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Comparison and Validation of Modelling Methods for Non-Homogenous Walls Incorporating Vacuum Insulation Panels

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ABSTRACT

This paper compares the effective thermal resistance of 5 wall assemblies incorporating vacuum insulation panels (VIP) encased in extruded polystyrene (XPS), known as composite panels, through three different evaluation methods. The methods consisted of using steady-state and in-situ experimental testing as well as computer simulation. The computer modelling of the wall assemblies used simplifications, such as symmetry, and involves creating a thermal model for each unique 2D profile within the wall assembly independently. The results of the modelling method were compared to an experimentally calculated thermal resistance based on measured heat flux through a representative assembly under steady-state conditions in a guarded hot box and the measured heat fluxes under in-situ conditions at the Natural Resources Canada CanmetENERGY seasonal test facility. The feasibility of using a composite panels to address concerns of VIP constructability was determined to be successful with a strong dependence on the ratio of the VIP dimensions to the overall performance of the wall assembly design. An effective thermal resistance range of 8.44 m^2K/W to 9.07 m^2K/W was found during steady-state testing in the guarded hot box, and an agreement within 0.1% to 7.9% was found between steady-state and computer model results. In addition to the initial modelling, a 4.5% agreement was achieved with a new method using simplifications that are based on the coverage area of the unique cross section. The approach utilizes the current simplifications used for homogenous walls, and further develops the methodology to prove they are applicable to non-homogenous wall assemblies as well.

1. INTRODUCTION

As of 2012, space heating accounted for 62% of Canada's secondary residential energy use, the most significant category by a large margin (Natural Resources Canada, 2014). New strategies and policies to reduce overall energy consumption, with a focus on reducing space heating energy, have been implemented in the residential sector. Voluntary performances standards have been developed for new homes including R-2000 (Natural Resources Canada, 2015), LEED Canada for Homes (Canada Green Building Council, 2014) and Passive House (Canadian Passive House Institute, 2014). These standards add a series of performance criteria, in addition to conventional building code, in an effort to reduce a home's energy consumption and include a limit on energy and water consumption, and prescribe minimum levels of insulation, ventilation, etc. Generally, extensive modelling, proof of concept and/or builder training are required to obtain the energy efficiency designation.

A common method of maintaining a home within the constrained energy budget is to increase the overall air tightness and insulation in the dwelling above conventional construction standards through additional sealing and insulation. The approach often taken to increase the insulation value is to introduce additional levels of insulation. This practice however is not always possible or favourable. For example, adding thickness to the walls may increase the dwelling's footprint or reduce the useful floor space within the home. As a consequence, many studies are being performed on vacuum insulated panels (VIPs), which offer a high thermal resistance per unit thickness when compared to conventional materials. VIPs consist of a metallic enclosure and a vacuum maintained inside, effectively eliminating the conduction through the centre of panel, however a thermal bridge will occur along the edges (Mukhopadhyaya et. al, 2011; Baldwin et. al, 2015). Literature (Mukhopadhyaya et. al, 2014) has shown that a VIP can reach a thermal conductivity of 0.0034 W/m·K, at the centre of panel, however a previous study found that a reduction of 32% of the thermal resistance at the panel perimeter exists (Conley and Cruickshank, 2016). There are concerns about whether the fragility and the non-homogenous nature of the panels will cause problems within residential dwellings and associated modelling.

The constructability of VIPs in building envelopes have been highlighted as a problem in publications (Mukhopadhyaya et. al, 2011). Since the identification of this problem, different techniques have been implemented in order to augment the constructability of VIPs and make them feasible within buildings. The most common approach has been to integrate VIPs within foam sheets and utilize them as a prefabricated panel with designated points for mechanical fastening. The motivation behind this technique is to mitigate the risk of puncture through improper placement of fasteners during the construction of the envelope and to keep the building practices of VIPs similar to the current state of standard materials.

To date, limited work has been conducted on modelling the non-homogenous nature of the panels in building applications. A weighted average method (Staube and Smegal, 2011) has been used to model wall envelopes. For standard wall construction that uses homogenous materials, the weighted average method utilizes the framing factor (FF), known as the amount of wall area that incorporates structural support, in order to reduce the size of experimental model. The method was used (Schiedel et. al, 2013) such that a repeatable section using a significantly smaller width and a fictitious stud size. This method reduces the overall size of the model and is a simplifying convention used by researchers and building science professionals. Currently, a standard of simplifying cross sections does not exist for wall envelope assemblies that contain multiple non-homogenous layers (e.g. walls incorporating VIPs).

2. EXPERIMENTAL APPROACH

In total, 5 different wall compositions and designs were evaluated at steady-state conditions within Carleton University's guarded hot box and one wall was evaluated at in-situ conditions using the Natural Resources Canada (NRCan) CanmetENERGY seasonal test facility. The purpose of the tests was to experimentally validate models that were built in THERM (THERM, 2015), a steady-state heat transfer simulation software used to determine the thermal resistance of wall assemblies.

2.1 Experimental Wall Assemblies

VIPs encased in foam or an insulation material, is a concept that has been studied (Erbenich and Knoll, 2011) as an approach to increase the use of VIP on construction sites. However, this method of protection was not nearly tested or metered as much as the current study. In the application of this study, it was important to allow sufficient space between and around the VIPs to insure a minimal chance of puncture by mechanical fastening during installation. By delivering the panels as a prefabricated piece, it would limit the changes to construction practices currently in place thereby improving the constructability of the novel material.

The composite panels prototyped under this study were designed as two 12.7 mm (0.5") thick sheets of extruded polystyrene (XPS) on either side of the VIP, acting as the shell, and additional 25.4 mm (1") thick XPS spacers around the VIPs. VIPs from two different manufacturers were used and had sizes of 863 mm by 559 mm (34" by 22") and 559 mm by 559 mm (22" by 22") from one manufacturer and 498 mm by 597 mm (19 3/8" by 23 1/2") panels from another manufacturer; an example of the wall composition can be found in Figure 1. The variation in the composite panel design was performed by changing the size of spacer between the VIPs, the orientation of the VIPs and the type of VIP within the panel. This led to the development of five different types of composite panels to

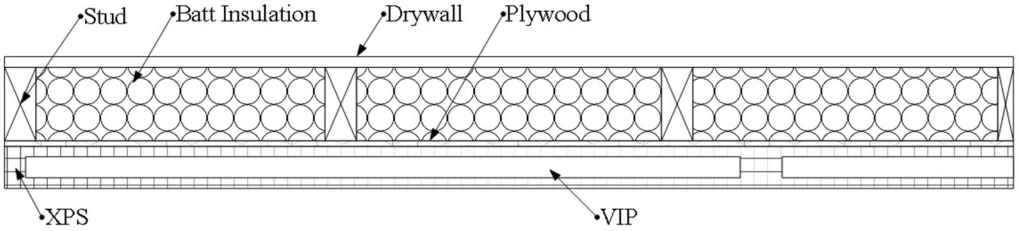

Figure 1: Horizontal cross section with material composition of composite panels labelled

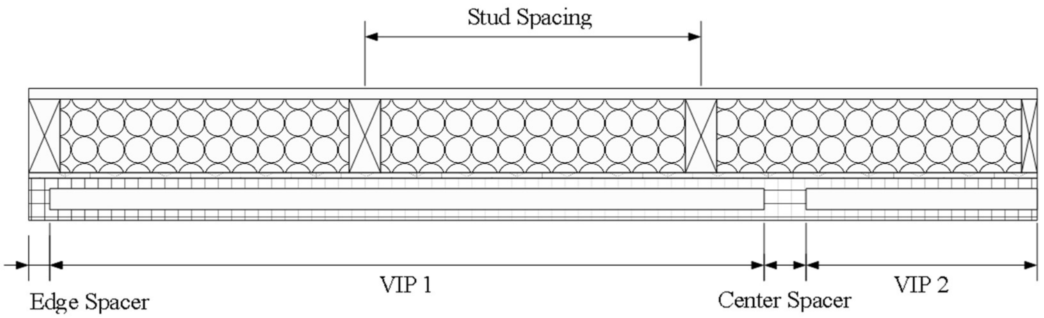

Figure 2: Horizontal cross section with dimensions labelled. Dimensions for each wall assembly found in Table 1

be tested at steady-state and modelled using THERM. Figure 2 is similar to Figure 1 but the composition labels were removed and the related dimensions (edge spacer, VIP spacer and two VIP sizes) were labelled instead. The associated dimensions were added to Table 1 for all five composite panel designs.

Table 1: Horizontal dimensions of the composite panels up to the middle of the wall

Test	Stud spacing, mm (in)	Edge spacer, mm (in)	Centre spacer, mm (in)	VIP 1, mm (in)	VIP 2, mm (in)
1	305 (12)	25 (1)	51 (2)*	559 (22)	559 (22)
2	406 (16)	25 (1)	51 (2)	864 (34)	279 (11)**
3	406 (16)	0 (0)	25 (1)	597 (23.5)	597 (23.5)
4	406 (16)	25 (1)	0 (0)	597 (23.5)	597 (23.5)
5	406 (16)	25 (1)	51 (2)*	559 (22)	559 (22)

*There are two centre spacers in half the composite panel.
**The centre of a 22” VIP aligns with the line of symmetry.

For each wall assembly, a large number of cross sections are present when the composite wall panels are utilized. Unlike conventional wall envelopes when layers of insulation are homogenous in the vertical direction with the exception of the stud layer, there are two additional compositions that are introduced based on the stud and VIP locations. The four unique cross sections in the assembly are stud-VIP, stud-no VIP, cavity-VIP and cavity-no VIP.

2.2 Guarded Hot Box

The guarded hot box test facility at Carleton University (Baldwin et. al, 2015) evaluates that overall thermal resistance of a wall assembly. The experimental set-up consists of three distinct controlled chambers: climate, metering and guard. The conditions within the chambers are set to simulate the outdoor and interior temperature conditions during the test period. As illustrated in Figure 3, the metering chamber is located within the guarded chamber in order to minimize or eliminate the heat loss through the metering chamber walls by maintaining a small temperature difference of approximately 0.1°C between the two chambers. Since the conduction through the chamber walls is driven by temperature difference, maintaining the chambers at roughly the same temperature throughout the test period limits heat loss and forces the heat input to the metering chamber through the specimen. The test facility follows ASTM C-1163 (ASTM, 2011) to determine whether steady-state conditions are met. The conditions are averaged over a 4 hour test period and the test continues until steady-state conditions are achieved. According to ASTM C-1163 this occurs when, for five consecutive test periods:

- the average specimen surface temperature in the metering chamber did not vary by more than ± 0.25°C.
- the average specimen surface temperature in the climate chamber did not vary by more than ± 0.25°C.
- the average temperature within the air curtain did not vary by greater than ± 0.25°C.
- the average energy input to the metering chamber did not vary by more than ± 1%.

After these requirements have been met, the collected data from 5 consecutive time periods can be averaged and analyzed to determine the overall thermal resistance, R, in m^2K/W of the assembly through Equation 1

$$R=\Delta T/(q/(t\cdot A)) \tag{1}$$

where ΔT is the temperature difference between the average hot and average cold side temperatures in °C, q is the energy input to the metering chamber in Wh, t is the time period of the test in hours and A is the metered area in m^2.

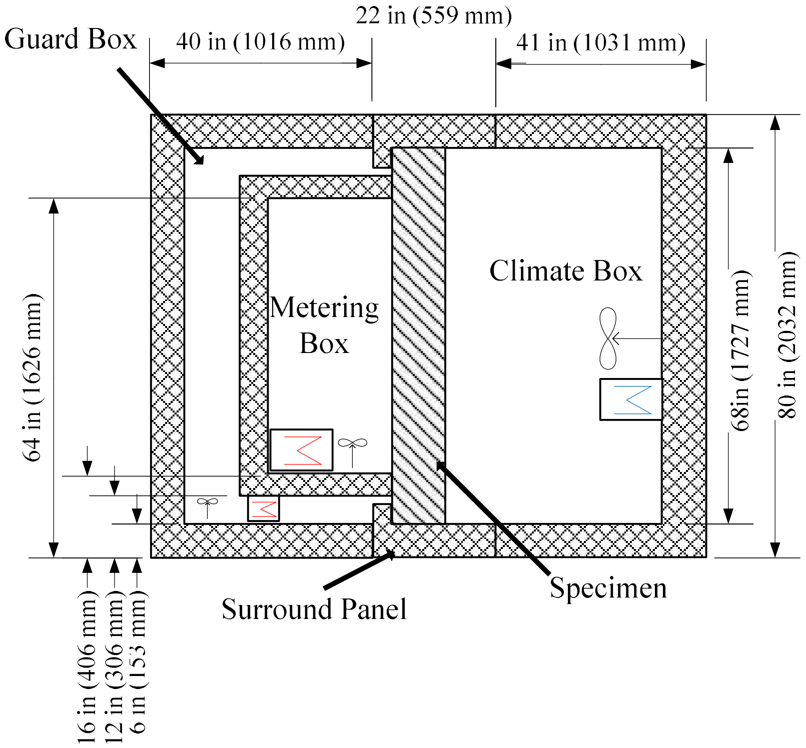

Figure 3: Schematic of Carleton University's guarded hot box

2.3 In-Situ Seasonal Test Facility

To compliment the steady-state test results of the guarded hot box facility and provide another experimental comparison, the initial design iteration was tested at in-situ conditions. During in-situ wall testing, the interior temperature and humidity are tightly controlled at steady conditions while the exterior conditions are determine by the naturally varying outdoor environment. In contrast to steady-state conditions, the wall assembly is under test conditions for a full seasonal cycle and allows for the moisture transport and hygrothermal performance to be monitored and evaluated. At the NRCan CanmetENERGY seasonal test facility, there is the opportunity to monitor three separate 2.45 m by 2.45 m (8' by 8') wall assemblies and evaluate the heat and moisture transport through the assemblies with the use of thermocouples, heat flux plates and other moisture monitoring devices. The measurements are taken at 10 minute interval. By using the heat flux and temperature difference at the specific cross sections of the overall wall assembly, the thermal resistance can be experimentally obtained.

In order to find the heat flux at the four unique cross sections of the panels, heat flux plates were installed at each point and thermocouples were used to determine the temperature difference across those points. Using Equation 2 it is possible to calculate the thermal resistance for the points and the effective R-value of the wall can be computed using the weighted averages method

$$R=\Delta T / q'' \tag{2}$$

where ΔT is the temperature difference across the material in °C, q" is the heat flux measured in W/m^2 to find the thermal resistance, R in m^2K/W.

3. MODELLING APPROACH

An important aspect of wall assembly design is to develop calibrated thermal wall envelope models to easily assess the thermal performance. Within this study, models were developed to determine the effective thermal resistance and compare the results to the experimental data. The material properties and boundary conditions were taken from the THERM library or the manufacturers' material specifications sheets, when unavailable within THERM.

Previously, simplifications have been made in conventional wall assemblies by utilizing a fictitious stud size to represent the FF such that the geometry uses a larger, centred stud and properly portioned cavity area on one side, and a comparison between the actual and simplified geometries. It is generally acceptable to reduce the cross section using symmetry simplification and in some circumstances use the coverage area of material to create a singular cross section to input to the computer simulation. However, it is unknown whether these simplifications based on the framing factor and coverage area are valid when a wall assembly containing greater than two unique cross sections is modelled. Therefore, within this study a model was created for each of the five wall designs. Then a singular cross section was created based on the average coverage area of the four previously mentioned cross sections.

4. GUARDED HOT BOX RESULTS

In order to determine the thermal resistance of the assembly, the guarded hot box must reach steady state conditions outlined by ASTM C-1163 (ASTM, 2011). Figure 4 shows an example of the measured temperature profile through one of the cross sections over a 20 hour testing period. The temperature at each interface is denoted in the legend by the "outside-inside" materials, where "PLY" is plywood, "DRY" is drywall and "FIBER" is fiberglass insulation and the remaining acronyms have been defined. The graph shows that the temperature throughout the assembly and the interior surface remains essentially constant throughout the test. A cyclic temperature exists on the exterior wall surface due to the refrigeration unit cycling in the climate chamber. Another method to verify steady-state conditions, according to ASTM C-1163, is to determine if the heat transfer through the metering and guarded interface is less than 1% of the total energy input over the test period. The temperatures on the inside and outside of the metering chamber walls were instrumented with thermocouples, and since the effective thermal resistance and wall area are known, the heat loss from the chamber can be calculated. For example, when evaluating Test 3 the temperature difference was 0.01°C and the total heat transfer at the interface test was found to be 0.6 Wh, which was approximately 0.3% of the overall heat input during the test. Over the entire testing period of Test 3, 159.4 Wh of heat was added to maintain the steady-state conditions in the metering chamber over a 20 hour period. All of the energy flowed through the 1.83 m^2 metering area with an average temperature difference of 36.9°C across the

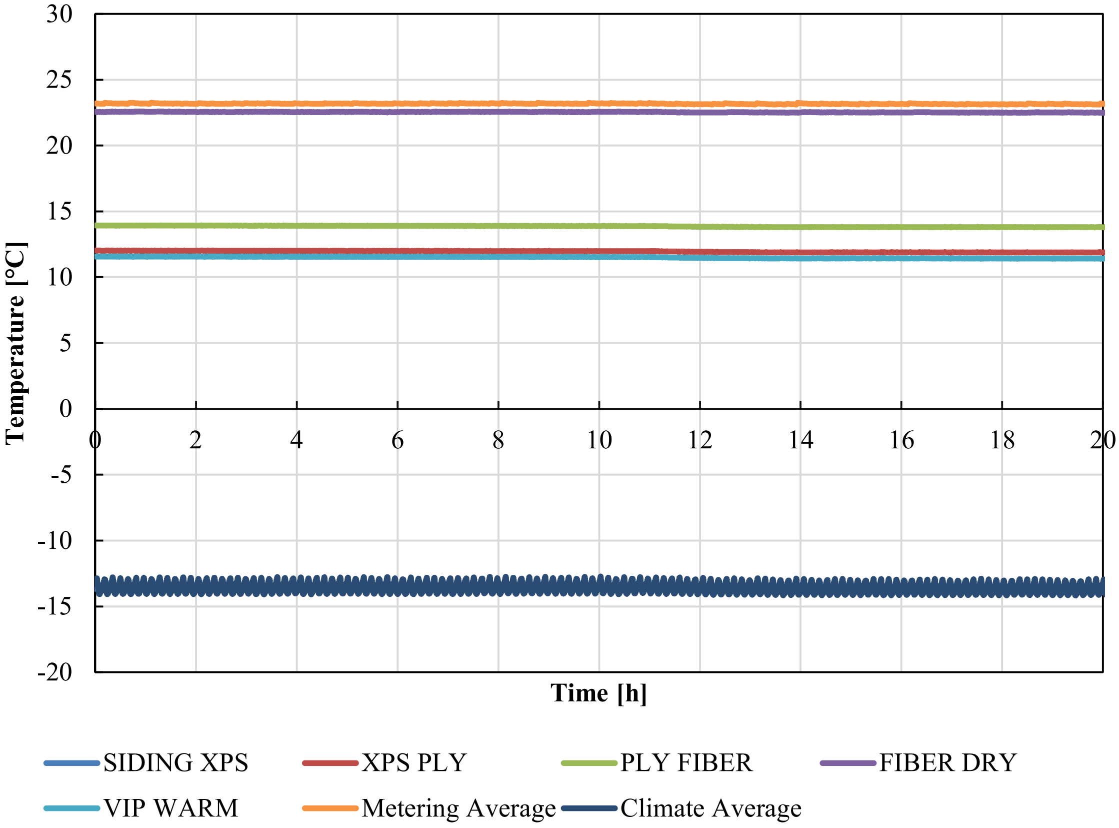

Figure 4: Steady-state temperature profile during guarded hot box test

assembly. Using Equation 1, the thermal resistance value for the wall design is 8.44 m^2K/W. In Table 2, the exterior and interior surface temperatures, the heat input to maintain steady-state conditions and the effective thermal resistance for the other four wall assembly designs are listed.

Table 2: Summary of steady-state test conditions and results from guarded hot box over 4 hour test period

Test	Climate (°C)	Metering (°C)	Heat Input (Wh)	Effective RSI (m^2K/W)
1	-13.3	23.0	139.9	8.97
2	-10.0	23.2	127.1	8.97
3	-13.7	23.1	159.4	8.44
4	-11.8	23.4	126.0	9.07
5	-11.8	23.3	126.0	8.97

5. IN-SITU RESULTS

The seasonal test facility is still in the initial year of operation and is able to test three experimental designs at a time. Therefore, at this point, the only wall design that has experimental in-situ data is the initial design iteration with the remainder of the wall designs to be tested in the coming years. The in-situ measurements were taken from January 19th 2016 to March 4th 2016 in Ottawa, Ontario, Canada. The indoor conditions were tightly controlled, while the exterior conditions comprised of the constantly changing outdoor environment. As such, Figure 5 shows the temperature profile with the first name indicating the interior facing material of the interface, for a point in line with the cavity and centre of VIP from the interior to exterior of the wall. On the exterior surface, it is obvious that the temperature is constantly changing, while the interior is remaining essentially constant with mild variance due to the heating unit cycling.

In accordance with ASTM C-1155 (ASTM, 2007), the thermal resistance of a wall assembly in-situ can be found when there is sufficient data points and a required convergence factor is met. Heat flux plates were placed at each

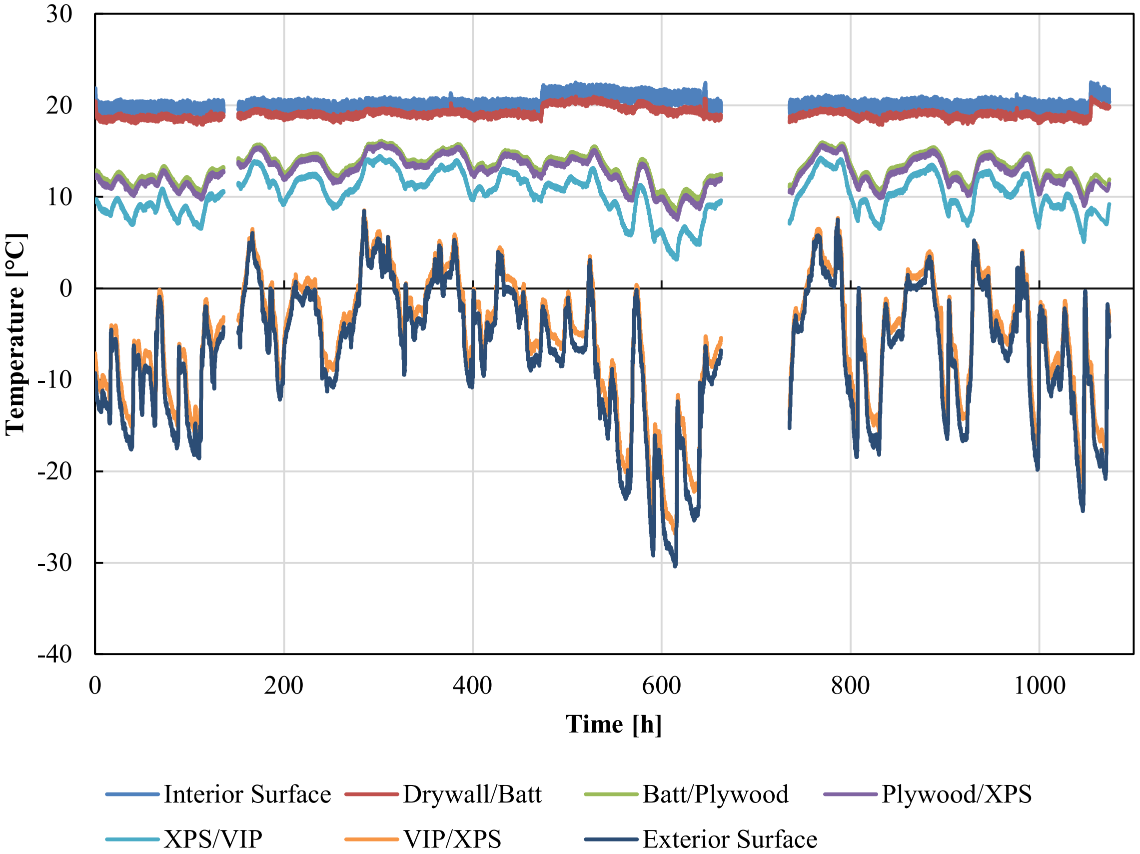

Figure 5: Temperature profile of VIP-no stud during in-situ testing from January 2016 to March 2016

unique cross section where a different heat flux would be occurring. Using the measured heat flux, the coverage area of that point specific point and the temperature difference an effective R-value can be found.Table 3 is a summary of the thermal resistance of each unique cross section based on the heat flux and temperature. The weighted RSI of each point is summed to find the effective thermal resistance assembly. Also included in the table is the thermal resistance of the centre of VIP, which was compared to the value from the manufacturer. If a large discrepancy exists, the experimental value will be used during simulations.

Table 3: Results from in-situ testing and effective thermal resistance

Cross Section	**RSI (m^2K/W)**	**% Area**	**Weighted RSI (m^2K/W)**
Stud-VIP	7.73	9.00%	0.70
Cavity-VIP	9.47	76.94%	7.29
Cavity-no VIP	4.68	9.34%	0.44
Stud-no VIP	2.91	4.72%	0.14
VIP	5.49		
		Effective RSI	8.56

6. MODELLING RESULTS

The modelling of the wall assemblies was split into two sections: accepted methods of simplifications, including symmetry and height ratios, and a new method presented where simplification are expanded to create a single representative cross section of the main wall.

6.1 Initial modelling

Each wall was modelled using a symmetrical simplification, such that only half of the wall geometry needed to be modelled in THERM. Since the walls were non-homogenous in the vertical and horizontal directions, two models needed to be used for each wall design; one that included VIPs and another that did not, due to encasing the perimeter of the VIP with XPS. This keeps the VIP from sliding out and aids in fastening the panel to the exterior wall. As mentioned prior, the THERM material library contained many of the necessary materials to replicate the main wall construction, however the VIPs did not exist and the thermal resistance per unit thickness was taken from the manufacturer's data sheet. A summary of the materials used are listed in Table 4. There are different VIP thermal conductivities listed for the different manufactures used during the study.

Table 4: Thermal conductivity values used during THERM simulations

Material Component	Thermal Conductivity (W/m·K)
Extruded Polystyrene (XPS)	0.026
Gypsum Wall Board	0.16
Lumber	0.14
Plywood (medium density)	0.17
Fiberglass Insulation	0.036
Vacuum insulation panels (VIPs)	0.0036 or 0.0043

In Figure 6, an example of the models for a VIP-present horizontal cross section is shown with the interior surface facing up. The boundary conditions on the left and right of the wall assembly are adiabatic, and the exterior and interior surfaces have "exterior winter", denoted by the blue surface, and "interior vertical surface", denoted by the red surface, conditions respectively. The set the temperature of the interior wall at 21.1°C and the exterior -17.8°C with film coefficients of 2.44 W/m^2K and 26 W/m^2K respectively. The boundary conditions used were within the

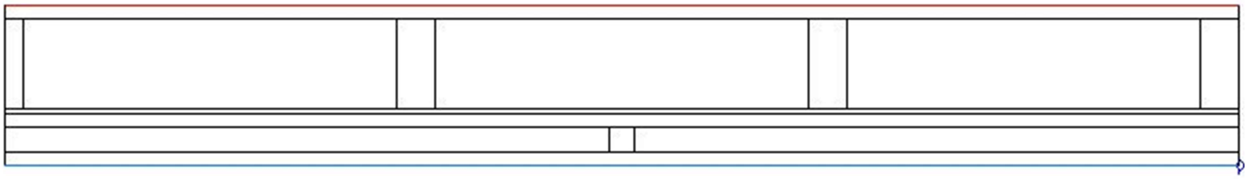

Figure 6: THERM VIP cross section of Test 3 using symmetry simplifications.

THERM library and were also used for other wall assembly models. For each cross section, the thermal resistance was evaluated based on the height ratio of cross section wall coverage to the overall wall height, and an effective thermal resistance value for the wall can be determined. In Table 5, the simulated thermal resistance values, height coverage and associated height ratio to find its contribution to the weighted and effective thermal resistance are presented for Test 1 and 2.

Table 5: Summary of THERM results using weighted average technique for Tests 1 and 2

	Component	RSI (m^2K/W)	Height (mm, in)	Height Ratio	Weighted RSI (m^2K/W)
Test 1	VIP	8.67	2286, 90	0.94	8.13
	No VIP	4.35	152, 6	0.06	0.27
				Effective RSI	8.40
Test 2	VIP	9.27	2235, 88	0.92	8.50
	No VIP	4.48	203, 8	0.08	0.37
				Effective RSI	8.87

6.2 Single representative cross section

The simplifications used in other publications for walls without a second non-homogenous layers solely account for the FF within the assembly. However, when the composite panels are introduced the amount of XPS and VIP also need to be taken into consideration. Another aspect that should be accounted for is the amount of coverage area where the VIP aligns with the stud. In order to deal with all these parameters and include them to create a single cross section in THERM, percentages of VIP coverage, XPS coverage, VIP stud coverage, XPS stud coverage and framing factor were determined and implemented onto a 610 mm (24”) wide cross section. The cross section was organized, as seen in Figure 7, such that for the wall framing two fictitious stud sizes were used where the sum is based on the framing factor and the distribution is based on VIP-stud and XPS-stud coverages. The amount of VIP and XPS inside the composite panel is based on the overall layer composition. The coverage percentages and thermal resistance results for a representative assembly of Test 1 and Test 2 are summarized in Table 6.

Table 6: Geometry of single representative cross section

	Framing factor	VIP (mm)	XPS (mm)	VIP-stud (mm)	XPS-stud (mm)
Test 1	14%	523	85	39	46
Test 2	11%	523	85	44	23

7. COMPARISON OF METHODS

The experimental data from the in-situ and steady-state guarded hot box testing can provide an experimental validation for the computer simulation models and provide insight to whether the assumptions and simplifications that were made are accurate. Since the in-situ data is Test 1, 305 mm (12”) on-centre (OC) framing with 863 mm by 559 mm (34” by 22”) and 559 mm by 559 mm (22” by 22”) VIP encased in XPS, the thermal resistance values were compared. The effective RSI values found from the in-situ and steady-state tests were 8.56 m^2K/W and 8.97 m^2K/W respectively and when compared to the THERM simulations, a percent difference of 1.9% and 6.5% was found. The results are summarized in Table 7. The advantages of using the new modelling method presented in the study is the

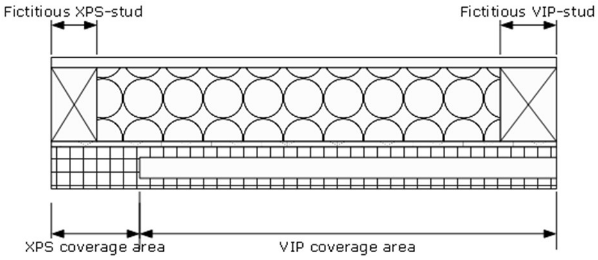

Figure 7: Single representative cross section using fictitious stud sizes

ability to simulate the main wall section using a single cross section. Even though more calculations of the coverage areas are required, the ability to edit, modify or change the dimensions in the new modelling method is improved. The benefits include the ability to utilize four dimensions in the composite panel and two fictitious stud sizes to construct a representative cross section that describes a complex, non-homogenous wall assembly.

Table 7: Percent difference of all evaluation methods for Test 1

	In-Situ	**Steady-State**	**Single Cross Section**	**THERM**
RSI (m^2K/W)	8.56	8.97	8.15	8.40
% Difference	1.9%	6.5%	4.2%	-

Furthermore, when the other steady-state results were compared to the simulation results, a large variation in differences existed. When Test 2 and 3 were analyzed the difference of effective thermal resistance was found to be 1.1% and 0.1% respectively, however the difference for Test 4 was found to be about 7.9%. The Test 4 wall design utilized a layer of VIP without XPS spacers between the VIPs to create the greatest effective thermal resistance. However, when this was applied within the simulation for a full scale wall assembly, XPS was required to fill the gaps caused by the geometry of the VIPs. The geometry caused approximately 165 mm (6.5") of XPS spacers to be present at the left and right composite panel edges, and a total of 445 mm (17.5") of XPS at the top and bottoms of composite panels. When excluding the no VIP section of the simulation, a thermal resistance becomes 9.25 m^2K/W, which reduced the percent difference to 2.0%. Therefore, if the geometry of the panels are not easily incorporated into a standard wall construction, such that a large amount of XPS is required to fill in the composite panel, a large degradation in thermal performance will exist. In Table 8, the effective thermal resistances from the steady-state testing and the computer simulations were summarized for the remaining wall designs.

Table 8: Percent difference of steady-state and computer modelling for each wall design

	Steady-State	**THERM**	**% Difference**
Test 1	8.97	8.40	6.5%
Test 2	8.97	8.87	1.1%
Test 3	8.44	8.43	0.1%
Test 4	9.07	8.38	7.9%
Test 5	8.97	8.62	3.9%

8. CONCLUSIONS

In conclusion, the steady-state and in-situ experimental testing and THERM modelling effectively evaluated the thermal resistance of five different wall envelope design utilizing VIPs encased in XPS composite panels. It was observed that VIP geometry can have a dramatic impact on the overall thermal resistance of the wall design. For the second set of manufactured VIPs, the VIP dimensions required more XPS than the initial set of panels that underwent testing and lower thermal performance was found due to the dimensions causing a larger fraction of XPS surrounding the perimeter of the panels.

The composite panels are a feasible solution to the significant constructability challenge that exists and must be addressed before VIP can be implemented into residential housing. When modelling the panels, either using symmetry or new method utilizing the ratio of coverage area of specific cross sections were found to be efficient at estimating the effective thermal resistances for Test 1 and 2. However, the benefits of being able to modify the representative cross section easily and the ability to use a single cross section to measure the thermal resistance are reasons to recommend using this method. In contrast to the first modelling method, it is much easier to compare the composition and coverage area of two separate wall designs using the new method since the geometries of the wall designs would be similar. The coverage areas of VIP and XPS and the associated material coverage at stud locations, from the fictitious sizes added to the model, can be clearly seen and compared in the cross section in Method 2, unlike Method 1 where it would require more information about the wall assembly, specifically height ratios of cross sections.

Furthermore, optimizing the dimensions of the VIPs within the assembly and the amount of XPS required to safely install the composite would be a valuable tool during the design of composite panels. The amount of XPS should be minimized since the effective thermal resistance of that cross section on 12” and 16” OC are 4.35 and 4.48 m^2K/W, nearly half of the effective thermal resistance when VIP are introduced to the cross section, but a minimum amount of XPS must be present as a tolerance for mechanical fastening to the dwelling. During this study, it was found that a 1.5” strip could be sufficient, however the necessary marking of where the XPS spacers are located on the surface of the composite panel is needed mitigate the risk of puncture.

REFERENCES

ASTM. (2007). *Standard Practice for Determining Thermal Resistance of Building Envelope Components for In-Situ data.* Conshocken, PA: ASTM International.

ASTM. (2011). *Standard Test Method for Thermal Performance of Building Materials and Envelop Assesmblies by Means of a Hot Box Apparatus.* West Conshohocken, PA: ASTM International.

Baldwin, C., Cruickshank, C. A., Schiedel, M., & Conley, B. (2015). Comparison of steady-state and in-situ testing of high thermal resistance walls incorporating vacuum insulation panels. *6th Internation Building Physics Conference.* Turino.

Canada Green Building Council. (2014). *Leed Canada Rating Systems*. Retrieved from http://www.cagbc.org/CAGBC/LEED/CommercGreenBuild/RatingSystems/CAGBC/Programs/LEED/CommercialInstitutional/RatingsSystems/LEED_Canada_Rating_S.aspx?hkey=5490b62b-b10f-45b7-9c41-2b5a299655b8

Canadian Passive House Institute. (2014). *Canadian Passive House Institute*. Retrieved from http://www.passivehouse.ca/

Conley, B., & Cruickshank, C. A. (2016). Evaluation of Thermal Bridges in Vacuum Insulation Panels Assemblies through Steady-State Testing in a Guarded Hot Box. *eSim 2016.* Hamilton.

Erbenich, G., & Knoll, S. (2011). New Modular VIP Systems (For Advanced Handling on Construction Site). *10th International Vacuum Symposium.* Ottawa.

Mukhopadhyaya, P., Kumaran, K., Ping, F., & Normandin, N. (2011). Use of vacuum insulation panel in building envelope construction: advantages and challenges. *13 th Canadian Conference on Building Science and Technology*, (pp. 1-10). Winnipeg.

Mukhopadhyaya, P., MacLean, D., Korn, J., van Reenen, D., & Melleti, S. (2014). Building applications and thermal performance of vacuum inuslation panels (VIPs) in Canadian subarctic climate. *Energy and Buildings, 85*, 672-680.

Natural Resources Canada. (2014). *National Energy Use Handbook: 1990 to 2011.* Ottawa: Office of Energy Efficiency, Natural Resources Canada.

Natural Resources Canada. (2015, 12 04). *The R-2000 Standard*. (Natural Resources Canada) Retrieved from http://www.nrcan.gc.ca/energy/efficiency/housing/new-homes/5087

Schiedel, M., Baldwin, C., & Cruickshank, C. A. (2013). In-situ experimental validation of THERM finite element analysis for a high R-value wall using vacuum insulation panels. *International Conference on Energy Sustainability.* Minneapolis.

Staube, J., & Smegal, J. (2011). *Builiding America Special Research Project: High-R Walls Case Study Analysis.* Sommerville, MA.: Building Science Corp.

THERM. (2015, March 10). (Lawrence Berkeley National Laboratory (LBNL)) Retrieved from http://windows.lbl.gov/software/therm/therm.html

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