.69**	**0.45**	**0.63**	**0.52**	**0.54**	**0.70**	**0.72**	**0.56**	**0.77**	**0.91**	**0.39**	**0.00**	**0.40**
Normalized GWP	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	GWP	59.51	53.95	59.51	72.20	19.65	61.74	38.83	60.11	61.74	62.60	63.81	86.50	47.33	112.60	100.36	106.14
	Score	**0.43**	**0.37**	**0.43**	**0.57**	**0.00**	**0.45**	**0.21**	**0.44**	**0.45**	**0.46**	**0.48**	**0.72**	**0.30**	**1.00**	**0.87**	**0.93**
Normalized Costs	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	Cost	**$198.15**	$165.85	**$197.59**	**$201.00**	**$153.12**	**$201.85**	**$157.28**	**$305.32**	**$202.97**	**$182.34**	$202.13	**$343.22**	**$302.33**	**$305.95**	**$252.08**	**$233.32**
	Score	**0.24**	**0.07**	**0.23**	**0.25**	**0.00**	**0.26**	**0.02**	**0.80**	**0.26**	**0.15**	**0.26**	**1.00**	**0.78**	**0.80**	**0.52**	**0.42**
Normalized Days over 80% RH	Case #	Case 1aii	Case 1b	Case 2a	Case 2b	Case 3	Case 4a	Case 4b	Case 4c	Case 4d	Case 5a	Case 5b	Case 6a	Case 6b	Case 7	Case 8a	Case 8b
	Outward	2	1	2	1	9	16	15	2	1	**45**	**45**	2	3	0	**42**	2
	Inward	9	2	3	2	4	0	0	3	5	9	2	3	0	0	70	0
	Norm. Out	0.04	0.02	0.04	0.02	0.20	0.36	0.33	0.04	0.02	1.00	1.00	0.04	0.07	0.00	0.93	0.04
	Norm. In	0.01	0.03	0.04	0.03	0.06	0.00	0.00	0.04	0.07	0.13	0.03	0.04	0.00	0.00	1.00	0.00
	Average Out/In	0.03	0.03	0.04	0.03	0.13	0.18	0.17	0.04	0.05	0.56	0.51	0.04	0.03	0.00	0.97	0.02
	Overall Days over 80%	**0.03**	**0.03**	**0.05**	**0.03**	**0.13**	**0.18**	**0.17**	**0.05**	**0.05**	**0.58**	**0.53**	**0.05**	**0.03**	**0.00**	**1.00**	**0.02**
Overall Normalized Score	Normalized scores with weighting	6.66	5.17	6.35	5.76	2.60	5.90	3.77	6.81	5.60	7.86	7.35	9.35	7.88	7.61	9.24	6.17
	Inversed weighted scores	0.15	0.19	0.16	0.17	0.38	0.17	0.27	0.15	0.18	0.13	0.14	0.11	0.13	0.13	0.11	0.16
	Overall Scores	**0.16**	**0.31**	**0.18**	**0.24**	**1.00**	**0.23**	**0.57**	**0.14**	**0.26**	**0.07**	**0.10**	**0.00**	**0.07**	**0.09**	**0.00**	**0.20**

References

ASHRAE. (2008). ASHRAE standard 160P-criteria for moisture control design analysis in buildings, *American Society of Heating and Refrigeration Engineers.*

ATHENA Institute. (Undated). ATHENA Impact Estimator for Buildings*. Retrieved June 11, 2011, from* http://www.athenasmi.ca/tools/docs/ImpactEstimatorFactSheet.pdf

Bare, J., & Gloria, T. (2005, November). Life cycle impact assessment for the building design and construction industry. *Building Design and Construction.* Retrieved May 25, 2011, from http://www.dcat.net/workshoptoolkit/Workshop_Toolkit/White_Papers_files/bdc0511LCIApaper.pdf

Black, C. D. (2006). *Mould resistance of full scale wood frame wall assemblies.* Unpublished master's thesis. University of Waterloo, Waterloo, Canada.

Bomberg, M., & Onysko, D. (2002). Heat, air and moisture control in walls of Canadian houses: A review of the historic basis for current practices*. Journal of Thermal Envelope and Building Science, 2*6(1), 3-31.

Bribian, I. Z., Capilla, A. V., & Uson, A. A. (2010). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential*. Building and Environment, 46*

Brown, W. C., Roppel, P., & Lawton, M. (2007), Developing a design protocol for low air and vapour permeance insulating sheathing in cold climates. *Buildings X Conference*, Dec. 2-7, 2007. Atlanta, Ga.

Buildinggreen.com. (2009). *Polystyrene insulation: Does it belong in a green building?* Retrieved July 9, 2011, from http://www.buildinggreen.com/auth/article.cfm/2009/7/30/Polystyrene-Insulation-Does-It-Belong-in-a-Green-Building/

Buildinggreen.com. (2009). *Restrictions on widely used chemicals sought*. Retrieved July, 11, 2011, from http://www.buildinggreen.com/auth/article.cfm/2009/6/30/Restrictions-on-Widely-Used-Chemicals-Sought/

Buxbaum, C., & Heiduk, E. (2008). *PH-CALCULATION – dynamic simulation with WUFI [PowerPoint slides in pdf form].* Retrieved from http://www.nachhaltigwirtschaften.at/hdz_pdf/0812_ph-summerschool_03_04_ph_calculation_wufi.pdf

Canadian Mortgage and Housing Corporation. (2007, Understanding vapour permeance and condensation in wall assemblies. *CMHC Research Highlights,* (Technical Series 07-123)

Carmody, J., & Trusty, W. (2005). *Implications.* Retrieved July/13, 2011, from http://www.informedesign.org/_news/mar_v05r-p.pdf

Carpenter, S. C., & Schumacher, C. (2003). Characterization of framing factors for wood-framed low-rise residential buildings. *ASHRAE Winter Meetings CD, Technical and Symposium Papers, 200*3 103-110.

Centre for Window and Cladding Technology*. Comparision of widely available simulation software*. Retrieved July, 11, 2011, from http://www.cwct.co.uk/thermal/software/software.htm

Cole, R.,J., & Larsson, N. (1997). Green building challenge '98. Paper presented at the *Proceedings of CIB 2nd International Conference on Buildings & the Environment,* Paris, France. *,* 1 19.

Burnett, J. (2006). *Forestry commission Scotland greenhouse gas emissions comparison - carbon benefits of timber in construction.* Retrieved from http://www.sevenstanes.gov.uk/pdf/crwoodproducts31.pdf/$FILE/crwoodproducts31.pdf

Frenette, C. D., Bulle, C., Beauregard, R., Salenikovich, A., & Derome, D. (2010). Using life cycle assessment to derive an environmental index for light-frame wood wall assemblies. *Building and Environment, 45*(10), 2111-2122. doi:10.1016/j.buildenv.2010.03.009

Horvat, M., (2009), *Building Envelope Performance Protocol and Assessment Tool – for light-frame building envelopes used in residential buildings*, VDM Verlag, Germany.

Hukka, A., & Viitanen, H. A. (1999). A mathematical model of mould growth on wooden material. *Wood Science and Technology,* (33), 475.

Hutcheon, N. B., & Handegord, G. O. P. (1995). *Building science for a cold climate*, Institute for Research in Construction, Canada.

Incropera, F. P., & DeWitt, D. P. (1996). In Nancy Prinz T. K. (Ed.), *Introduction to heat transfer* (3rd ed.). United States of America: John Wiley & Sons.

Institut Bauphysik. (2008). *WUFI ORNL/IBP (Version v4.2) [Computer software]. Stuttgart, Germany. Retrieved April 29, 2011. Available at http://www.hoki.ibp.fhg.de/wufi/bezug_e.html*

Isaksson, T., Thelandersson, S., Ekstrand-Tobin, A., & Johansson, P. (2010). Critical conditions for onset of mould growth under varying climate conditions. *Building and Environment, 45*(7), 1712.

Karagiozis, A. (Undated). *Comparison of water vapor permeance data of common interior building materials in north american wall systems [PowerPoint slides in pdf form].* Retrieved from http://www.kuleuven.be/bwf/projects/annex41/protected/data/ORNL%20May%202005%20Prese%20A41-T2-US-05-1.pdf

Karagiozis, A., Hartwig, K., & Andreas, H. (Undated). *WUFIORNL/IBP Hygrothermal Model*. Retrieved from http://www.ornl.gov/~webworks/cppr/y2001/pres/111509.pdf

Karagiozis, A. N., & Kuenzel, H. M. (2010). The effect of air cavity convection on the wetting and drying behavior of wood-frame walls using a multi-physics approach. *ASTM Special Technical Publications, (1509 STP)* 48-67.

Karagiozis, A. N., & Kumaran, M. K. (1993). Computer model calculations on the performance of vapor barriers in Canadian residential buildings. *ASHRAE Transaction, 99*(2) 991.

Kassab, M., Zmeureanu, R., & Derome, D. (2003). Life-cycle analysis of improvements to an existing energy-efficient house in Montreal. *Architectural Science Review, 46*, 341.

Kosny, J. C., Jeffrey, E., & Desjarlais, A. O. (1997, Thermal breaking systems for metal stud walls - can metal stud walls perform as well as wood stud walls*? ASHRAE Transactions,* (103), 518.

Kosny, J., Yarbrough, D. W. & Childs, P. (2001). *Couple secrets about how framing is effecting the thermal performance of wood and steel-framed walls.* Retrieved July, 21, 2011, from http://www.ornl.gov/sci/roofs+walls/research/detailed_papers/thermal_frame/

Lawrence Berkeley National Laboratory. (2011). *Two-dimensional building heat-transfer modeling*. Retrieved July 11, 2011, from http://windows.lbl.gov/software/therm/therm.html

Lee, W. L., Chau, C. K., Yik, F. W. H., Burnett, J., & Tse, M. S. (2002). On the study of the credit-weighting scale in a building environmental assessment scheme*. Building and Environment, 3*7(12), 1385-1396.

Lstiburek, J., W. (2009). Five things*. ASHRAE Journal,* (July), 52-56.

Lstiburek, J., W. (2009), Material view of mold*. Building Science Insights.*

Lstiburek, J. (2005), The Future of Framing is Here. *Fine Homebuilding (November).*

Maref, W., Armstrong, M., Rousseau, M. Z., Nicholls, M., & Lei, W. (2010). *Effect of wall energy retrofit on drying capability.* National Research Council. Canada.

McGowan, A. G., & Desjarlais, A. O. (1997). Investigation of common thermal bridges in walls. *Proceedings of the 1997 ASHRAE Winter Meeting,* Philadelphia, PA, USA. *, 10*3(1) 509-517.

McGowan, A., & Desjarlais, A. (Undated). Comparison of thermal bridging calculation methods. *Proceedings of the ASHRAE/DOE/BETEC Thermal Performance of the Exterior Envelopes of Buildings VI*, December, 1995.

Ojnanen, T., & Kumaran, K. (1996). Effect of exfiltration on the hygrothermal behaviour of a residential wall assembly*. Journal of Thermal Insulation and Building Envelopes, 1*9, 215.

Ontario Association of Architects. (2003). *OAA mould control practice guide, published By OAA*

Ontario Building Code 2006: Containing the Building Code Act and O. Reg. 403, (2006). *Ontario building code 2006: Containing the building code act and O. reg. 403*. Toronto: Ontario Ministry of Municipal Affairs and Housing, Building and Development Branch.

Ontario Building Code 2006: Supplementary Standard SB-12 Energy Efficiency for Housing, (2009). Containing the Building Code Act and O. Reg. 403, (2006). *Ontario building code 2006: Containing the building code act and O. reg. 403*. Toronto: Ontario Ministry of Municipal Affairs and Housing, Building and Development Branch.

Papadopoulos, A.,M. (2005). State of the art in thermal insulation materials and aims for future developments*. Energy and Buildings, 3*7(1), 77.

Pierquet, P., Bowyer, J., L., & Huelman, P. (1998). Thermal performance and embodied energy of cold climate wall systems*. Forest Products Journal*, *4*8(6), 53.

Residential wall systems: R-30 and beyond. Retrieved September 15 2010, from http://www.carb-swa.com/articles/carbnews%20articles/CARBNews_Feb2010.pdf

Saaty, T. L. (2003). Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research, 145*(1), 85-91. doi:10.1016/S0377-2217(02)00227-8

Schecter, A., Pavuk, M., Päpke, O., Ryan, J., Birnbaum, L., & Rosen, R. (2003). Polybrominateddiphenyl ethers (PBDEs) in U.S. mothers' milk*. Environmental Health Perspectives, 11*1(14), 1723.

Steel Framing Alliance. (2008). *Thermal design and code compliance for cold-formed steel walls.* Retrieved June 19, 2011 from http://www.steelframing.org/PDF/FinalDesignGuideSept82008.pdf

Straube, J. F., & Burnett, E. F. P. (2005). *Building science for building enclosure*s (1st ed.). Building Science Press, Minnesota, USA.

Straube, J., & Burnett, E. (2001). *Manual on moisture analysis in building*s. West Conshohocken, PA: ASTM.

Straube, J., & Finch, G. (2009). *Ventilated wall claddings: Review, field performance, and hygrothermal modeling.* Report No. 0906.Building Science Press, Minnesota, USA.

Straube, J., & Smegal, J. (2009). *Building America special research project: High-R walls case study analysis*. Report No. 0903.Building Science Corporation.

Timusk, J., & Doshi, H. B. (1986). Effect of insulating sheathing on heat and moisture flow *Canadian Journal of Civil Engineering, 1*3(6), 674-680.

Trethowen, H. A. (1997). How are U on your R's. *IRHACE Annual Conference,* Napier, New Zealand.

Trusty, W.,B., & Meil, J. K. Building life cycle assessment: residential case study. Retrieved from: http://www.tud.ttu.ee/material/piirimae/LCA/Case%20studies/LCA%20building.pdf

Twiddy, D. (2011). *Best wall challenge assemblies*. George Brown College student project, Toronto, Ontario

Wang, J. and P. Morris. 2010. A Review on conditions for decay initiation and progression. International Research Group on Wood Preservation. Document No. IRG/WP 07- 10-20444, IRG, Stockholm, Sweden.

Wilson, A. G., & Nowak, E. (1959). *Condensation between the panes of double windows*. Retrieved 03/29, 2011, from http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rp/rp100/rp100.pdf

XCO_2 Conisbee Ltd.(Undated). *Insulation for sustainability - A guide*. London, UK:

Zabalza Bribian, I., Valero Capilla, A., & Aranda Uson, A. (2009). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment, 46*(5), 1133-1140.