Evaluation of the Long-Term Performance of Vacuum Insulated Panel Walls and the Energy Use Assessment of a Net Zero Energy House

Anil Parekh, M.A.Sc., P.Eng.
Natural Resources Canada
Ottawa, Ontario
Member, ASHRAE

Christopher Mattock B.A.E.D.
Principal HD+C Ltd.
Vancouver, British Columbia

ABSTRACT

In 2011, Canada's pioneering EQuilibrium Homes Initiative developed and sponsored by Canada Mortgage and Housing Corporation (CMHC) supported the construction of a number of net-zero energy demonstration homes across Canada. One of the most successful projects, Harmony Home located in Burnaby, British Columbia, demonstrated the use of vacuum insulated panels (VIPs) for above-grade walls, low u-factor windows, high performance mechanical systems and grid connected photovoltaics to achieve zero energy levels. The exterior VIP wall assemblies consisted of 15 mm thick VIPs in the center of the stud cavity, covered by a 50 mm foil-faced isocyanurate foam board on the exterior and open cell spray-foam on the interior. This provided an estimated effective insulation, averaged over the entire wall, of 38.5 ft²F/Btu (R) or 6.8 m²K/W (RSI). This field study evaluated the long- term performance of this home after five years of operation with respect to heat transmission through the building envelope, moisture performance of VIP wall assemblies and annual energy consumption. The thermographic survey of wall assemblies and joints showed that vacuum insulation panels are intact and, overall, building envelope is in excellent condition. In-situ wall assembly moisture measurements, gathered in four wall sections in different orientations, within the framing and sheathing showed no appreciable moisture accumulation.

The energy use data over a period of five years showed varying trends: (1) photovoltaic systems were performing as per the design intent; however, on year-to-year basis, there was a significant ±20% variation in electricity generation mainly due to climate conditions; (2) occupant-driven load showed little changes; and (3) significant variations in space heating and space cooling requirements. Overall, the Harmony Home demonstrated comparatively close to net-zero energy performance over the years.

INTRODUCTION

Canada is leading the development of clean energy technologies for residential and commercial buildings to achieve net-zero energy use targets. CMHC's flagship Equilibrium Houses Program led the demonstration of market-ready clean energy technology solutions for achieving net-zero energy performance levels [CMHC 2011]. The key questions about net-zero houses relates to long-term energy performance:

- response to differing climate conditions on a year to year basis;
- reliability and durability of innovative building envelope system such as the use of vacuum insulation panels, aerogel blankets, high-R windows, and so on;
- energy performance of solar thermal and solar electricity generation systems; and
- homeowner driven energy usage for electricity and space conditioning as well as atypical loads.

This paper reviews the long-term performance of a NZE home in terms of energy use, building envelope durability and the performance of the exterior walls that incorporated vacuum insulation panels of a well-documented net-zero energy home.

PROJECT OVERVIEW

The Harmony House Project is a single family home of 438 m^2 (4,714 ft^2) completed in Nov 2011. It was constructed under a national net zero energy EQuilibrium Housing Demonstration Initiative sponsored by Canada Mortgage and Housing Corp with technical support provided by Natural Resources Canada. The home is located in the greater Vancouver British Columbia area ASHRAE Climate Zone 5C (Marine) annual heating degree days (base 18^{o}C) over past 25 years range from 2497 DDC (4495 DDF) to 3065 DDC (5517 DDF).

Figure 1: Harmony House front; south elevation showing triple-glazed windows, PV array; and interior. (www.harmony-house.ca)

Project Design

The Design team's goals for the project included:

- Design and construct a net zero energy home that would exceed client expectations in terms of aesthetics, comfort, functionality and energy performance.
- Reduce space heating energy consumption by 75 to 80% compared to current local building code through a combination of super insulation, airtightness, high performance glazings, heat recovery ventilation and high efficiency space heating equipment.
- Negate the need for mechanical cooling through control of solar heat gains in late spring, summer and early fall and the use of wind and stack driven air flow cooling. This in a climate in which climate models predict will have greater increases in cooling requirements than the global average due to climate change.
- Minimize electrical power consumption for lighting, appliances and heating equipment through use of high efficiency equipment and controls
- Provide power for all energy requirements on an annual basis using onsite renewable energy through a combination of passive solar heating, daylighting, wind and stack driven air flow cooling, solar DHW and grid connected PV
- In addition to powering the home provide power to cover transportation energy use

The design team's other environmentally related goals included utilization of: recovered materials; resource efficient materials; recycled materials; chemically inert interior finish materials to minimize off gassing; rain water harvesting for landscape irrigation; and water efficient plumbing fixtures.

Building Enclosure

The building enclosure systems used in the home consisted of the following:

- 5" (125mm) thick basement floor slab with 15 mil polyethylene moist / gas barrier on R 20 (RSI 3.5) extruded polystyrene foam on 4" (100mm) thick ¾" (19mm) drain rock.
- Basement walls consist of insulated concrete forms, joints air sealed with closed cell spray foam for airtightness with 8" reinforced concrete cores, self-adhering water proof membrane and dimpled plastic drainage plane. The interior face of the foundation walls are covered in drywall. Assembly has an effective thermal resistance of R40 (RSI 7)
- The foundation walls rest on footings that were cast using reinforced polyethylene "fabric" forms allowing for easy leveling of the ICF wall and providing a capillary break between the footing and the ground.
- Above grade walls (Fig 2) consisted of Drywall, 2x6 studs @ 24" on centre, 2 7/8" (73mm) castor bean oil based open

cell spray foam , 5/8" (15mm) vacuum insulation panel , 2" (50mm) foil faced isocyanurate foam board, ½" (13mm) plywood sheathing , taped spun bonded polyolefin building wrap , 1x4 (19 x 89mmvertical strapping and wood fiber reinforced cement cladding. This assembly has an effective thermal resistance of R38.5 (RSI 6.8)

- The cathedral ceiling consisted of drywall, 16" (405mm) deep wood I joists @ 24" (610mm), 16" (405mm) castor bean oil based open cell spray foam, 5/8" (16mm) plywood sheathing , vapor permeable self-adhering membrane , 2" (50mm) foil faced isocyanurate foam board , roofing underlayment , standing seam metal roof. This assembly has an effective thermal resistance of R60 (RSI 10.57)
- The attic ceiling consisted of drywall , raised heel roof truss, 4" (100) castor bean oil based open cell spray foam, blown cellulose fiber This assembly has an effective thermal resistance of R60 (RSI 10.57)
- Windows and glass doors consisted of pultruded fiberglass frames with insulated cores, triple glazing IG units with two low E coatings, argon gas fill. The effective thermal resistance for windows and glazed doors ranged from R4.7 (RSI 0.8) to R 6.6 (RSI 1.2).
- Air Barrier Systems - Basement floor slab and radon gas barrier, ICF walls with spray urethane sealing at numerous joints, open cell spray foam in exterior wood frame walls with VIPs sealed to studs, open cell spray foam in cathedral and attic ceilings.

Design of Super Insulated Thin Wall Assemblies

One of the primary innovations in the home was the development of a super insulated thin wall assembly which has an effective thermal resistance of R38.5 (RSI 6.78) and the same thickness as a conventional 2x6 wall (Fig 1). Use of thick super insulated wall assemblies can be problematic in urban locations due to set back requirements, cost of land and possible reductions in floor areas. Cost analysis also indicates that super insulated thin wall assemblies have the potential for being less expensive than conventional super insulated wall assemblies when lost floor area is accounted for. Depending on the local market builders are showing resistance to adopting thicker wall technologies such as higher levels of exterior insulation, double stud and wood I studs. This wall assembly utilizes vacuum insulation panels (VIPs) which consist of a rigid fiberglass core, getters, desiccants and a composite aluminum / plastic skin. The initial vacuum in the panels is less than 5mbar. The particular panels used were rated at R60/inch (0.42 RSI /mm) and were 5/8" (15mm) thick. In addition VIPs are becoming cheaper, more durable and have a longer service life than in the past. The VIPs were located near the centre of the assembly to minimize puncturing by nails or screws. Castor bean oil based open cell spray foam was used for the inner layer of insulation and to provide an effective air barrier within the assembly. The wall assemblies also utilized advanced framing techniques to reduce thermal bridging.

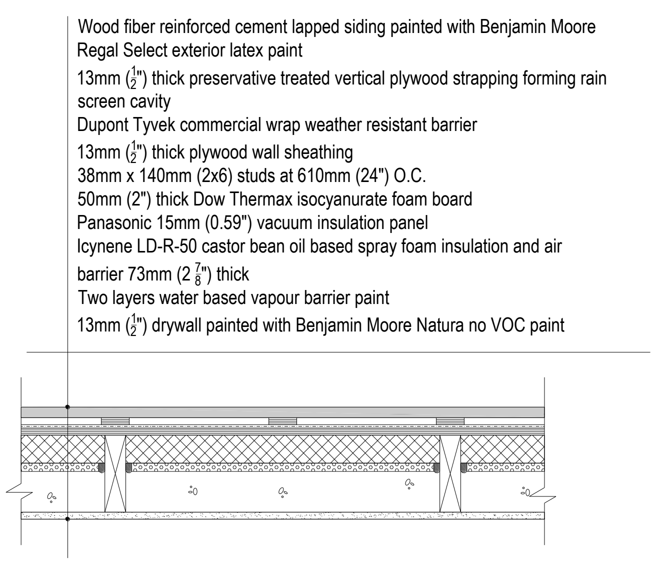

Figure 2: Exterior above grade wall assembly plan section

Space Heating System

Space heating is provided by a combination of passive solar heat gain, internal heat gains and a high efficiency cold climate air source heat pump. South facing windows represent 7% of the heated floor area of the home and contribute 20% of the annual pace heating. Cold climate air source heat pump rated at 9.8 HSPF provides 40% of the space heating with the remaining 40% provided by internal heat gains. The forced air heating system distribution also serves to redistribute solar heat gains within the home.

Reducing Occupant Driven Energy Loads

The design team focused on reducing other aspects of energy use in the home in order to reduce the size of the PV array required. These areas of energy use included lighting, appliances, ventilation, and domestic water heating and cooling.

The strategies for reducing energy consumption for lighting included daylighting, use of high efficiency lamps and fixtures and use of lighting controls to coordinate with daylighting and occupant activities. Enhanced daylighting was achieved through the use of an open floor plan; clerestory windows into common space; large areas of view window; tall windows with typical head height of 8'; north facing skylights into main open space and upstairs bathrooms; reflective interior wall and ceiling finishes, and light sharing between spaces using glass railings, interior glass doors and interior skylights.

The majority of lamps used in the home were LEDs with some tubular fluorescent lamps. Daylight sensing controls were used to reduce use of electric lighting in the main space of the home during the day. Motion detectors where used in other spaces to switch lights off when the spaces where not in use. A central "green switch" was used to shut off all unnecessary lighting when home unoccupied

Hot water conservation measures included low flow plumbing fixtures, water efficient horizontal axis washing machines and water efficient dish washers. The domestic water heating system consisted of two flat plate 4'x8' solar collectors with PV powered pump, heat exchanger and 40 gallon storage. The backup water heating is provided by an exterior air source heat pump. This combination of technologies resulted in an 80% reduction in domestic water heating energy requirements.

Figure 3: Construction of super insulated thin wall

Figure 4: Daylighting in living room

Although the air source heat pump system could provide mechanical cooling this aspect of the system was not implemented and instead a natural cooling strategy was employed. This included control of solar heat gains through horizontal overhangs over south facing windows, vegetation on the east side of the home and use of low E solar rejection coatings on west facing windows and glazed doors. Air flow cooling was driven by both stack effect and wind through a combination of large south facing opening windows, large north facing skylights and a short roof stack. Monitored performance reported by a research team at BCITi established that the natural cooling strategy met occupant expectations for thermal comfort.

Photovoltaic System

The photovoltaic system was designed to provide 16.35 MWH per year. It consisted of two PV arrays consisting of:

- Thirty four 225 watt poly-si panels with a power capacity of 7.65 kW oriented due south sloped at 25 degrees from horizontal. Predicted annual production 8.71 MWh
- Thirty two 225 watt poly-si panels with a power capacity of 7.2 kW oriented due south sloped at 5 degrees from horizontal. Predicted annual production 7.64 MWh
- Each array has a 7 kW inverter to convert DC to AC and sync with the electrical grid

Energy Use Estimate

A series of models were used in developing the design of this project including:

- For space heating and auxiliary space heating system sizing : HOT2000 ver 10.51
- Electric lighting loads were estimated using a spreadsheet that accounted for all light fixtures in the home, use of the space in which the lighting fixture was located, the daily hours of daylight typical for each month of the year and use of daylighting controls if applicable.
- Appliance loads were calculated using published data for all major appliances and generic values for smaller appliances. The performance of the photovoltaic and Solar domestic water heating systems were calculated using Retscreen

As Built Building Envelope		Effective RSI	Effective R
	Exterior Above Grade Walls	6.78	38.5
	Exterior Below Grade Walls	7.00	39.7
	Foundation Floor Slab	3.54	20.1
	Ceiling Insulation	10.50	59.6
	Fixed Windows	1.14	6.5
	Opening Windows	0.95	5.4
	Glazed Doors	0.95	5.4
	Skylights	0.63	3.6
Airthightness		1.13 ac/h @ 50 Pa	NLA 0.6 cm2/m2

Base Loads			
		kWh/day	kWh/yr.
	Lighting	5.19	1,894
	Appliances+ miscellaneous	18.10	6,607
	Exterior Use	1.14	416
	HVAC Fans		
	HRV/Exhaust	2.51	915
	Space Heating	0.01	5
	Total Average Electrical Load	26.95	9,837

Figure 5: Building envelope insulation values and electricity baseloads for the Harmony House.

Energy Balance Sheet			
Annual Energy consumption (GJ)		**Renewable Energy Generation (GJ)**	
Space heat	7.7	Photovoltaic system	45.9
DHW	13.0	Solar DHW	9.2
Ventilation	1.1		
Baseloads	32.1		
TOTAL	**53.9 GJ**		**55.1 GJ**
	511 Therm		**522 Therm**

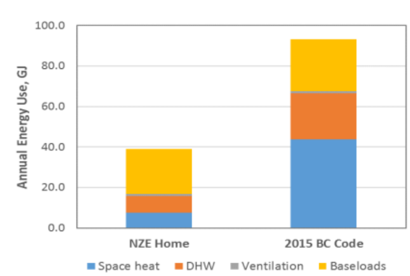

Figure 6: Annual energy use balance for Harmony House. As per 2008 BC Code, energy use estimate is 93 GJ (881 Therm).

Figures 5 and 6 shows the 'as-built' energy analysis results of the Harmony home. With the 'as-built' building envelope and systems, annual energy consumption is almost equally matched with on-site renewable energy generation. If this house was built according to standard 2008 City of Vancouver code requirements, its annual energy consumption estimate is 93 GJ (881 Therms).

The net-zero energy home reduced the space heat requirements from 43.7 GJ to mere 7.7 GJ – a whopping 83% reductions mainly due to very efficient building envelope components. Figure 7 shows the path to net-zero beginning with building envelope measures (higher insulation, low u-factor windows), efficient HVAC (cold climate heat pump), very efficient lighting, appliances and miscellaneous electricity devices and then, finally, introduce the solar hot water and photovoltaic system to match the remainder. Our analysis shows that, in Canadian climates, solar electricity generation of 8 MWh to 12 MWh (or equivalently 6 kW to 12 kW PV System) is required to reach the net-zero energy on annual basis. Incremental cost ranges from $45,000 to $65,000 to achieve net-zero energy target compared to 2015 Code built homes.

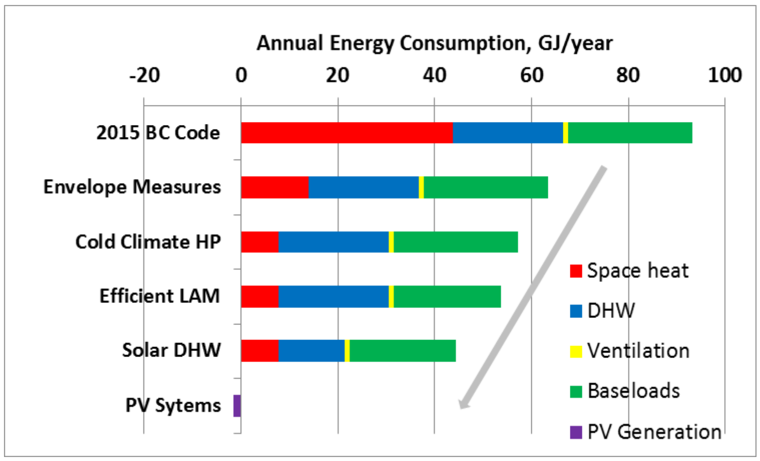

Figure 7: Path to Net-Zero – technology and systems approach to achieve balance of energy consumption and generation.

FILED ASSESSMENTS AND PERFROMANCE MONITORING RESULTS

Electrical Energy Consumption and Production

The only purchased fuel in this home is electricity. This allowed for the use of BC Hydro utility bills as an accurate measure of the total energy consumption of the home. Annual summaries, drawn from the utility bills, of the total power consumption and PV power production for the years 2014, 2015 and 2016 is shown in the following table. Utility bills analysis is normalized for the weather data for these years. Figures 8, 9 and 10 shows the energy use and generation profiles for the house. On an average energy use predictions were within 4% over the years compared with measured data. The renewable energy generation, particularly PV production, was 20% over estimated compared to year-to-year generation. This is always going to be challenging.

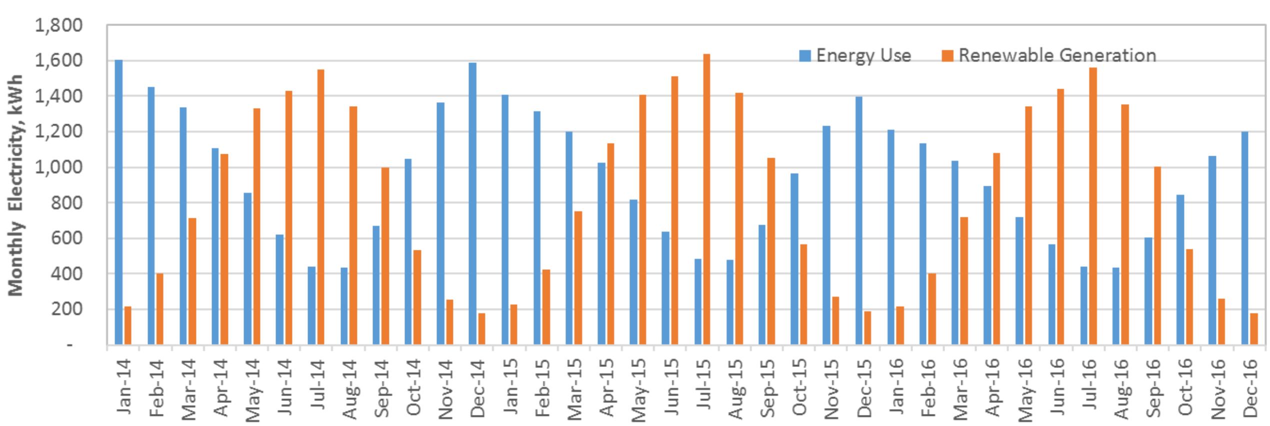

Figure 8: Monthly measured energy consumption and renewable energy generation (PV + Solar DHW).

	Energy Use Profile (kWh)			
	Measured (average for 2014-2016)		Predictions	
	Consumption	Generation	Consumption	Generation
Jan	1,407	219	1,243	250
Feb	1,300	410	1,020	454
Mar	1,190	728	1,015	939
Apr	1,009	1,095	885	1,406
May	796	1,361	895	1,789
Jun	609	1,460	857	1,817
Jul	457	1,584	871	1,994
Aug	450	1,370	878	1,712
Sep	649	1,017	869	1,230
Oct	952	547	957	671
Nov	1,220	261	1,070	290
Dec	1,394	181	1,250	203
Total	**11,434**	**10,233**	**11,811**	**12,755**

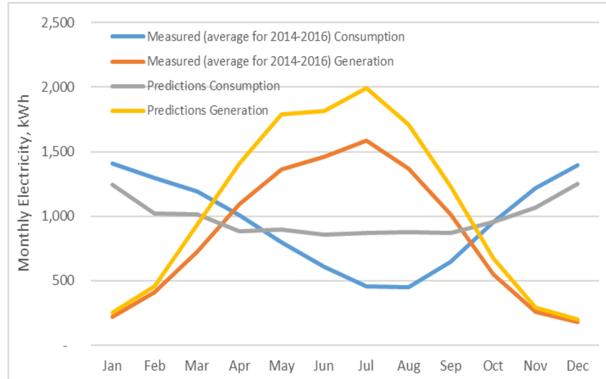

Figure 9: Comparisons with the measured and predictions.

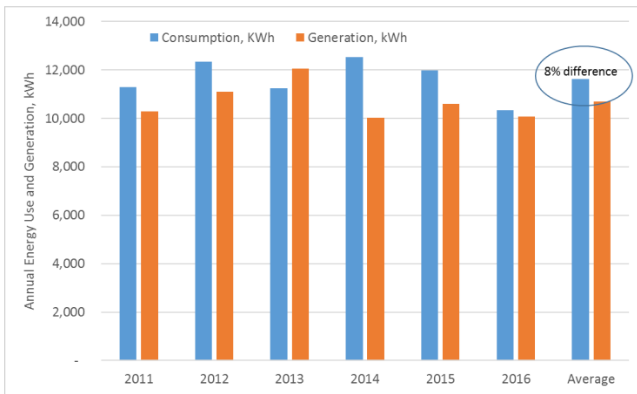

Figure 10: Comparisons over six years with the measured and predictions.

Airtightness measurements

The air barriers in the Harmony House project consist of the basement floor slab with a continuous polyethylene moisture barrier below, ICF concrete basement walls (with numerous closed cell spray foam patches), Icynene LD-R-50 Castor Bean Oil spray-foam in the above grade walls and the ceilings. Upon completion of the construction of the home it was airtightness tested and found to have an air change rate of 0.73 ACH @ 50 Pa and a normalized leakage area (NLA) of 0.30 cm^2/m^2@ 10Pa.

In March 2017, the house was airtightness tested using fan door depressurization following the CGSB 149.10 testing standard. It yielded an air change rate of 1.13 ACH or 1.89 $m^3/h/m^2$ of enclosed area with +/-3.3% of uncertainty. All exterior doors were locked and closed. This included the door to the garage as the garage space was excluded from the test volume. Ventilation openings for the HRV and dryer vent are sealed from the outside. These were located on the north and east façade underneath the porch. All windows were closed and locked and internal doors were open.

Based on the initial and recent airtightness testing it is apparent that the air leakage rate of the home has increased over time approximately 54%. The locations of increased air leakage were investigated and were determined to be the following:

- Perimeters of opening windows needs to be corrected through adjustments to the multipoint locking hardware
- Perimeters of exterior doors needs adjustments to the multipoint locking hardware
- Sprinkler head penetrations through exterior ceilings, these occur at one or more locations in each room and appear to be a major location of air leakage.

Thermographic Survey – Infrared Scan with Pressurization

The infrared scan was performed in general conformance with ASTM E1186 "Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems" using the infrared scanning with pressurization techniques. Prior to conducting the infrared scan a propane fired fan heater was used to force heated air into the building to create a positive building pressure and high temperature difference relative to the exterior.

Figure 11: Propane fired fan heater and an interior view of the front door opening with panels the fan heater flex ductwork installed

The ASTM standard states, "Normally, a pressure differential of 10 to 50 Pa is adequate in most cases" and that "pressure differentials of as high as 50 Pa will enhance airflow through the air leakage sites and aid in the rapid cooling (or heating) of the building surfaces". An average positive and negative pressure differential of 40 and 25 Pa respectively was achieved during the test. The positive pressure differential was applied at 7:00pm on the day of testing, and maintained for an hour prior to commencing the scan. All the exterior walls were scanned, as well as the roof. The positive pressure infrared scan was conducted from 8:00 pm to 8:25 pm at an ambient exterior temperature of 7°C and a dew point of 7°C. The negative pressure infrared scan was conducted between 9:00 pm and 9:30 pm at similar conditions of 7°C exterior temperature and 7°C dew point. The interior temperature was raised prior to testing using the fan heater. The internal temperature at the start of the test was 28°C.

Infrared Scanning and Air Leakage Detection vs Thermal Conduction

An infrared scan identifies locations on the building that are significantly warmer or colder than the surrounding building surface temperatures. Some known hot spots such as louvers, vents, and mechanical equipment will be much warmer or colder than the surrounding surface temperatures. When the cause of hot or cold spots is unknown they are referred to as thermal anomalies. Thermal anomalies are generally a result of either a thermal bridge, such as a structural member passing though the insulation, or air leakage. It is possible to isolate thermal bridge anomalies from air leakage anomalies by performing a thermographic scan under both positive and negative pressure. When the building is pressurized warm air is forced out through the holes in the air barrier. This results in a warming of the wall components adjacent to the exfiltrating air, which is visualized by the thermographic camera. When the building is depressurized; the warm exterior surfaces are no longer exposed to exfiltrating air and will begin to cool. Under negative pressure the thermal bridge anomalies will be unaffected by the change in pressurization and will remain a similar temperature on both the positive and negative scan. To determine the locations of probable air leakage, the results of both the positive and negative pressure infrared scans are compared. All areas with warm thermal anomalies during the pressurized scan that were subsequently reduced during the depressurized scan are identified as air leakage anomalies.

A few of the images take during this test are shown below. The image sets show a visible light photograph, an infrared positive pressure scan, and an infrared negative pressure scan of the same areas of the building. Commentary is provided with each image discussing areas of potential air leakage. The combination of infrared scans found numerous locations of suspected air leakage through the building enclosure assemblies and interfaces.

Figure 12: Kitchen patio doors on East Elevation.

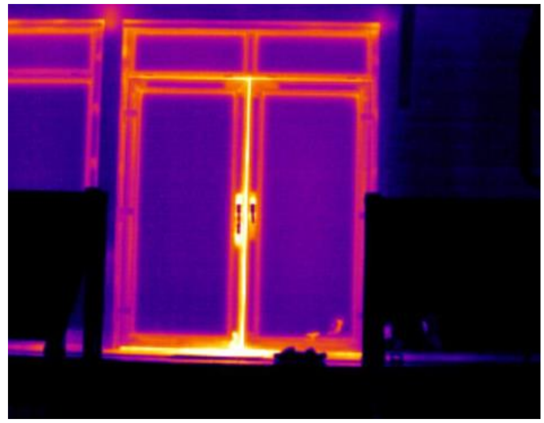

Figure 13: Positive Pressure Thermal Scan Anomalies at patio doors.

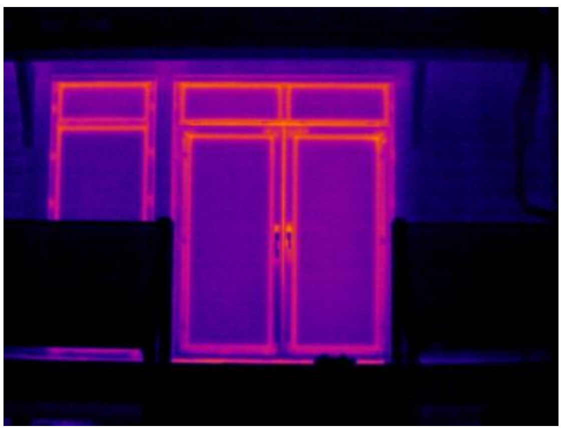

Figure 14: Anomalies are still present but reduced suggesting both air leakage and thermal bridging.

Figure 15: Shed roof line, and exhaust vent along North Elevation.

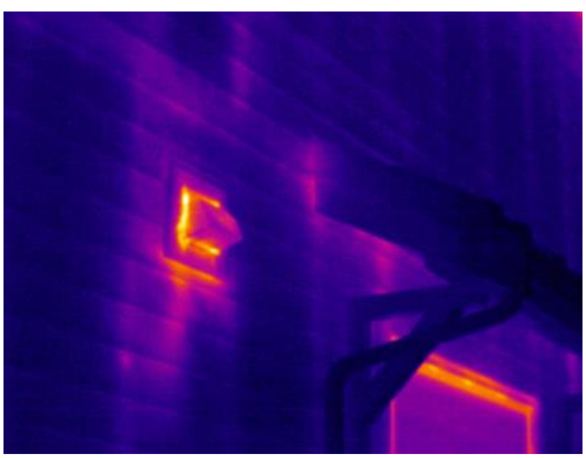

Figure 16: Positive Pressure Thermal Scan Anomalies at hood and shed roof line

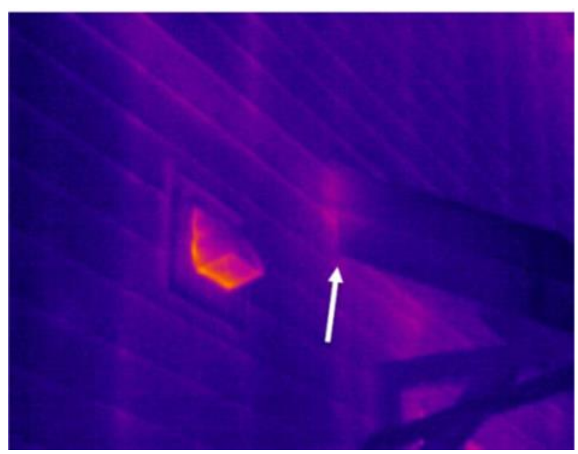

Figure 17: Negative Pressure Thermal Scan Anomalies are still present suggesting thermal bridging.

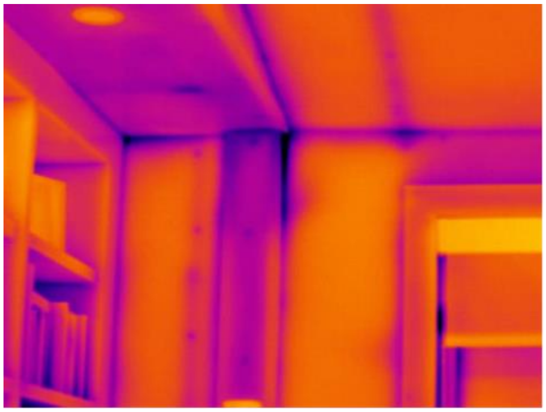

Figure 18: Office south facing wall thermal vertical thermal anomaly see adjacent photo

Figure 19: Office south wall during insulating showing PSL column seen as thermal anomaly

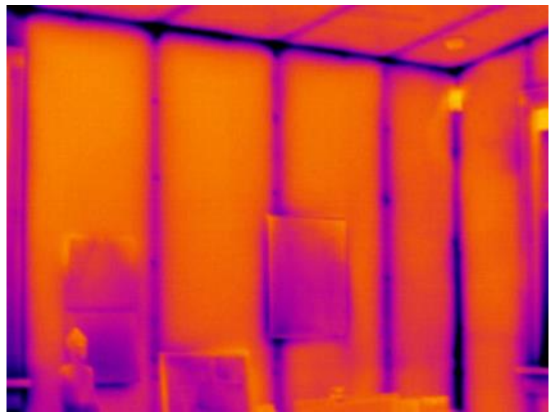

Figure 20: Construction view of interior office space west side of south facing wall

Figure 21: Thermal scan of interior office space west side of south facing wall

In general, there were few air leakage anomalies noted. Air leakage was typical at operable vents and doors but was not excessive. This could be reduced by adjusting the multipoint locking mechanism at these locations. There were a few isolated air anomalies noted in the walls but all appeared to be small. There did appear to be significant air leakage occurring at the underside of the roof soffits particularly on the north elevation. We reviewed the interior and this likely a result of the fire sprinkler penetration into the ceiling. If the sprinkler lines penetrate the air barrier, then this would account for the thermal anomalies in the soffits. We also noted 3 locations on the underside of the ceiling where there was a thermal anomaly. This could be a result of a void in the open cell insulation where a concavity was formed when the insulation was scrapped after it finished curing or from less than complete filling of the cavity. One of these locations appears to be related to a structural column due to its location the shape and size of the anomaly.

BUILDING ENVELOPE - FRAMING MOISTURE

The durability of the building envelope is primarily related to the moisture content of the framing and structural sheathing. Hygrothermal simulations run at the time of the design of this project indicated that the most elevated moisture content for the entire home would be experienced in the north wall sheathing and outer framing. This indeed proved to be the case during the first round of monitoring.

48 sensors measuring temperature, RH and moisture content were installed for the original building envelope performance monitoring. The data produced by these sensors was collected through an internet gateway and stored by the sensor / gateway manufacturer Omnisense Inc. Sensors located on the inside and outside faces of the framing for all orientations were still functioning on November 25, 2016. A review of data from the first round of monitoring showed a close correlation between the

moisture content of the north wall sheathing and the moisture content as measured by the sensor located at the outside centre of the north wall bottom plate (N4). In order to minimize the invasive nature of this study the existing functioning sensors were used for evaluating the moisture content of the house framing and sheathing.

Using the existing functioning sensors a survey of the moisture content of the house framing was carried out for a period from November 2016 to March 2017 for North, East and West walls. The measured temperature and wood moisture content at selected locations is shown below. As can be seen the moisture content of the homes framing is in all cases below 19% which is the maximum allowable moisture content for framing under the BC Building Code. At these levels deterioration of the framing due to fungus mold and mildew is eliminated. The low moisture content can be attributed to an effective air barrier preventing entry of indoor moisture laden air, a vapour barrier preventing diffusion of indoor moisture, a rainscreen and weather resistant barrier that has prevented entry of exterior precipitation and that have also effectively promoted drying through natural convection and vapour diffusion.

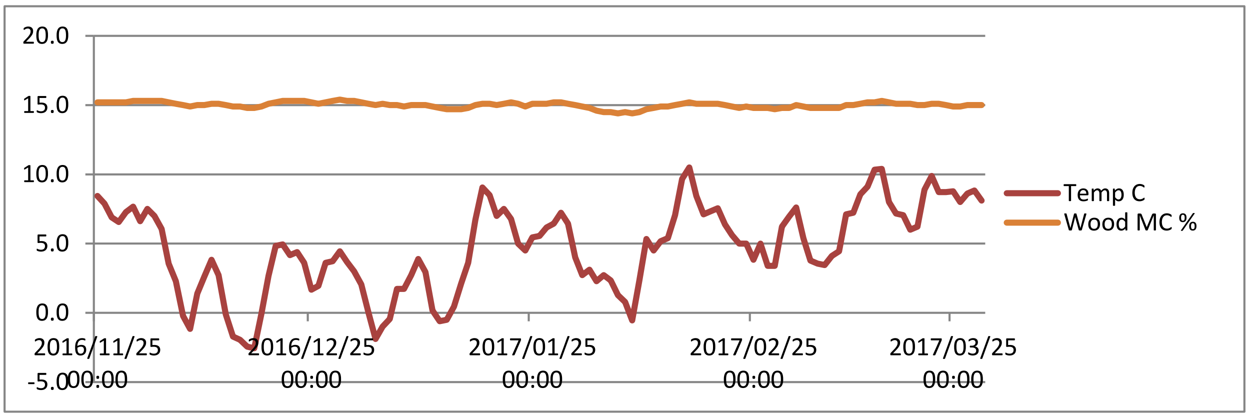

Figure 22: Moisture content and temperature vs time for sensor N4 located in the North exterior wall adjacent to the exterior sheathing. This represents the most critical location for elevated moisture content in the entire homes framing. With a MC in the range of 15% the framing is below the 19% MC called for in the BC Building Code.

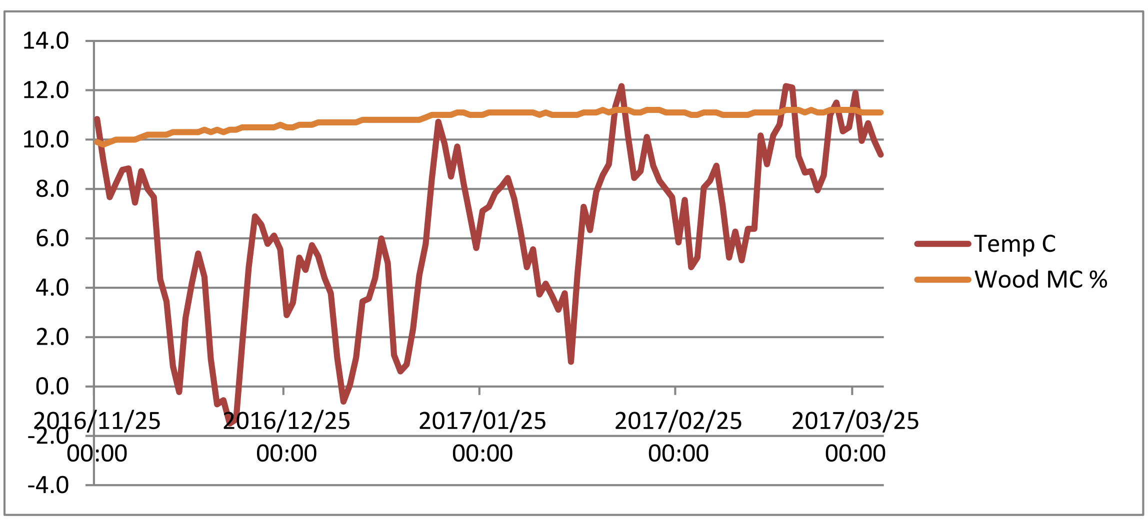

Figure 23: Moisture content and temperature vs time for sensor E4 located in the East exterior wall adjacent to the exterior sheathing. With a MC in the range of 11% the framing is well below the 19% MC called for in the BC Building Code.

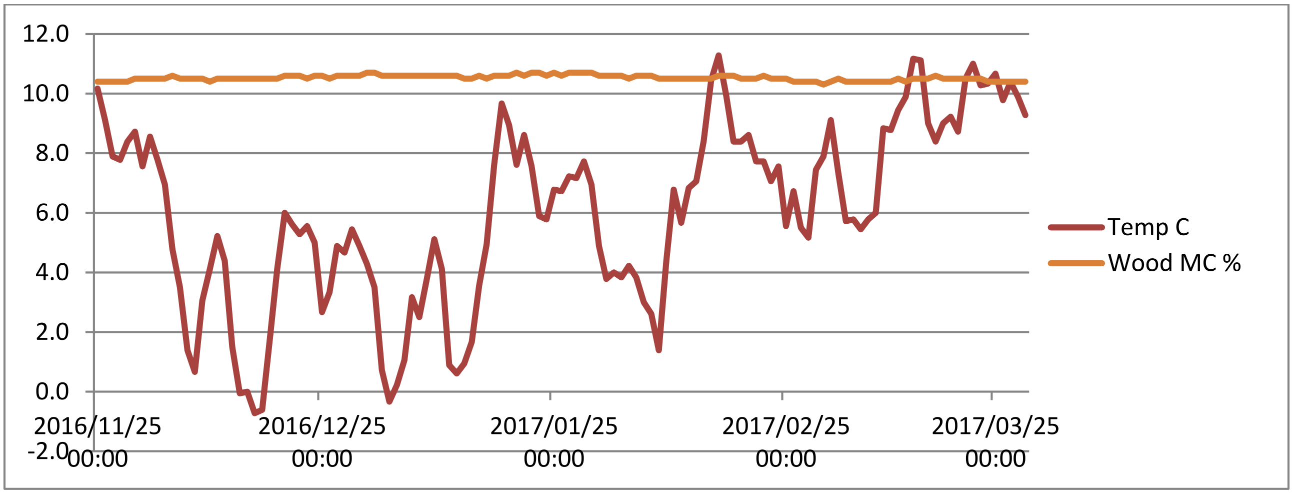

Figure 24: Moisture content and temperature vs time for sensor W4 located in the West exterior wall adjacent to the exterior sheathing. With a MC in the range of 10% the framing is well below the 19% MC called for in the BC Building Code.

CONCLUSIONS / LESSONS LEARNED

- Home essentially performs to net-zero energy target with year-to-year variations due to climate and occupant behavior. The envelope related loads (space heating) are much lower and are close to design intent. Renewable energy systems, particularly, photovoltaic systems are under performing compared to design stage estimates. More detailed PV energy generation predictive methods should be used.
- Vacuum insulation panel (VIP) wall assemblies continue to perform after 5 years in place. Use of VIPs demands strict spacing of framing and care in handling
- The combination of a continuous air barrier, weather resistant barrier and rain screen results in wood framing and sheathing with moisture content well below 19% as prescribed by building code
- The air barrier performance changed over time due to framing shrinkage, leakage around sprinkler heads, loosing of opening windows and exterior doors.

ACKNOWLEDGEMENTS

We would like to acknowledge the following individuals and organizations that helped make this project possible:

- Numerous individuals at the Research Division of Canada Mortgage and Housing Corporation and at CanmetENERGY Natural Resources Canada for their guidance and support
- Numerous suppliers in building industry in British Columbia who supported the project with products, materials and expertise.
- B.C. Hydro and Power Authority for technical support and cooperation
- The project clients Les and Lynda Moncrieff for their amazing patience and continuing cooperation.

REFERENCES

J. Ellis, J. Schwartz & R. Mora (2016): Assessment of natural ventilation effectiveness for an active NetZero energy house, International Journal of Ventilation.

C. Mattock March 2017: Building Envelope Assessment and Long Term Energy Use Performance of a Net Zero Energy House Project, Housing and Buildings R&D CanmetENERGY Natural Resources Canada

C. Mattock March 2008: Review and Evaluation of Vacuum Panel Insulation for use in Net Zero or Near Net Zero Energy Low-Rise Residential Construction, Canada Mortgage and Housing Corporation External Research

C. Mattock "Tsuchiya Twoby Home Net Zero Energy Super E House Project Report" Natural Resources Canada March 30, 2008

P. Mukhopadyaya "High Performance Vacuum Insulation Panel" IRC NRC Research Update Global Insulation October 2006

Binz, A., A. Moosmann, G. Steinke, U. Schonhardt, F. Fregnan, H. Simmler, S. Brunner, K. Ghazi, R. Bundi, U. Heinemann, H. Schwab, H. Cauberg, M. Tenpierik, G. Johannesson and T. Thorsell. 2005. Vacuum Insulation in the Building Sector - Systems and Applications (Subtask B). IEA/ECBCS Annex 39, pp. 1-134.

Bomberg, M.T. and M.K. Kumaran. 1991. "Evaluation of Long-Term Thermal Performance of Cellular Plastics Revisited." ASTM Special Technical Publication, 1116, Symposium on Insulation Materials: Testing and Applications (Gatlinburg, TN, USA, October 10, 1991), Philadelphia, PA: The American Society for Testing and Materials, pp. 123-141. (ISBN: 0803114206), (NRCC-35950) (IRC-P-3197 ASTM-STP-1116).

ECBCS (Energy Conservation in Buildings and Community Systems). Annex 39 High Performance Thermal Insulation Systems. <www.ecbcs.org/ annexes/annex39.htm>.

Glacier Bay, Inc. and. Web page. <www.glacierbay.com>.

Heinemann, U., R. Caps and J. Fricke. 1999. "Characterization and Optimization of Filler Materials for Vacuum Super Insulations." Vuoto scienza e tecnologia 28(1-2): 43-46, ISSN 0391-3155.

Kistler, S.S. 1935. "The Relationship between Heat Conductivity and Structure in Silica Aerogel." Journal of Physical Chemistry 39: 79.

Kumaran, M.K., M.T. Bomberg, R.G. Marchand, M.R. Ascough and J.A. Creazzo. 1989. "A Method for Evaluating the Effect of Blowing Agent Condensation on Sprayed Polyurethane Foams." Journal of Thermal Insulation 13 (October): 123-137. (Also published in CFCs and the Polyurethane Industry: Vol 2 : (A Compilation of Technical Publications, 1988-1989), (NRCC-35473) (IRC-P-3106).

Kumaran, M.K., P. Mukhopadhyaya, J. Lackey, N. Normandin and D. van Reenen. 2004. "Properties of Vacuum Insulation Panels: Results from Experimental Investigations at NRC Canada." Joint NSC (Taiwan)/ NRC (Canada) Workshop on Construction Technologies, Taipei, Taiwan, pp. 147-156.

Mukhopadhyaya, P., K. Kumaran, J. Lackey, N. Normandin and D. van Reenen. 2005. "Long-Term Thermal Resistance and Use of Vacuum Insulation Panel in Buildings." 10th Canadian Conference on Building Science and Technology, 2005, Ottawa, Canada.

"High Performance Thermal Insulation Systems – Vacuum Insulated Products" Proceedings of the International Conference and workshop EMPA Duebendorf, January 2001