Building application and thermal performance of vacuum insulation panels (VIPs) in Canadian subarctic climate

Mukhopadhyaya, P.; MacLean, D.; Korn, J.; van Reenen, D.; Molleti, S.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/j.enbuild.2014.08.038
Energy and Buildings, 85, pp. 672-680, 2014-12

Highlights

- VIP-foam sandwich elements are attractive for energy retrofit of building envelope.
- Construction challenges with VIP can be addressed through appropriate design.
- Insignificant thermal performance change of VIPs in 3 years in subarctic climate.

IVIS 2013 – Extended Paper

Building Application and Thermal Performance of Vacuum Insulation Panels (VIPs) in Canadian Subarctic Climate

P. Mukhopadhyaya[a],*, D. MacLean[b], J, Korn[c], D. van Reenen[a], S. Molleti[a]

[a] National Research Council Canada, Ottawa, Ontario, Canada

[b] Energy Solutions Centre, Whitehorse, Yukon, Canada

[c] Yukon Housing Corporation, Whitehorse, Yukon, Canada

*Corresponding author, Tel. +001 613 993 9600, email: phalguni.mukhopadhyaya@nrc-cnrc.gc.ca

Abstract

Vacuum insulation panels (VIPs) have thermal resistance values, at the centre of the panel, up to 10 times or more than those of conventional thermal insulation materials. In Canada, known for its predominantly extreme cold climate, the potential to apply VIPs in the building construction industry is estimated to be enormous, particularly with the introduction of the new 2011 National Energy Code of Canada for Buildings (NECB 2011). VIPs can play a major role in Canadian buildings to meet energy requirements of the NECB 2011. However, the lack of long-term performance credentials and various constructability issues are among the major barriers for mass application of VIPs in the Canadian construction industry. This paper presents the design strategy, construction details, instrumentation and thermal performance monitoring observations of a VIP retrofitted wall system in Yukon, located in Northern Canada. Experience gained from the construction process and available thermal performance data over a period of three years provide encouraging indicators for the constructability and long-term thermal performance of VIPs in Canadian subarctic weather.

Keywords: Vacuum insulation panel (VIP), Subarctic climate, Retrofit, Long-term performance.

Introduction

Although still virtually unknown in the Canadian construction industry, vacuum insulation panels (VIPs) have thermal resistance values, at the centre of the panel, up to about 10 times greater than those of conventional thermal insulation materials. Effective thermal resistance of a VIP insulated building envelope assembly, even after taking into account the loss due to thermal bridges [1], can be several times (about 5 times or more) higher than traditional insulated building envelope assemblies. VIPs are slowly but steadily gaining recognition for their potential use in the building envelope construction [2-4]. In Canada, the potential to apply VIPs in the building construction industry is estimated to be enormous, particularly with the introduction of the new 2011 National Energy Code of Canada for Buildings (NECB) that aims to achieve 25% less energy use in buildings than the energy code requirements set in 1997 [5]. Quite naturally, VIPs can play a major role in Canadian buildings to meet the new requirements of the 2011 NECB. However, the absence of long-term performance data and various constructability issues are perceived to be the major barriers keeping VIPs away from the Canadian construction industry [6].

Yukon, located in Northern Canada, is known for its subarctic weather, and because of its climate, thermal insulation plays a very important role in building envelope construction in this region. Use of high performance, lightweight and thin VIPs in northern buildings is potentially an attractive option for the construction industry because of its high insulation value per unit of thickness, low material volume, and reduced shipping costs to remote area. Regional stakeholders and researchers collaborated to retrofit a portion of the exterior of an institutional building in Yukon with VIPs.

The overall work plan of this initiative can be classified under three major tasks: (1) Laboratory characterization of thermal performance of VIPs, (2) Construction and instrumentation of VIP retrofitted wall, and (3) In-situ thermal performance assessment of VIPs.

This paper outlines the construction details, challenges regarding moisture management/condensation, and instrumentation used for long-term thermal performance monitoring of this VIP retrofitted wall system. Critical analysis of selected thermal performance data from three winter seasons are also presented in this paper.

It is hoped that observations presented in this paper would go a long way to instill confidence, on the use of VIPs for building envelope construction, not only among the stakeholders of the Canadian construction industry but also the global construction community.

Thermal performance of VIPs

The vacuum insulation panels (VIPs) to be used for the construction have been received from the manufacturer. The dimensions of VIP specimens are 560 mm (length), 460 mm (width) x 12 mm (thickness). One VIP board was tested, using heat flow meter apparatus with an accuracy of ±2%, to determine thermal characteristics just before field installation, and the R-value per in. of VIP at the centre of the panel was found to be about 42.5 (i.e. thermal conductivity 0.0034 W/m.K).

Construction with Vacuum Insulation Panels (VIPs)

The design, instrumentation and execution of the construction with VIPs are depicted in the following paragraphs.

Design Considerations

Economic Insulation Level

The existing wall selected for retrofitting with VIP insulation was made of 50 mm x 150 mm (2"x6") stud construction with fiberglass batt insulation and a concrete block exterior with a nominal total insulation value of RSI 3.5 (R20) (RSI: thermal resistance in SI units, $K.m^2/W$; R: thermal resistance as expressed in North America, $ft^2.°F.hr/Btu$). The insulation goal for this wall after retrofit was based on previous studies which showed that the economic wall insulation level in northern locations was in the order of RSI 8.8 – 10.5 (R50 to R60) [7], with higher values in attic areas. Thus it was originally proposed to install two layers of VIPs with a total nominal RSI value of 10.5 (R60).

Condensation

Information regarding the condensation issues with VIP insulated building envelope assemblies are available in the literature [8]. The existing wall insulation level is adequate to prevent condensation problems in the building. A continuous 0.15 mm or 6 mil (1 mil is a thousandth of an inch) polyethylene air vapour barrier was installed on the exterior of the existing block wall, so there is little likelihood of there being any condensation within the additional wall insulation. The amount of insulation added outside the new vapour barrier also conformed to the insulation ratio requirements in the Canadian 2010 National Building Code [9].

Any condensation on the exterior side of the vacuum insulation panels has the potential to result in deterioration of the insulation cover, and possible mechanical damage. In order to reduce the potential for this happening, the vacuum insulation panels were covered on the outside with a layer of foam board insulation. This raises the temperature of the exterior VIP surface, and minimizes the amount of moisture that is in contact with the insulation.

Mechanical Rubbing

The potential for mechanical rubbing of the VIPs against the rough surface of adjacent material was identified as a possible issue [8]. The mechanical rubbing can occur due to thermal expansion and contraction in response to changes in the ambient outdoor temperature, and due to building shifting. The need to prevent or mitigate mechanical rubbing between each VIP and any adjacent surface influenced the design.

The VIPs were glued directly to a layer of 25 mm (1") polystyrene foam board which ensured that the bottom surface of each VIP was attached to a smooth surface and protected from abrasion. A layer of 6 mm (1/4") flexible polyurethane foam was placed over the exterior surface of the VIPs to help prevent mechanical rubbing of the outside surface of each VIP against the 25 mm (1") polystyrene foam board placed on top of it.

Given the potential vulnerability of these vacuum insulation panels, the design used was such that VIPs could be relatively easily replaced if a problem occurred. The steel siding could be removed over the area affected. The 25 mm (1") foam board and 6 mm (1/4") flexible polyurethane foam could be removed, and the VIP replaced. The flexible polyurethane foam, foam board and steel siding could then be reinstalled.

Adhesive Selection

Two concerns with using spray (or other) adhesives were the possibility that they become a source of abrasion, and the possibility that the glue may attack the cover of the VIP, causing gradual structural failure over time, and subsequent loss of vacuum. Two approaches were used to deal with this. First, it was agreed by the contractor that he would try to minimize the use of spray adhesive if it was not needed. Second, various adhesives were tested before use.

One way to test spray adhesives to predict premature failure is to do a "thermal stress test" or "thermally accelerated life-cycle test" [10]. Such a test helps to predict if any of the adhesives being considered for use would cause premature failure of the aluminum composite cover on the VIPs. Four spray-on adhesives were tested by applying them to one side of the cover of two VIPs. The glues were allowed to dry for 30 minutes. One glue did not adhere well to the VIP and was eliminated from further testing. One VIP with three different adhesives on it was put into an oven that had been preheated to 76 °C (170 °F). The glues and the VIPs then were heated for two days. The insulation was observed after 5 days to see if there was any visible damage to the aluminum composite cover, and none was observed.

The adhesives were also sprayed onto sample pieces of 0.15 mm (6 mil) polyethylene, polystyrene, and flexible polyurethane foam. One glue was rejected for use with polystyrene as it tended to dissolve the polystyrene. Another was rejected for use with polyethylene, polystyrene and VIPs because it did not stick to any of these products.

Final Design

The cross-section of the design is shown in Figure 1 below. A 0.15 mm (6 mil) polyethylene air-vapour-moisture barrier was installed first on the existing concrete block wall, held in place with spray adhesive. 25 mm (1") polystyrene board was glued to the polyethylene to provide a smooth surface on which to mount the VIPs. 50 mm x 75 mm (2" x 3") studs were mounted on the polystyrene board and attached to the concrete wall with anchors (HPS-1 from Hilti). The VIPs (with a "peel and stick" adhesive on one side) were mounted between the 50 mm x 75 mm (2" x 3") studs. The VIPs were covered with 6 mm (1/4" nominal) flexible polyurethane foam material held in place with sheathing tape, instead of adhesive spray as originally planned. One inch (1") polystyrene board was placed on the outside of the VIPs to prevent condensation and to protect the VIPs from mechanical damage during and after construction. The layout of the VIPs is shown in Figure 2.

Instrumentation

Temperature sensors were installed to monitor the effectiveness of the insulation in this application. Temperature sensors for this purpose were located as shown in Figure 1 and Figure 3.

A cluster of four sensors (thermistors) were placed approximately 2 meters (6') from the south edge of the wall, and 1 meter from the top of the wall. They were placed to measure the temperature on the existing wall surface, on the exterior of the first polystyrene layer, on the exterior surface of the VIPs, and on the exterior surface of the second polystyrene layer.

The purpose of these sensors was to monitor the temperature on the surface of each layer of insulation.

Three sensors were placed on the existing wall approximately 2 meters (6') from the north edge of the wall retrofitted area. One sensor was located approximately 1 meter from the top of the wall. The others were placed approximately 2 and 3 meters (6' and 9') from the top of the wall. The purpose of these sensors was to monitor for thermal gradients from the top to the bottom of the wall.

As an initial step, a picture and thermal image of the wall were taken at the site as shown in Figures 4 and 5.

Construction

During construction, experience with installation of the VIPs was more positive than originally anticipated. Only one minor installation problem was encountered, and it was related to the use of anchors in masonry walls rather than installation of the VIPs.

Installation of the air/vapour/moisture barrier proceeded smoothly as was expected. Similarly, installation of the 25 mm (1") polystyrene foam board layer over the air/vapour/ moisture barrier also proceeded without incident. The spray adhesive used to hold the polystyrene in place was effective, meaning that no rework or significant adjustments were required.

Installation of the 50 mm x 75 mm (2" x 3") horizontal support members was started at the top of the wall. A jig was made from a piece of 50 mm x 75 mm (2" x 3") wood exactly the same length as that of the VIPs plus a small 3 mm (1/8") clearance. The jig was used to ensure that the supports were spaced apart so that the VIPs would fit in between over the full length of the wall.

This strategy was effective. None of the supports had to be moved as all the VIPs fit properly. Hence, the installation of the VIPs proceeded quickly (Figure 6).

Standard anchors were used. These anchors are designed for use with hollow concrete block walls and were spaced to carry the wall load. Some difficulties were encountered during construction in that some anchors did not appear to grip properly. This was resolved by installing a second anchor adjacent to any anchor that did not appear to be firmly set. Installation instructions were checked and more care was taken as well. Installing an additional anchor, when judged prudent, and taking care installing them resolved the concern.

The 6 mm (1/4") foam layer over the VIPs was cut to width using a straight edge and a knife so as to fit between the 50 mm x 75 mm (2" x 3") horizontal support members. This approach proved to be both fast and satisfactory. The width was accurate and little to no re-cutting was needed. Installation was simpler than expected as the foam was easily held in place using standard sheathing tape.

Using sheathing tape to hold the foam in place meant that no adhesive was in contact with the aluminium cover of the VIPs. This change from the original design meant that the risk of friction caused by dried adhesive was eliminated. The tape was not attached to the VIPs, with one or two exceptions. This meant that both surfaces of the foam were free to move, reducing the potential for mechanical rubbing on the VIP surface beyond that expected with the original design.

Installation of the second layer of 1" foam board also proceeded smoothly. Pieces were cut to size and a slight friction fit between the foam board and support members proved to be reliable for holding the polystyrene in place until the vertical steel siding could be installed. The steel siding was installed as construction proceeded in order to protect the VIPs installed each day. Plywood sheets screwed to the framing were used to protect the work that was not complete at the end of each day.

During construction, thermistors were installed in order to monitor the performance of the wall compared to a portion of the wall that was not insulated. The wiring was inset in a shallow handsaw cut in the foam insulation to protect it and prevent contact with the VIPs. The location of the thermistors on the insulated wall is as shown in Figure 3.

No exterior air/weather barrier was needed to meet code requirements in this location, but normally would be installed before installing the steel siding. Leaving out an exterior air/weather barrier also may facilitate taking infrared temperature measurements. It was expected that it would be necessary to remove a portion of the steel siding to take infrared measurements from the outside, as any air gap in the wall can interfere with infrared temperature readings. However, there was no air space beneath the steel siding, except at the ribs, and the initial infrared temperature readings looked good.

Because the location of the 50 mm x 75 mm (2" x 3") support members was accurate, it was possible to pre-drill the vertical siding at all locations where screw fasteners were required. The siding was stacked. The location for each hole was marked on the top piece of siding. After checking the dimensions to each hole, all pieces of siding were drilled at once.

Because all holes for fasteners were drilled before the siding was put on the wall, it was possible to visually check that all fastening points were directly over the support members. This was done by looking through the pre-drilled holes to see the wooden support member underneath. This step virtually guaranteed that none of the adjacent VIPs would be damaged due to misalignment of the siding. In fact, no VIPs were damaged during the construction process, to the best of our knowledge. There was concern that because the polystyrene was slightly higher than the supports the VIPs underneath could be compressed causing a failure of the vacuum seal. Care was taken with installation to avoid overstressing the VIPs. During the monitoring period, the condition of the VIPs will be checked to confirm whether or not shims under the supports are required.

As a final step, electrical and water lines, signs, etc. in the area were reinstalled. The siding, nearly complete is shown in Figure 7. An infrared image of the wall with the vacuum insulation panels installed is shown in Figure 8. Although the ambient temperature is higher than it was when the first infrared image was taken before adding insulation, it is clear that the area with the greatest heat loss is over the 50 mm x 75 mm (2" x 3") support members which are not covered with VIPs.

Results and Discussion: In-situ Thermal Performance

The results obtained from the field monitoring are summarized below.

The VIP insulated wall assembly was monitored over three winters. The time periods of the monitoring were:

- Winter 2011-2012: December 13, 2011 to April 15, 2012
- Winter 2012-2013: December 5, 2012 to May 23, 2013
- Winter 2013-2014: November 1, 2013 to January 9, 2014

Figure 9 shows typical recorded temperatures in the winter 2013-2014 within the VIP sandwich construction. The typical variation of temperature along the height of the exterior bock wall during winter 2012-2013 can be seen in Figures 10. The temperature variation for the top of the wall to the bottom is near zero when the temperatures are warmer (April onwards). During the coldest time period in the temperature variation is about 6°C, apparently due to stack effect.

The temperatures on the interior side of the wall assembly recorded from November, 2013 to January 2014 are shown in Figure 11. These plots show the outdoor air temperature reaching minus (-) 30°C in December 2013.

The temperature difference across each of the three insulation layers was compared to the total temperature difference across the three layers and then calculated as a percentage (see Appendix I for sample calculations). The results of these calculations are shown in Table 1. These results show that the temperature difference across the VIP is about 70% of the total temperature difference. Each of the dates in Table 1 shows approximately the same trend. In other words, the aging of VIP over a period of three years remains insignificant. The temperature difference across the VIP is 5.2 times greater than the interior XPS and 4.0 times greater than the exterior XPS. The higher insulation effectiveness of exterior XPS, compared to interior XPS, can be attributed to the lower outdoor temperature.

The graphs of the percentage of the temperature difference across each of the three insulation layers for the entire time period (three winters) are shown in Figures 12 to 14. These graphs clearly reconfirms the observations presented above based on the results presented in Table 1.

Furthermore, in February 2014, three years after the installation of VIPs, an infrared image of the retrofitted wall assembly was captured, as shown in Figure 15. This infrared image indicates no damage or failure of VIPs.
Overall, the results and discussion presented above demonstrate satisfactory and promising performance of VIPs in Canadian subarctic climate for a period of over three years without any sign of significant aging or damage.

Summary of Observations
The findings from the construction phase of this project and performance monitoring of vacuum insulation panels (VIPs) can be summarized as:

- The use of high performance VIP-foam sandwich (i.e. XPS-VIP-XPS) insulation elements for energy retrofit of existing building envelopes was found to be an attractive option in subarctic Canadian climate.
- Many seeming challenges, such as handling at construction site, puncture protection etc., associated with the application of VIPs in the construction industry can be addressed through appropriate design and construction techniques.
- There were no apparent changes in the in-situ thermal performance of the VIPs, exposed to subarctic climate, over a period of three years (2011 – 2014), relative to the performance of XPS insulation. In other words, rapid aging of VIPs in extreme cold climate does not look like a serious concern based on the observations made to date. However, further in-situ performance monitoring of these VIPs would generate valuable information for the construction industry in the coming days.

6.0 Acknowledgements
Authors acknowledge the support of Panasonic Canada Inc., and Panasonic Corporation for supplying the vacuum insulation panels used in this project, and for their technical expertise and support. Authors would like to thank Yukon Housing Corporation for providing a wall of one of their buildings for this project, and for providing monitoring equipment. Mr. Stephen Mooney, Director, Cold Climate Innovation, Yukon Research Centre, Yukon College, must also be credited for providing financial and technical supports for this collaborative project.

References

[1] K. Ghazi-Wakili, R. Bundi, B. Binder, 2004, Effective thermal conductivity of vacuum insulation panels, Building Research & Informationm 32 (4), 293-299.

[2] K. Choa, Y. Honga, J. Seob, 2014, Assessment of the economic performance of vacuum insulation panels for housing projects, Energy and Buildings, 70, 45–51

[3] P. Johansson, S. Geving, C-E Hagentoft, et al., 2014, Interior insulation retrofit of a historical brick wall using vacuum insulation panels: Hygrothermal numerical simulations and laboratory investigations, Building and Environment, 79, 31-45.

[4] S. Brunner, T. Stahl, K. Ghazi Wakili, 2012, An example of deteriorated vacuum insulation panels in a building façade, Energy and Buildings, 54, 278–282.

[5] National Energy Code of Canada for Buildings (NECB), 2011, National Research Council Canada, 1200 Montreal Road. Building M-58, Ottawa, Ontario, K1A 0R6, Canada.

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

[7] R. Dumont, 2007, On the road to net zero energy homes in cold climates: Canadian prairie contributions, Sustainable Northern Shelter Forum, SNS Forum Presentations, Cold Climate Housing Research Center (http://www.cchrc.org/docs/sns/Dumont.pdf).

[8] A. Binz, 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, T. Thorsell, 2005, Vacuum insulation in the building sector - systems and applications (Subtask B), IEA/ECBCS Annex 39, 1-134.

[9] National Building Code, Canadian Commission on Building and Fire Codes, 2010, National Research Council, Vol. 1, Section A-9.26.1.1.(2), Table A-9.25.5.2.

[10] A.S. Maxwell, W.R. Broughton, G. Dean, and G.D. Sims, 2005, Review of accelerated ageing methods and lifetime prediction techniques for polymeric materials, NPL Report, DEPC MPR 016, National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK, 1-84.

Appendix - Description of Analysis Procedure

This appendix describes the procedure used to determine the percentage of the temperature difference across the insulation layers in the wall assembly. A schematic diagram of the retrofitted wall assembly with the location of the temperature sensors (thermocouples) is shown in Figure A1.

The temperature difference (ΔT) was determined across each of the insulation layers. The three layers are:

- **XPS1** – First Layer of XPS (adjacent to existing block wall)
- **VIP** – VIP Insulation
- **XPS2** – Second Layer of XPS (adjacent to Steel Siding). Note that this temperature difference includes the second layer of XPS and the 6mm of foam.

The temperature difference (ΔT) was calculated for each layers as follows:

$\Delta T_{XPS1} = T32 - T34$

$\Delta T_{VIP} = T34 - T35$

$\Delta T_{XPS2} = T35 - T36$

The total temperature difference across all the layers of insulation (ΔT_{TOT}).

$\Delta T_{TOT} = T32 - T36$

The percentage of the temperature difference (%ΔT) for each layers, with respect to the total temperature difference is:

$$\%\Delta T_{XPS1} = \frac{\Delta T_{XPS1}}{\Delta T_{TOT}} \times 100$$

$$\%\Delta T_{VIP} = \frac{\Delta T_{VIP}}{\Delta T_{TOT}} \times 100$$

$$\%\Delta T_{XPS2} = \frac{\Delta T_{XPS2}}{\Delta T_{TOT}} \times 100$$

The percentage temperature difference was reported and plotted to indicate the effectiveness of the VIP and its overall contribution to the thermal performance of the assembly.

Sample Calculation

The following section shows a sample calculation to determine the percentage of the temperature difference across the insulation layers in the wall assembly. It shows the calculations for the average temperatures on December 20, 2011. Average temperatures for the date are shown in Table A1.

The temperature difference was calculated for each layer as:

$\Delta T_{XPS1} = T32 - T34 = 3.9 - 1.6 = 2.3$

$\Delta T_{VIP} = T34 - T35 = 1.6 - (-10.0) = 11.6$

$\Delta T_{XPS2} = T35 - T36 = -10.0 - (-12.8) = 2.8$

$\Delta T_{TOT} = T32 - T36 = 3.9 - (-12.8) = 16.6$

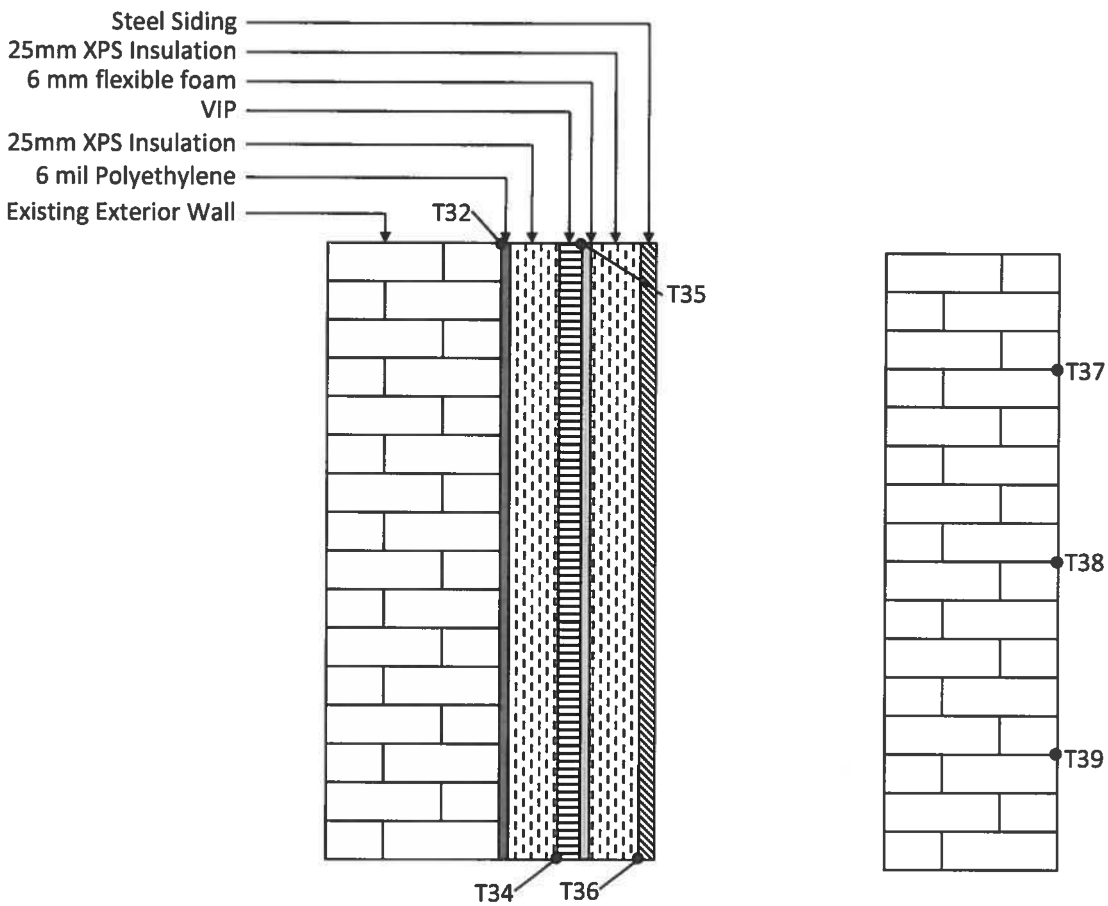
The percentage of the temperature difference was then calculated as:

$$\%\Delta T_{XPS1} = \frac{\Delta T_{XPS1}}{\Delta T_{TOT}} \times 100 = \frac{2.3}{16.6} \times 100 = 14\%$$

$$\%\Delta T_{VIP} = \frac{\Delta T_{VIP}}{\Delta T_{TOT}} \times 100 \frac{11.6}{16.6} \times 100 = 70\%$$

$$\%\Delta T_{XPS2} = \frac{\Delta T_{XPS2}}{\Delta T_{TOT}} \times 100 \frac{2.8}{16.6} \times 100 = 17\%$$

List of Figures



T32 - on existing block wall exterior surface
T34 - on 25 mm (1") 1st Styrofoam layer (on interior side of VIP)
T35 - on exterior of VIP
T36 - on exterior of 2nd 25 mm (1") Styrofoam
T37 - on existing block wall on exterior surface 950 mm (3'2") from top
T38 - on existing block wall on exterior surface – 1500 mm (5') from top
T39 - on existing block wall on exterior surface - 2800 mm (9'4") from top

Figure 1. Wall cross-section and location of temperature sensors.

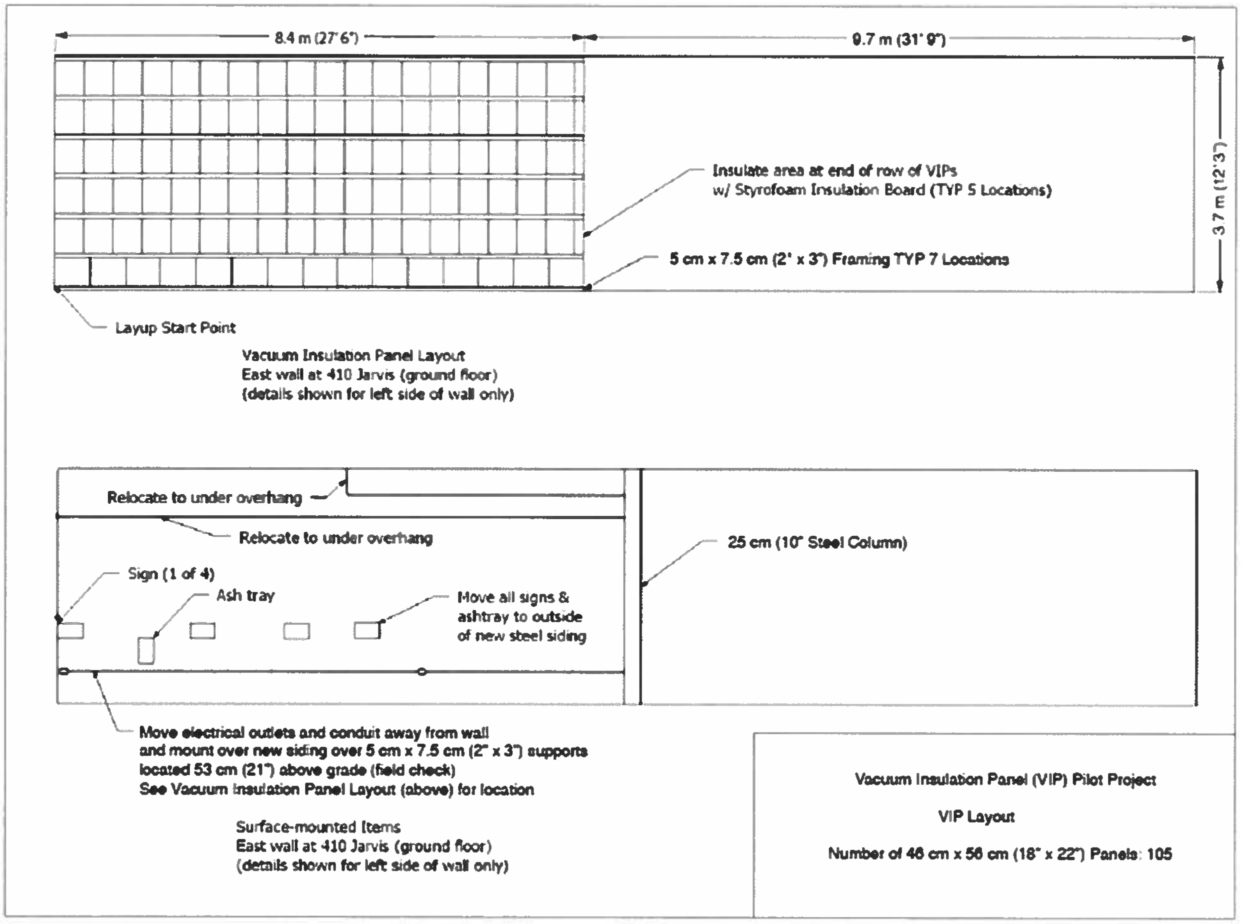


Figure 2. Vacuum insulation panel layout

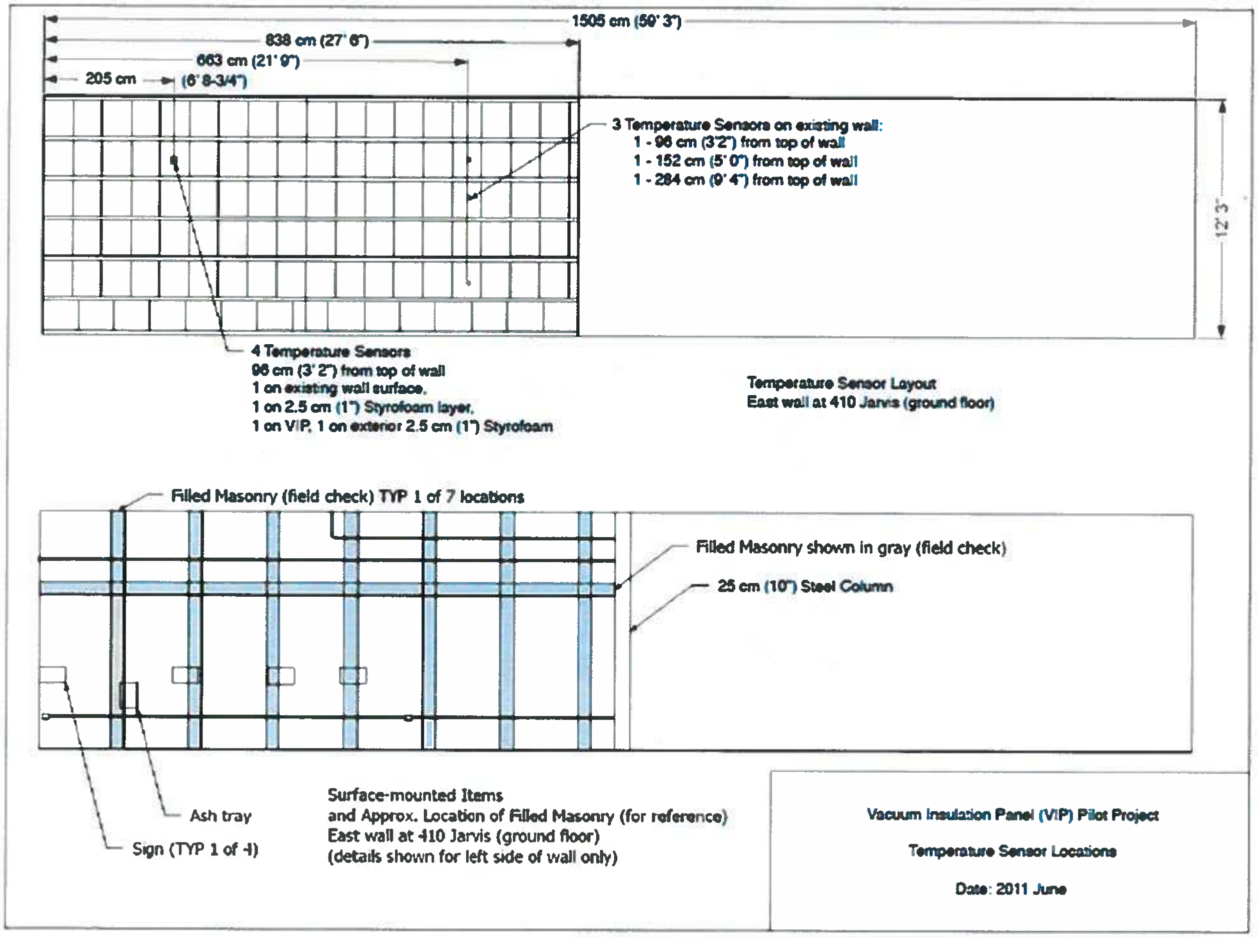


Figure 3. Temperature sensor locations

Figure 4. Wall selected for VIP retrofit project.

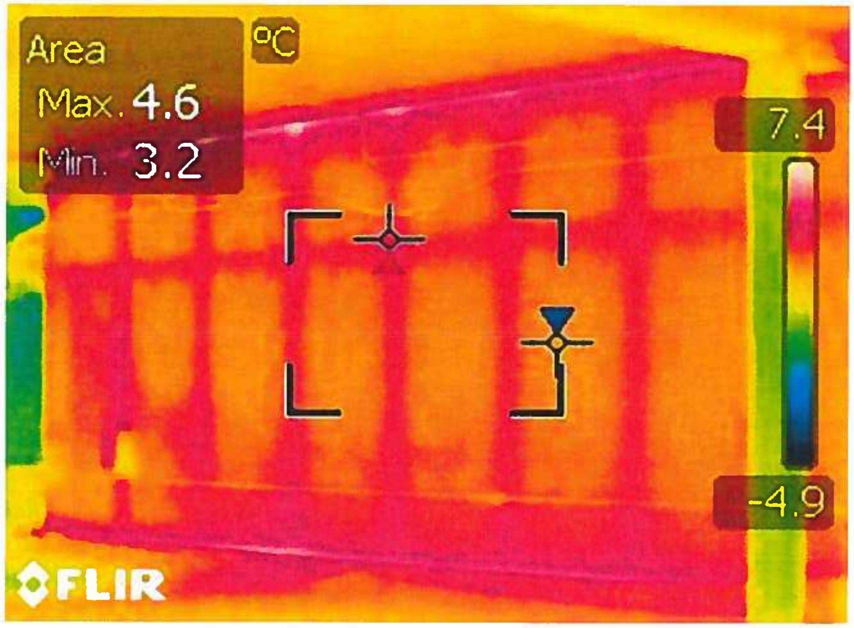


Figure 5. Infrared Image of the wall selected for the VIP retrofit project.

Figure 6. Installation of the vacuum insulation panels (VIPs).

Figure 7. Insulation and siding.

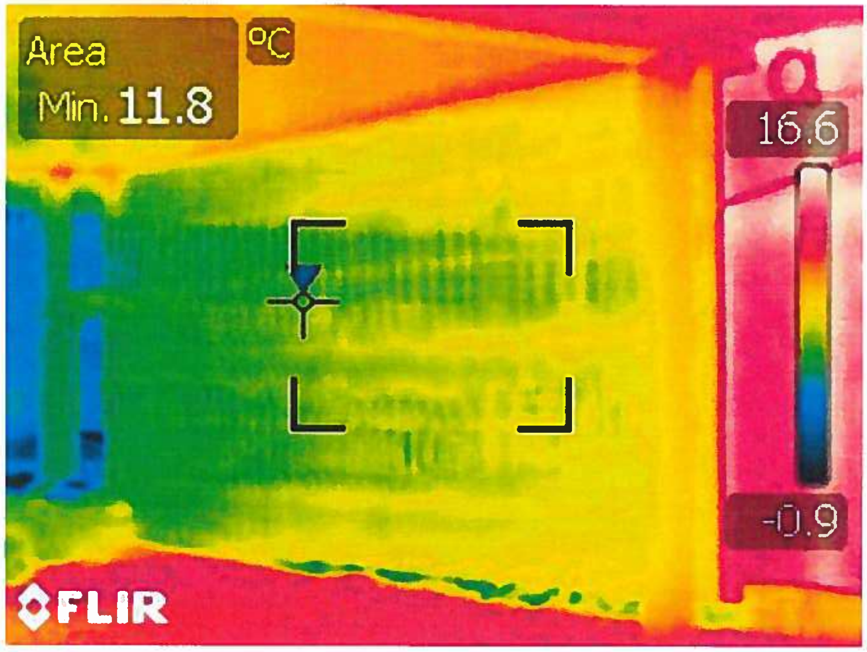


Figure 8. Infrared image of the wall with vacuum insulation panels installed.

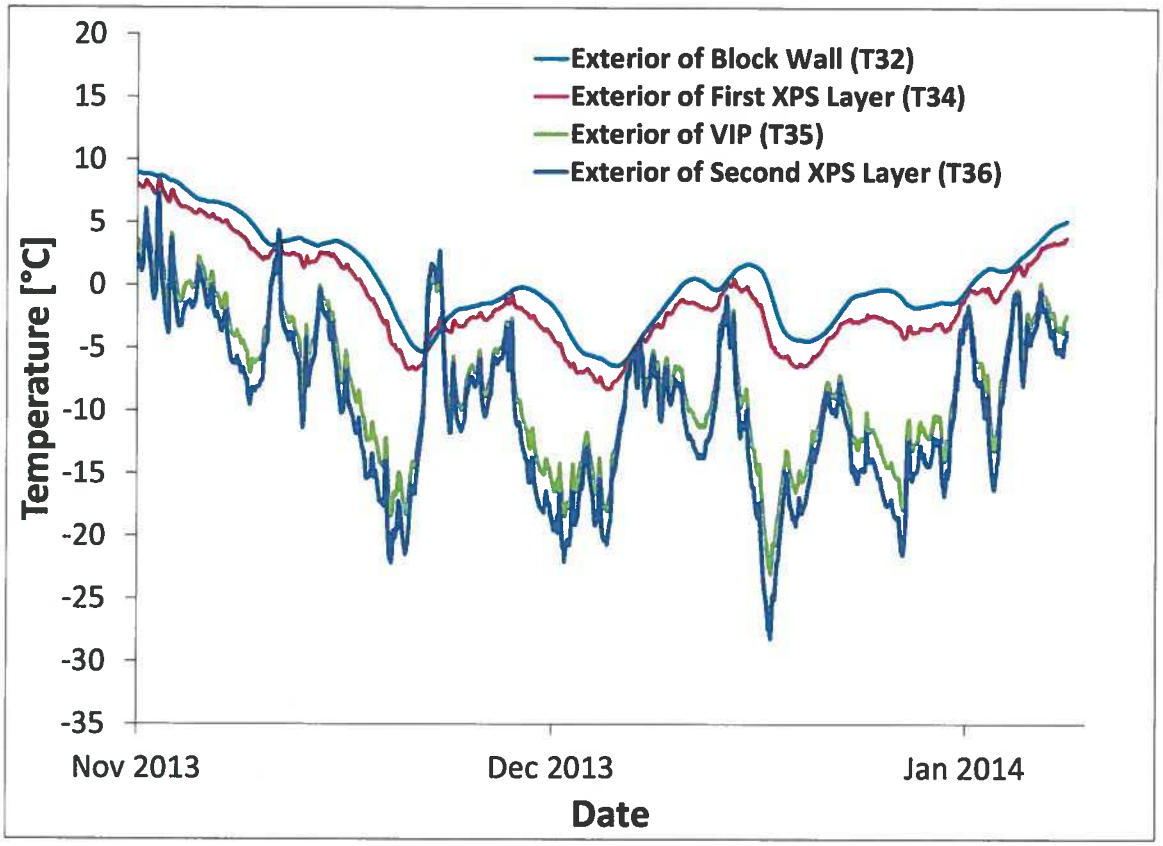


Figure 9. Hourly average temperatures for T32, T34, T35, and T36 – November 2013 to January 2014

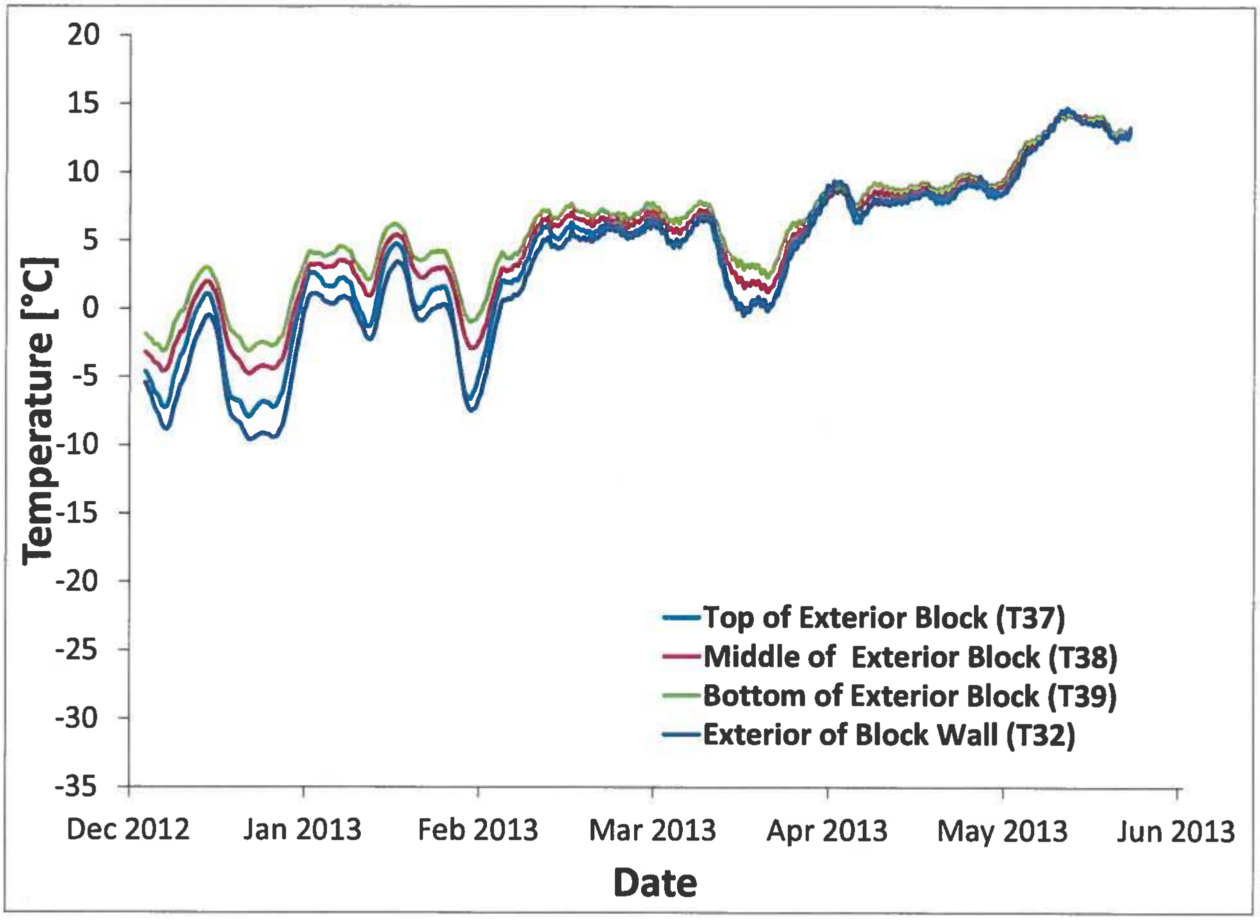


Figure 10. Hourly average temperatures for T32, T37, T38, and T39 – December 2012 to May 2013

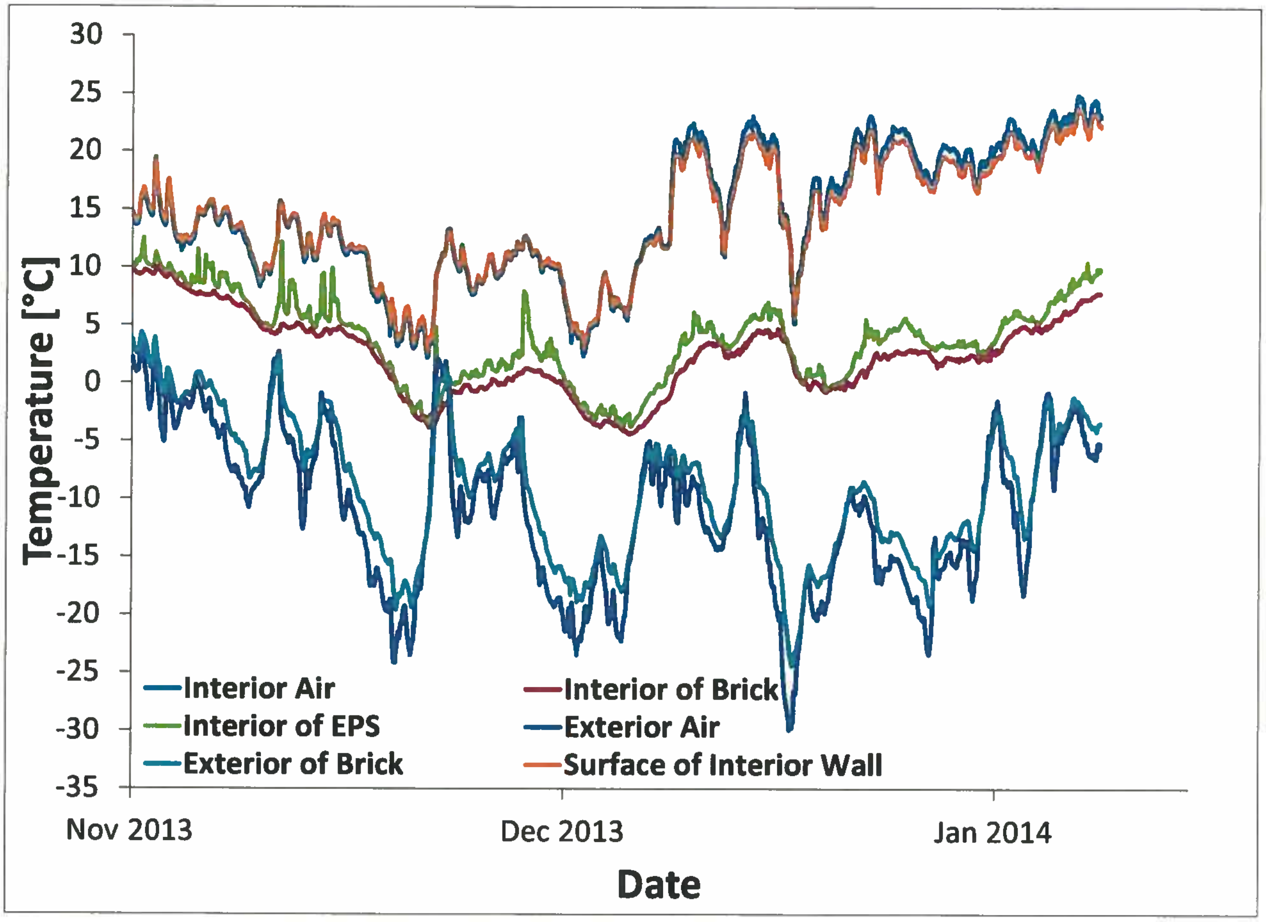


Figure 11. Hourly average temperatures for sensors on interior of wall assembly – November 2013 to January 2014

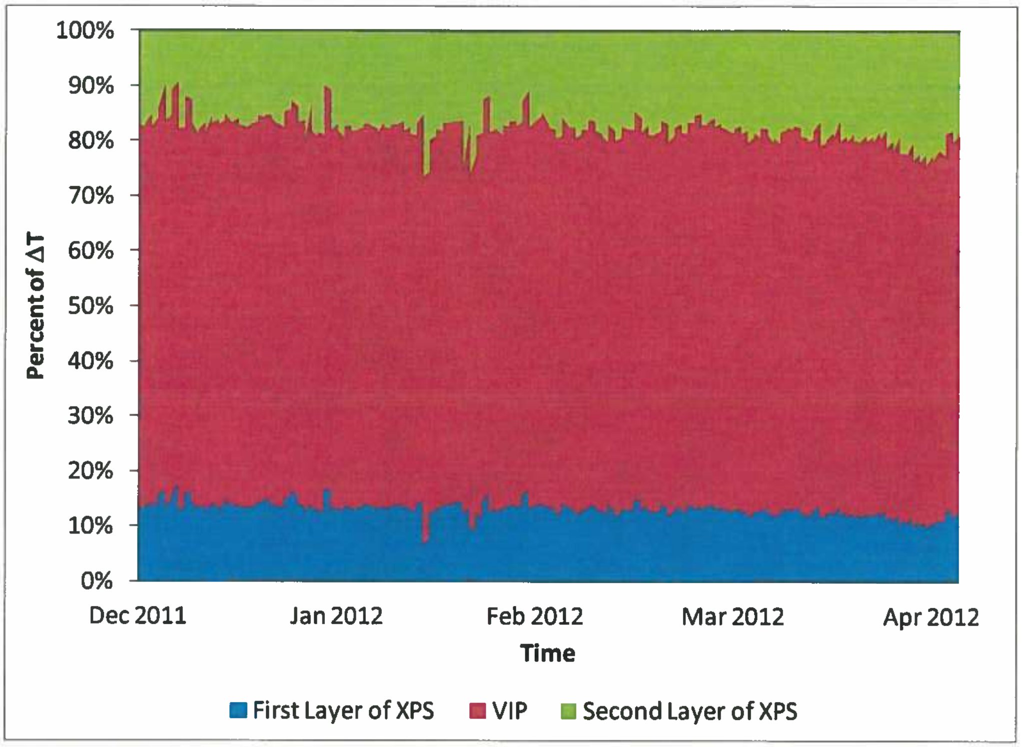


Figure 12. Percentage of Temperature Difference graphs for December 2011 to April 2012

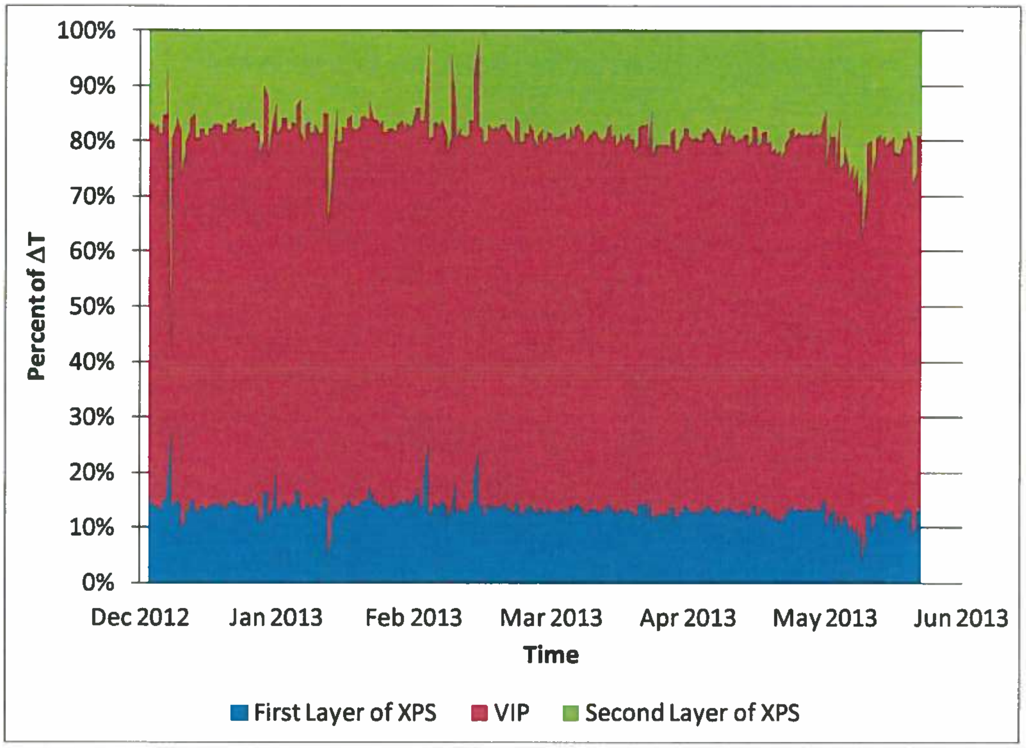


Figure 13. Percentage of Temperature Difference graphs for December 2012 to May 2013

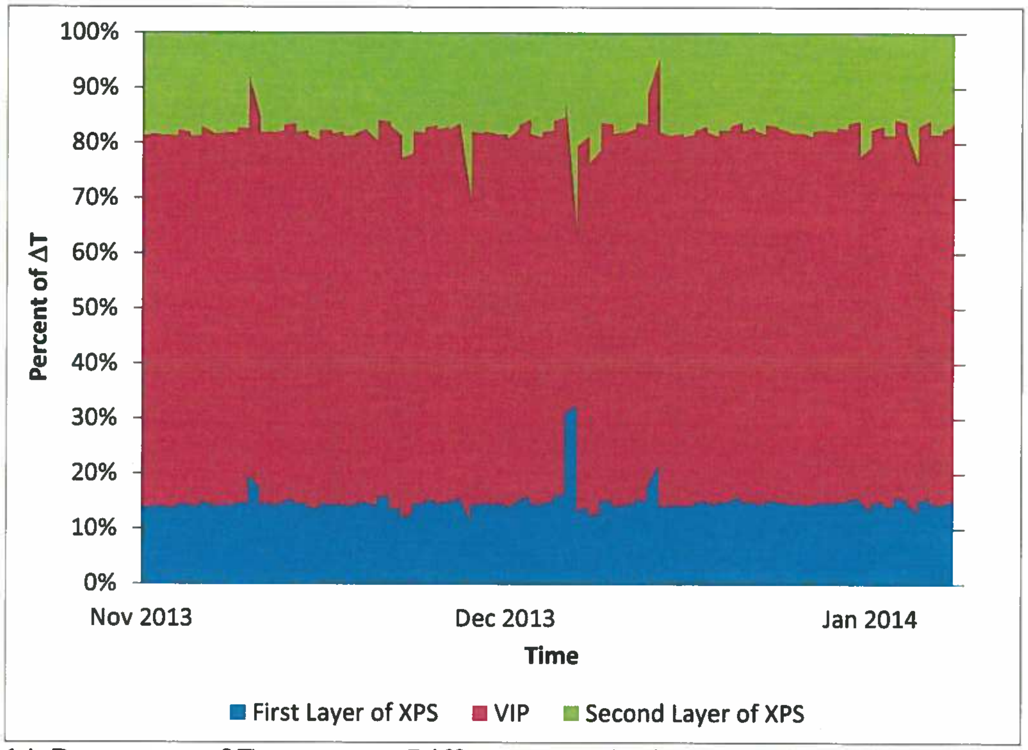


Figure 14. Percentage of Temperature Difference graphs for November 2013 to January 2014

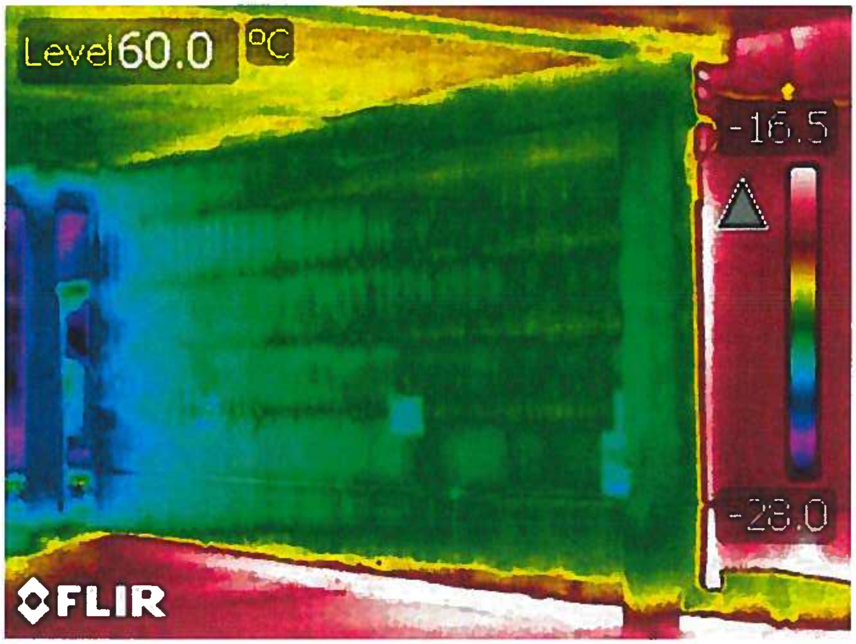


Figure 15. Infrared image of the wall after three years (February 2014)

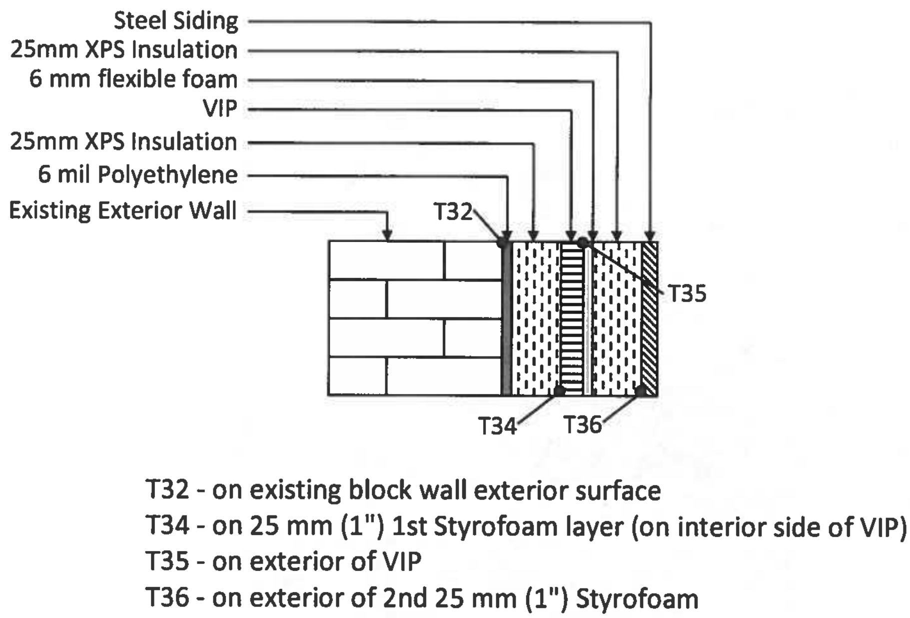


Figure A1. Schematic diagram of the retrofitted wall assembly with temperature sensors

Table 1 - Percentage of temperature difference across insulation layers around VIP assembly for selected dates

	Percent Delta T		
Date	**First XPS**	**VIP**	**Second XPS**
20-Dec-11 (0:00 to 6:00)	14%	70%	17%
20-Jan-12 (0:00 to 6:00)	13%	70%	17%
20-Feb-12 (0:00 to 6:00)	14%	70%	17%
20-Mar-12 (0:00 to 6:00)	13%	69%	18%
14-Apr-12 (0:00 to 6:00)	13%	69%	17%
Average	**13%**	**69%**	**17%**

	Percent Delta T		
Date	**First XPS**	**VIP**	**Second XPS**
20-Dec-12 (0:00 to 6:00)	14%	69%	17%
20-Jan-13 (0:00 to 6:00)	15%	69%	16%
20-Feb-13 (0:00 to 6:00)	14%	70%	17%
20-Mar-13 (0:00 to 6:00)	14%	69%	19%
20-Apr-13 (0:00 to 6:00)	14%	70%	17%
20-May-13 (0:00 to 6:00)	14%	69%	17%
Average	**14%**	**69%**	**17%**

	Percent Delta T		
Date	**First XPS**	**VIP**	**Second XPS**
20-Dec-13 (0:00 to 6:00)	15%	67%	18%
08-Jan-14 (0:00 to 6:00)	14%	68%	18%
Average	**15%**	**67%**	**18%**

Table A1. Average temperatures (°C) at each layer of wall assembly

Date	Ext. Block Wall (T32)	Ext. First XPS (T34)	Ext. VIP (T35)	Ext. Second XPS (T36)	Top Ext Block (T37)	Mid Ext. Block (T38)	Bottom Ext Block (T39)
20-Dec-11	3.9	1.6	-10.0	-12.8	4.6	5.3	6.1