CHALLENGES OF HIGH RSI-VALUE BUILDING ENVELOPE RETROFITS

Brock Conley, Carleton University, Christopher Baldwin, Carleton University, Cynthia Ann Cruickshank, Carleton University, Mark Carver, Natural Resources Canada

ABSTRACT

This paper studied the challenges associated with retrofitting the building envelope with vacuum insulation panels (VIPs) encased in expanded polystyrene (EPS) as a retrofitted exterior insulation on above grade walls of residential buildings. The wall assemblies were made to replicate a renovation of an enclosure that was built during the 1960s. The exterior insulation of one assembly was renovated using 50.8 mm (2") of EPS and represents the baseline performance of current common practice. Another assembly was built with 20 mm (0.7") thick vacuum insulation panels (VIPs) encased in the equivalent thickness EPS to represent the high RSI-value retrofit. The hygrothermal results from the CanmetENERGY Building Envelope Test Hut (CE-BETH) showed that the sheathing in the high performance assembly did not reach any elevated levels of moisture content and relative humidity from February 2017 to June 2017. The relative humidity between the wood studs remained below 60% RH for the majority of the test period but began to trend upwards as the season transitioned to spring. The results from the first four months of the yearlong evaluation showed that the building envelope contained sufficient drying potential and could be a feasible solution for retrofit applications.

INTRODUCTION

In Canada, energy consumption in the residential building sector accounts for 16.5% of all secondary energy use and 14% of all greenhouse gas emissions (Natural Resources Canada 2015). Of this, space heating and cooling accounts for 63% of energy consumption. The energy consumption trends in Canada resembles different regions across the globe, as buildings in the United States and Europe account for 40% and 38% of their energy use respectively (United States Department of Energy 2016, EuroStat 2016). Space conditioning accounts for the greatest percentage of the energy use in the residential sector and varies between 49% and 64% across the listed regions (United States Department of Energy 2016, EuroStat 2016). These statistics suggest that reducing the amount energy used for space conditioning can have the greatest impact on the energy performance of a building. However, national energy targets cannot be met if new homes are the only buildings targeted for improvement, due to the slowed growth of the building stock and that it represents a small portion of the current building stock.

The building envelope provides a barrier between the indoor and outdoor conditions and can suppress the energy transfer from the indoor environment. A cost-effective and common practice to improve the energy performance is through insulating the building envelope above code-built homes. With the added insulation, the building envelope has a higher thermal resistance value and can reduce the rate of energy transfer into and out of the conditioned space. As such, with a more thermally resistive building envelope, the space requires less mechanical heating or cooling energy to compensate for the building's interaction with the exterior environment. Building envelope improvements are an effective method for reducing the space conditioning loads, and therefore reduce the energy consumption and greenhouse gas emissions in the residential sector. However, insulation may not be continuously added as there are limits to the allowable envelope thickness and the return on investment diminishes as insulation value increases.

The current building stock data, compiled by Statistics Canada (Statistics Canada 2016), separate the dwellings into their decade of construction. According to the data acquired from the 2011 census, the data showed that dwellings constructed before 1990 accounted for 72% of the occupied dwellings in Ontario, while dwellings built pre-1970 accounted for 40%. In Canada, the number of occupied buildings from a vintage was similar to Ontario. The number of occupied buildings from a certain age period along with the expected new constructions past 2011 is shown in Figure 1.

Due to the distribution of occupied building vintages in Canada, a large majority of people live in buildings constructed at a time with different minimum requirements or criteria. An example of this can be seen with the revisions in building codes from 1960 to 2017. The National Building Code of Canada in 1970 prescribed a minimum insulation level based on the number of total annual degree-days and the type of fuel supplied to space conditioning systems (NBBC 2015). The highest minimum level of insulation the code prescribed for above grade walls in 1790 was an RSI 1.76 (R10.0). For comparison, the current Ontario Building Code (Ontario Building Code 2014) prescribes the above grade wall to be at least RSI 3.87 (R22.0) which demonstrates the insulation level improvements in buildings. While the minimum insulation levels have changed over time, there has also been an increase of more ambitious voluntary codes.

Voluntary codes and performance standards for residential buildings have been increasing in number with a drive towards energy efficiency and Net-Zero homes. A common theme through most, if not all, of these standards is increasing thermal insulation level far above code built homes, sometimes approaching RSI 8.0 (R45). However, these standards would have a minimal impact if they were only implemented onto new construction since 40% of the occupied dwellings were built to prior to 1970. The pre-1970s dwellings when including the forecasted results to 2030, from Figure 1, will still account for roughly 35% of the occupied dwellings and the insulation levels remain below the code built homes, and well below the voluntary codes. Therefore, the older dwellings will remain a target for reducing the energy consumption of residential buildings. The disparity of energy consumption through space heating between older buildings in Canada as of 2014 is illustrated in Figure 2. Residential dwellings constructed before 1960 accounted for 30% of the total space heating energy while dwellings built before 1983 accounted for 60% of the total space heating energy. It becomes quite clear that older buildings account for the majority of the energy consumption in the building stock and this must be addressed.

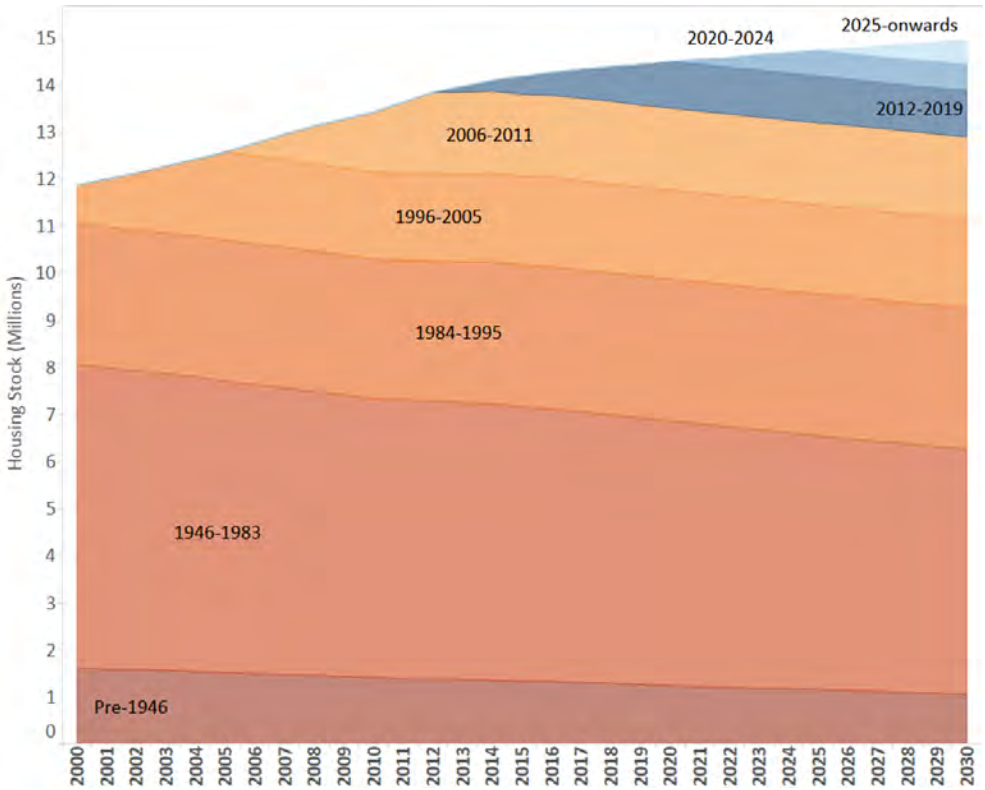

Figure 1: The number of new constructions and the forecast going forward in Canada (Carver 2016)

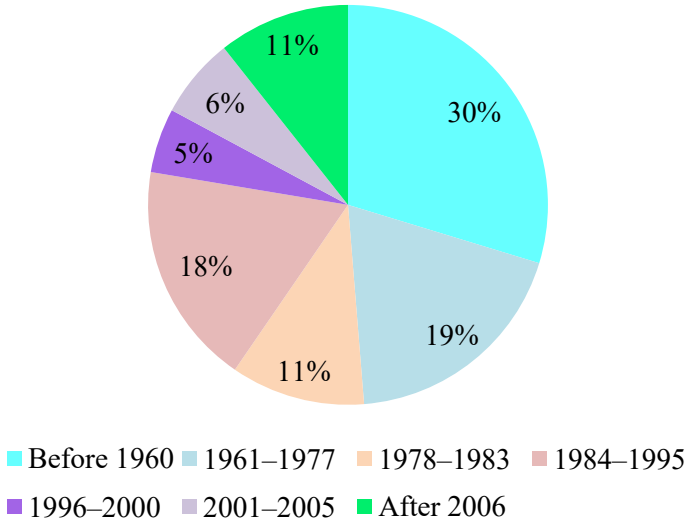

Figure 2: Residential building space heating energy consumption separated by building vintage (Natural Resources Canada 2015)

Occupants also view pre-1970 homes as homes that require repair or renovation. During the 2011 census, occupants described what level of maintenance their home required in three categories: regular maintenance only, minor repairs, or major repairs. Regular maintenance was considered to be annual tasks such as painting the interior walls and removing clogs from eaves troughs and gutters. Minor repairs constituted of small issues such as small cracks in the interior walls and missing shingles or siding. Major repairs

constituted of necessary changes to the dwelling such as bulging or damp walls as well as many other large-scale renovations. These results are not indicative of any energy improvements, or solely related to the building envelope, however, they do show that older dwellings require more investment to remain a livable space. If occupants view their dwelling as requiring significant investment or repair, this would be an opportunity to improve the building's energy efficiency and consumption during the renovation planning. The energy improvements could be a part of the necessary renovations, or as an extra that could be installed during the same construction period to limit disruptions to the occupants.

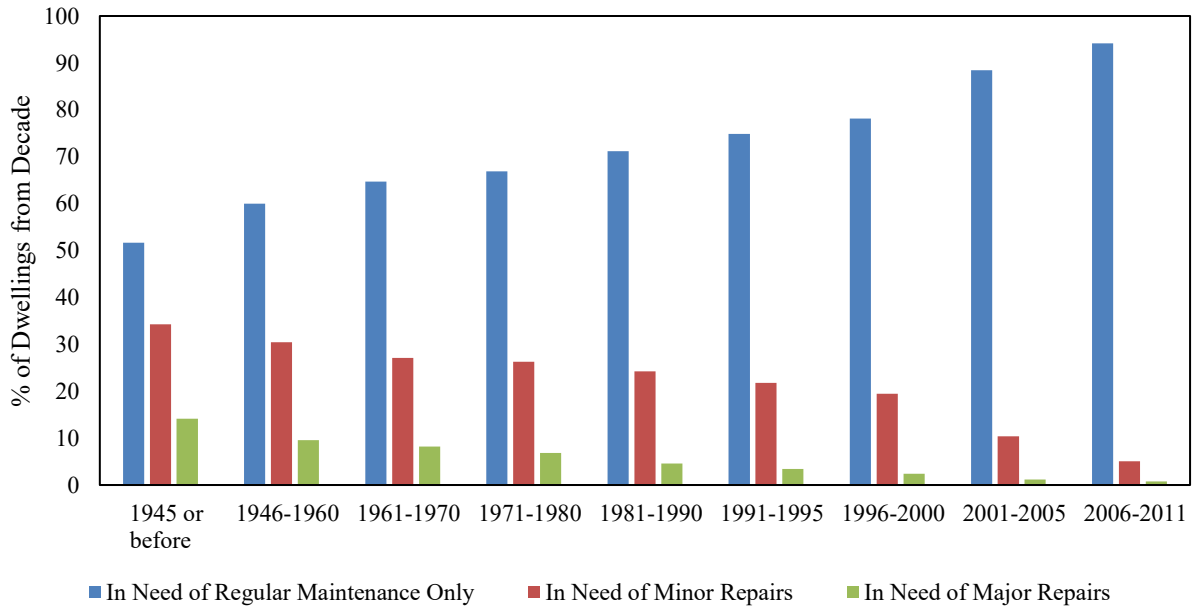

Figure 3: The condition of dwellings in Ontario as described by the tenants as of 2011. Data from the National Household survey (Statistics Canada 2016)

BUILDING ENVELOPE RETROFITS

The construction of new homes is slowing and buildings built previous to 1990 will be occupied far into the future. The insulation levels of the older dwellings do not meet the current (or future) trend of the national energy codes. As such, retrofitting the envelope or enclosure of a building presents an opportunity to improve the existing building and its energy consumption.

Fundamentals

The building envelope of an above grade wall can be retrofitted by making changes to the interior or exterior of the wall.At the interior of the sheathing, a retrofit or renovation would consist of adding or replacing the insulation between the structural members or adding insulation on the interior of the structural members. Meanwhile, retrofitting the exterior of the envelope could be performed by removing and replacing exterior materials up to the sheathing or by adding insulation directly on top of the cladding. Design considerations for both types of retrofit applications include thermal, moisture, installation considerations, aesthetics and

cost.

The interior can provide many thermal benefits, however concerns regarding the moisture control and installation make this approach it less appealing. If the cavity between the structural members does not contain insulation or has low quality insulation, it represents an opportunity to improve the envelope by adding blown in or high performing batt insulation. Another option would be to remove the gypsum board, vapour barrier, and install a double stud wall with 2x4 lumber with the cavities filled with insulation. While the effective thermal resistance of these envelopes would be improved, the moisture movement through the assembly would need to be carefully considered. The impact of improving the interior insulation would be a lower surface temperature at the sheathing, which could lead to dew point temperature and condensation formation concerns. Additionally, this type of retrofit will be intrusive and disruptive to occupants and, in the case of a double stud wall, would reduce the livable floor area within the dwelling. These issues could detract from the attractiveness of the retrofit application and cause occupants to opt for an exterior retrofit instead.

An exterior building envelope retrofit is able to provide similar thermal benefits as the interior retrofit without disrupting the interior. There are different exterior approaches that exist that would provide a thermal performance comparable or exceeding what an interior retrofit would provide. Additional layers of rigid foam board can be added onto the exterior to obtain the necessary RSI value, however the building is limited by the minimum setbacks for the property. When retrofitting the exterior, the building envelope can be upgraded but the total thickness, property lines and moisture levels within the assembly remain a concern as well as accounting for other envelope elements such as penetrations and connections to the roof or foundation.

It is important to note that for both the interior or exterior approaches, the building envelope thickness increases. The space inside or around the dwelling is a valuable cost to retrofitting the envelope and improving the thermal performance and building efficiency. The value of livable floor area in a home is rising and could be upwards of $200 per square foot (Parek 2012). A similar issue could exist around the exterior perimeter of the building as it approaches the minimum necessary setback from the property lines. A solution would be to address minimizing the increase of wall thickness and augmenting the RSI-value of the envelope.

Thin High RSI-Value Envelope

A thin high RSI-value envelope assembly is an RSI 7.0 (R40) (or greater) assembly with a thickness equal to homes built to the current building code. This type of assembly would allow dwellings to improve the energy efficiency of their home without sacrificing the valuable space inside or outside the building. These restrictions require a high performing insulation for the building and as such, common building insulations alone may not be sufficient. The potential use of vacuum insulation panels (VIPs) have been investigated as a solution to the building insulation retrofit issue, however they also present further challenges of integration.

A VIP is a porous material enclosed in a metallic foil with an internal pressure maintained near 10 mbar, such that conduction and convection through the panel are effectively eliminated (Mukhopadhyaya, et al. 2014). The VIP can provide a thermal resistance of RSI 7.0 (R40) for a 25.4 mm (1”) thickness, showing

promise for meeting the thermal performance targets necessary for the building envelope. However, there are challenges that hinder the use of VIPs in building envelopes. First, the panels are very fragile, such that if the VIP's foil enclosure is punctured or broken and the internal vacuum is lost, the thermal performance benefits above conventional insulation are nearly lost. The risk of puncture during installation from a stray nail or mishandling should be considered during design and construction. Secondly, the panels contain a significant change in RSI-value at the edges and do not act as a continuous insulation when applied to the exterior of the envelope. These issues need to be considered before the full integration of VIPs in building envelopes.

EXPERIMENTAL SETUP

In order to predict the effectiveness and applicability of a building envelope retrofit, annual in-situ monitoring or annual heat and moisture transfer modelling can be done. The experimental monitoring is conducted by taking temperature, humidity, and moisture content measurements throughout the year.

Sample building assemblies were installed and monitored (in-situ) at the CanmetENERGY Building Envelope Test Hut (CE-BETH) with temperature, relative humidity, and moisture content sensors to evaluate the feasibility of a retrofit design. The facility is located in Ottawa, Canada and the samples are oriented eastward. The in-situ facility has equipment that enables control of the interior air conditions (temperature and relative humidity) while the exterior of the assembly is exposed to the ambient environmental conditions in Ottawa, Canada.

The air temperature and humidity level on the interior surface are controlled to approximate the typical conditions found within a residential dwelling located in a cold, Canadian climate. The air temperature was be maintained at 21°C ±1°C during the test period. These temperatures represent common set-points in residential buildings. The relative humidity was maintained between 35% and 45% during the winter and spring. These set-points were chosen since they are slightly above the common conditions in homes, for various health, comfort and safety reasons. Maintaining slightly higher levels of RH in the winter will subject the assembly to a larger vapour pressure gradient. This increases the vapour drive and the associated risk of condensation and the associated threat to occupant health and durability of the assembly.

During the winter months, it is typical to see a drop in indoor relative humidity because the cold, dry air that infiltrates the home does not contain much moisture. This low interior humidity level, typically below 25-30%, may cause discomfort for the occupants, who may experience symptoms like dry eyes, sore throat and dry skin. However, at a higher level of relative humidity, a risk of condensation exists on cold surfaces, such as windows or within the building envelope, and will increase the likelihood of mold or rot for wood framed assemblies. While ASHRAE (ASHRAE 2016) specifies a range of 25% to 60% RH for occupant comfort, most Canadian homes will have an indoor relative humidity of 35% (ASHRAE 2016). This way, by maintaining a slightly higher relative humidity than the ideal set point, the walls assemblies will undergo testing at potentially worst-case conditions. In this manner, if the wall is deemed safe at the test indoor conditions, they will also be safe under the typical operating conditions.

In one of in the test bays within CE-BETH, a specimen was installed to mimic a building envelope of a dwelling built during the 1960's era with the exterior insulation retrofitted. To compare the high

performance assembly, the 2.4 m by 2.4 m (8' by 8') test area was divided in half to contain a baseline assembly and a high performance assembly. The 1.2 m by 2.4 m (4' by 8') high performance assembly was built on 2x4 wood studs at 400 mm (16OC) spacing with plywood sheathing and no interior vapour barrier. A weather barrier was added before combination of VIP and EPS as exterior insulation with 19 by 64 mm (1x3) strapping and vinyl siding to complete the assembly. Homes constructed in the 1970s were generally more vapour-open than code-built homes in 2016, and as such the interior vapour barrier was not included. The baseline assembly contained the same components except for the exterior insulation, where 50 mm (2") of EPS instead of the VIP/EPS composite panel. A drawing of the baseline and high performance assemblies as it was installed in the CE-BETH are included in Figure 4.

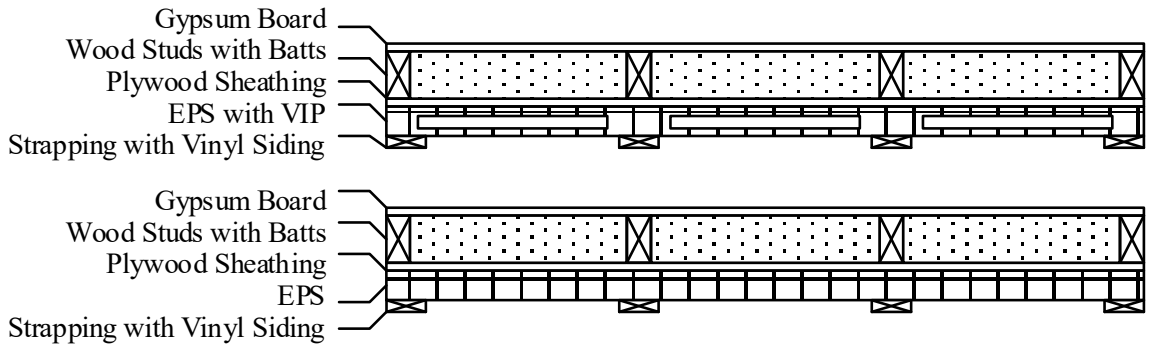

Figure 4: Composition of the high performance (top) and baseline (bottom) building envelopes installed in CE-BETH

Thermocouples were placed at the interface of every unique cross section in each building assembly specimen, such that baseline assemblies will have 2 unique cross sections (stud and cavity) and the high performance walls will have 3 unique cross sections (stud, cavity-EPS, and cavity-VIP). A total of 10 and 17 thermocouples were embedded in the baseline and high performance assemblies, respectively.

The moisture content sensors (MCS) were added to the structural sheathing and wood studs to monitor the moisture levels to ensure the conditions did not reach a point where moisture related deterioration could occur. In both wall assemblies, MCS were added along the bottom plate of the frame, the stud and bottom plate interface, at the stud 30" from the bottom and within the cavity on the sheathing 30" from the bottom plate. Moisture gradients and drying potential were assessed through measuring the moisture content in the wood-based components throughout the seasonal cycle. RH sensors were placed at the interior surface, inside the wall cavity and within the VIP pockets. This data provided a relative humidity gradient through the assembly and further augmented the moisture measurements by determining if there are any potential long-term moisture issues of the design. The instrumentation locations are shown in Figure 5 for high performance and baseline assemblies.

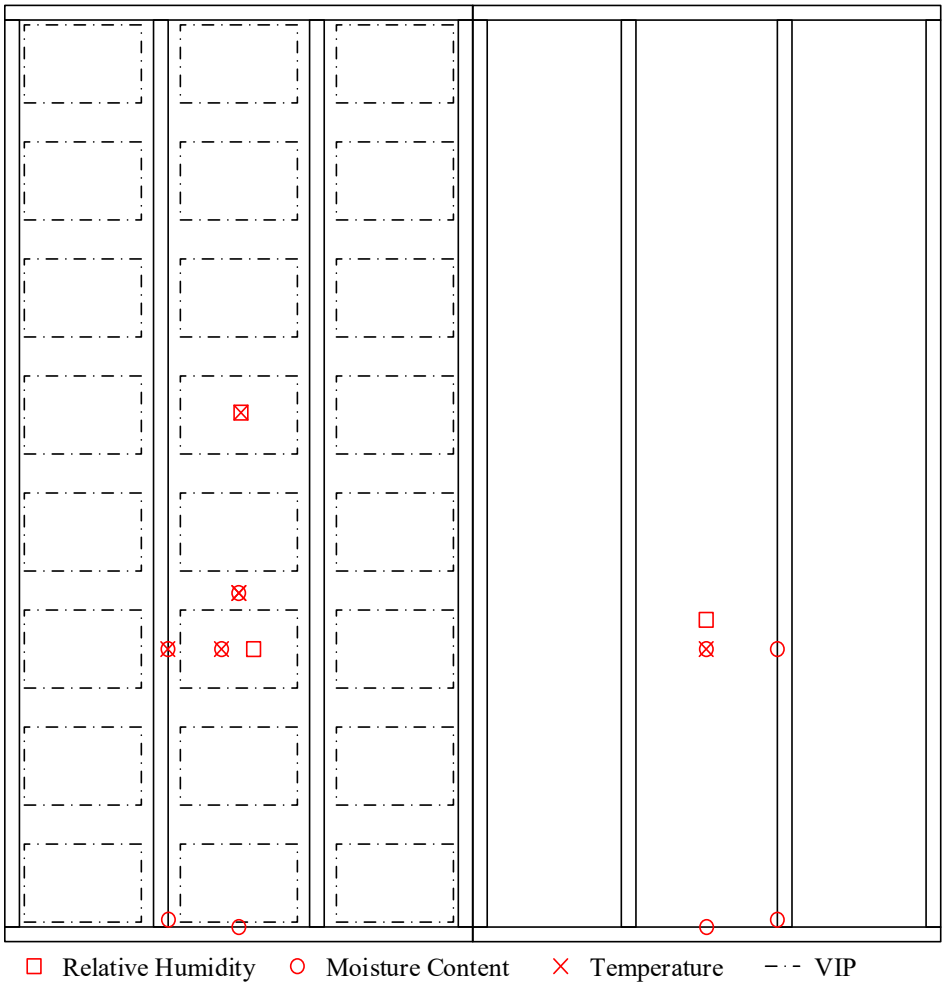

Figure 5: The instrumentation for building envelopes during annual in-situ evaluations

PRELIMINARY RESULTS

The assemblies were installed at the CE-BETH facility at the end of November 2016 with comprehensive data acquisition beginning January 31st 2017. During this time, the data was logged at 5-minute intervals (temperature, RH) or 15-minute intervals (moisture content) with gaps caused by modifying sensors or periodic power outages. The preliminary results from the first 4 months of 2017 are presented in the following figures.

Figure 6 shows the temperature at the VIP-cavity section of the high performance assembly. In Figure 6, the legend lists the interface surface temperature as "interior-exterior" materials (e.g., EPS-VIP) and the X-Y coordinates on the wall assembly from the bottom right interior corner. Since CE-BETH is facing east, there are spikes in temperature associated with the early morning sun exposure that is obvious during the beginning of spring by elevated temperature within the building envelope. The CE-BETH facility is capable of cooling; however, the controls were deactivated during May 2017 due to power outages (see gaps in the plotted data) and caused the interior temperature to approach the exterior temperature.

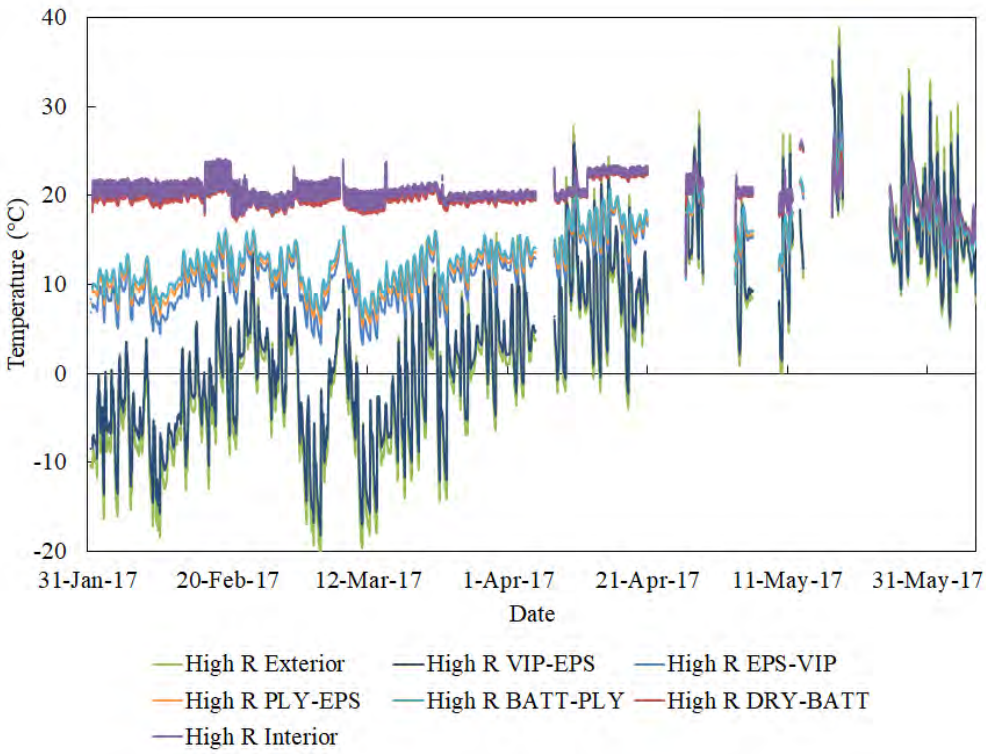

Figure 6: The temperature profile through VIP retrofit solution from January 31st 2017 to June 7th 2017. Temperatures taken at each interface in line with the center of VIP.

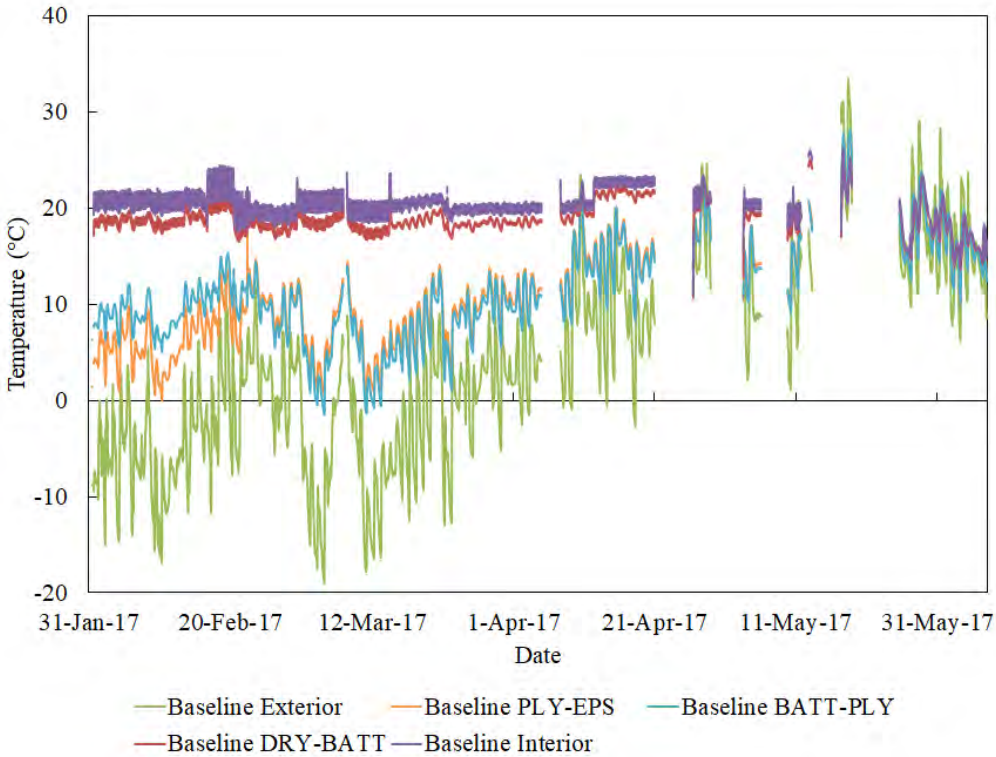

Figure 7: The temperature profile through a baseline retrofit solution from January 31st 2017 to June 7th 2017. Temperatures taken at each interface in line with the center of the cavity.

As the season changed to spring, the humidity in the facility began to climb due to the increased outdoor humidity. The relative humidity around organic materials, such as the structural members and sheathing, must remain below 80% RH with temperatures between 5°C and 40°C to eliminate the risk of mold growth and related deterioration (ASHRAE 2016). Figure 8 shows the relative humidity inside the cavity and around the VIPs at various elevations along with the interior and exterior relative humidity. Figure 8 utilized the same syntax as Figure 6 to describe locations of measurements within the building envelope assembly. With the 35% RH interior set-point, the cavity was not exposed to elevated relative humidity level which shows promise that the envelope may succeed the annual test conditions.

Along with the surface level relative humidity in the cavity between the studs, the moisture content of the wood-based materials needed to be measured and compared to the failure criteria. The MCS use stainless steel screws fastened into select structural members, as close to the sheathing as possible, to measure the moisture content in the wood. The measurements were monitored to ensure the moisture content did not exceed 20% for a prolonged period of time and cause potential moisture related deterioration. They were installed at three levels to ensure the moisture content was independent of elevation. As such, sensors were installed on the bottom plate, 762 mm (30”) and 914 mm (36”) from the top of the bottom plate. These locations were chosen based on their proximity to other temperature and relative humidity measurements, which will be used to verify measurements.

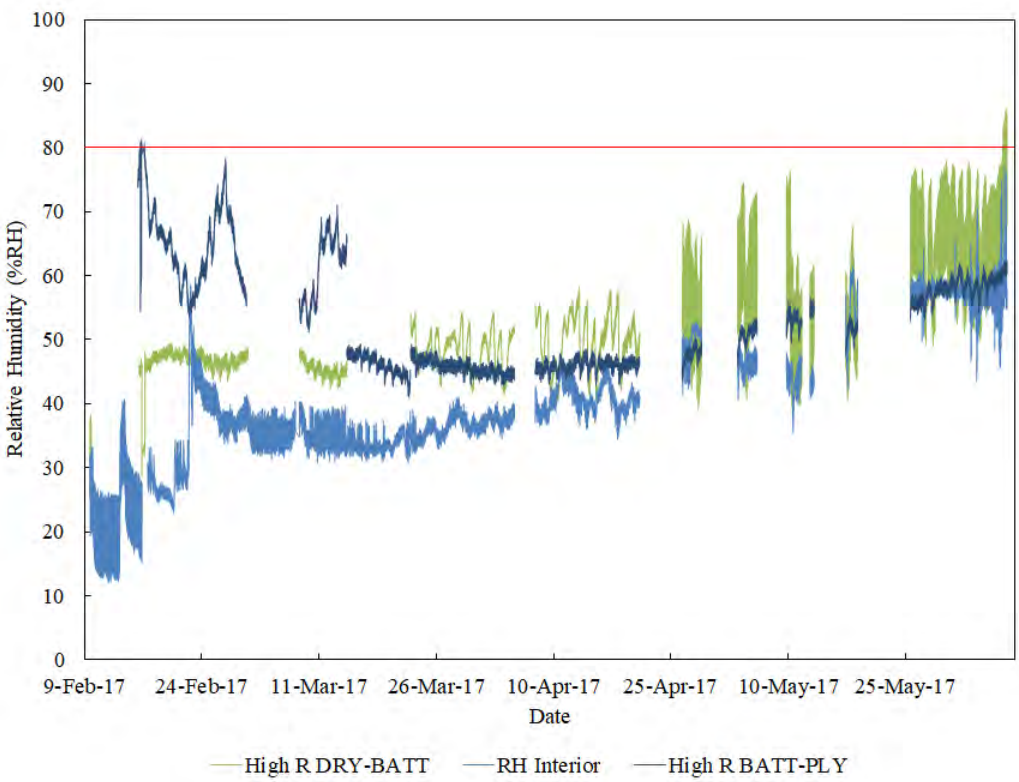

Figure 8: The relative humidity profile through a VIP retrofit solution from February 9th 2017 to June 7th 2017

The data that was logged from February to June showed that the moisture levels in the structural members did not increase, aligning with the expected result. The structural members were located closer to the interior and as a result, remained near the interior conditions. Consequently, the temperature or relative humidity

never reached the 80% RH level near the wood based products. During the first four months after installation, the structural members remained, unaffected by any moisture accumulation, however the plywood sheathing could have been prone to high moisture contents in the assembly.

MCS were fastened to four locations on the sheathing of the baseline and high performance assemblies. There were two MCS added at 762 mm (30") and 914 mm (36") up from the bottom plate in the center of the cavity. This provided one measurement aligned with a center of VIP in the exterior insulation and one measurement aligned with the EPS in the exterior insulation. These were positioned as the two highest risk areas for moisture content increase. The data was logged for February to June and results are plotted in Figure 9. In the baseline assembly, the measured moisture content remained below the 20% moisture content threshold, but was increasing during May 2017. The elevated moisture content coincided with increased relative humidity within CE-BETH and the wall cavities. The moisture content in the sheathing behind the EPS was found to be increasing during the same period, however, did not reach 20% moisture content level. The moisture content at each point in the structural members and sheathing remained below the 20% moisture content threshold for potential mold growth and rot, however, there is not sufficient data to conclusively determine if this assembly is suitable in the Ottawa climate. As such, the test assembly needs be exposed and monitored for the remainder of the 2017 seasonal cycle.

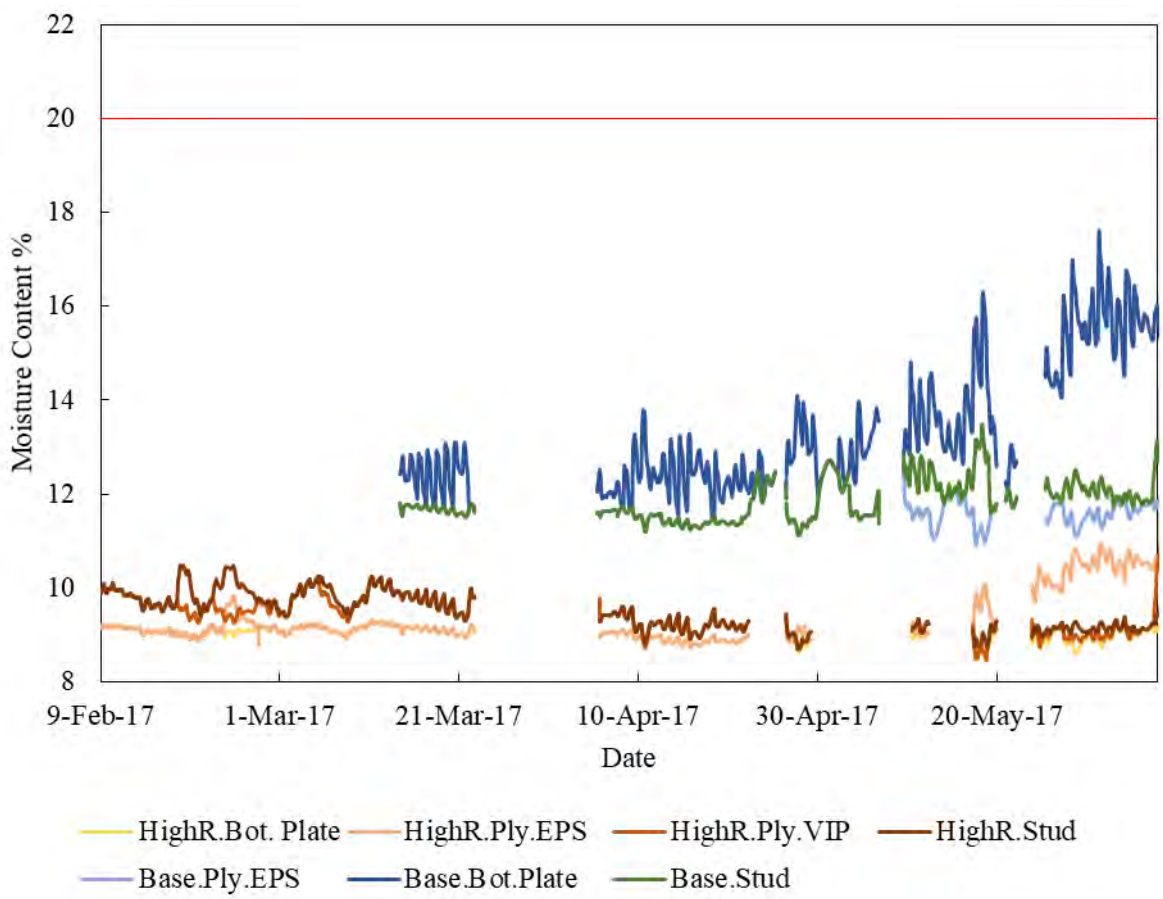

Figure 9: Moisture measurement of structural members (wood studs) and sheathing (plywood) from the baseline and high performance assemblies from February 9th 2017 to June 7th 2017

ANALYSIS AND DISCUSSION

Retrofitting the building envelope to a thin profile is possible with VIPs in the exterior sheathing. Integrating VIPs into the exterior insulation would provide sufficient insulation for a high RSI-value envelope. The VIPs are however, vapour impermeable, which could cause issues near the wood-based components by limiting the outward drying potential of the assembly. Since the exterior insulation also contains vapour permeable EPS, it may provide sufficient drying potential for a building envelope in a cold, humid climate such as Ottawa. The experimental data presented through this study is preliminary, as it is the first four months of a yearlong study on the moisture transport through a thin, high RSI building envelope retrofit assembly with no interior vapour barrier. While the moisture from the winter season was not trapped and high levels of moisture content in the wood-based materials were not seen, it is too early to confirm that this assembly could be feasible for this climate.

The advantage of this envelope arrangement is demonstrated by the moisture levels at the sheathing of the high performance assembly at points in line with the VIP and EPS in the exterior insulation. The measured moisture content at these points compared to the baseline was significantly lower, likely due to a higher temperature caused by the increase in exterior insulation value. The relative humidity in the high performance envelope remained safely below the 80% threshold at the surface of organic materials where moisture related deterioration can occur. The relative humidity was elevated at the drywall and batt insulation interface, however, there is no deterioration that can occur at that point. It is interesting to note the change in moisture performance since the beginning of spring. In both assemblies, the moisture content and relative humidity began to increase, and while it was still below the 20% moisture content threshold, the moisture content had not stopped trending upwards. If this trend continues over the 2017 summer season, the applicability of this envelope system would be questioned.

Continued monitoring of the building assemblies is required to ensure that the assemblies have sufficient drying potential. After a full year of exposure to climatic conditions and data acquisition, the relative humidity and moisture content readings of these assemblies will be compared to a set of failure criteria to determine whether they have sufficient drying potential or any risk of organic growth or related deterioration caused by moisture issues.

CONCLUSION

While homes that require “major repair” are a subjective measure from non-experts, the principle that these homes may require significant investment in the near future provides an opportunity. The envelope, as mentioned, is a target and measurably increased above today’s code-built homes, should be targeted during major renovations to these older dwellings to improve them to meet code today. The building envelope for the dwellings built before the 1970s clearly lack the construction necessary to perform up to the current energy performance standards and represent an opportunity to significantly lower the consumption of energy in the building stock.

At the CE-BETH facility, a specimen was built to represent a building envelope built in the 1970s era residential dwelling with a combination of VIP/EPS exterior insulation. The temperature, relative humidity throughout the assembly and moisture content of the wood-based materials were monitored and the results

were presented for January 2017 to June 2017. By controlling the temperature and relative humidity inside the test facility, the measured relative humidity and moisture content within the cavity remained well below the safety threshold. Beginning in May 2017, the moisture levels began to increase steadily within the assembly. The assembly will continue to be monitored under the test conditions for the remainder of the year to determine whether the assembly is suitable for the cold and humid climate.

REFERENCES

ASHRAE. 2016. *Standard 160-2016 -- Criteria for Moisture-Control Design Analysis in Buildings.* Atlanta, GA: American Soceity of Heating, Refrigeration, Air-conditioning Engineers.

Carver, Mark. 2016. "Envelopes Gaps and Drivers." Workshop, Ottawa, Ontario.

EuroStat. 2016. *Final Energy Consumption , EU-28, 2014.* European Commission.

Ministry of Municipal Affairs. 2014. *Ontario Building Code.* Toronto, Ont: Minisitry of Municipal Affairs - Building and Developement Brach.

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

Natural Resources Canada. 2015. *Energy Use Data Handbook 1990 to 2013.* Ottawa, Ontario: Natural Resources Canada - Office of Energy Efficiency.

NBBC. 2015. *National Building Code of Canada 2015.* Ottawa, Ont: Institute for Research in Construction, National Research Council of Canada.

NECB. 2015. *National Energy Code of Canada for Buildings 2015.* Ottawa, Ont: National Research Council of Canada.

Parek, Anil. 2012. "Next Generation Standards for Housing Efficiency." *The New Energy Code: A Driver for Efficiency in Building and Construction Workshop.* FP Innovations, February.

Statistics Canada. 2016. *2011 National Household Survey.* Statistics Canada. 11 23. Accessed 06 27, 2017. http://www12.statcan.gc.ca/nhs-enm/2011.

United States Department of Energy. 2016. *International Energy Outlook 2016.* Washington, DC: U.S. Department of Energy.