Hygrothermal Monitoring of Two Pilot Prefabricated Exterior Energy Retrofit Panel Designs

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Abstract. NRCan undertook a proof-of-concept project to retrofit a small building with prefabricated wall panels in 2017 in Ottawa, Canada. The retrofit used two wall panel designs: nailbase and woodframe. The Nailbase panel consisted of fiberglass batt, an expanded polystyrene (EPS) core, oriented strand board (OSB) sheathing, a rainscreen, and cladding. The Woodframe panel also featured OSB sheathing and included a 90 mm stand-off gap filled with dense-packed, fibrous insulation. A side-by-side comparison of cost, constructability, and performance was performed. The wall assemblies were instrumented to monitor the temperature, relative humidity, and moisture content of sensitive layers. The data was used to evaluate the hygrothermal performance, moisture accumulation, and risk of associated problems such as mould growth. This paper presents the monitored hygrothermal data from 2017 to 2021, compares the two approaches and assesses their feasibility. During construction, some of the fibrous insulation may have been wetted by wind-driven snow before completion. The data showed that this moisture was able to dissipate without significant risk. The sheathing of the Woodframe panel experienced a higher peak moisture content during the dry-out period. Otherwise, both panel designs showed limited potential for mould growth on monitored surfaces over the monitored period.

1. Introduction and Motivation
The Canadian housing stock consists of 11 million low-rise detached, semi and row-attached dwellings [1]. More than two-thirds of these units were built before energy efficiency standards. To enable net-zero emissions by mid-century, the heating demand of the current building stock needs to be significantly reduced. Natural Resources Canada’s (NRCan) Prefabricated Exterior Energy Retrofit (PEER) [2] project seeks to develop, test, and validate innovative prefabricated building envelope technologies for retrofitting existing Canadian homes using a panelized approach. Anecdotal barriers to traditional deep building envelope retrofits include unpredictable costs; high occupant and neighbour disruption; long completion times and moisture related risks due to the reduced drying potential post retrofit. Reducing these barriers and enabling industrialization of building envelope retrofits are key aims of the project. European approaches (such as those employed in the EnergieSprong initiative [3]) have demonstrated significant reductions in time, cost, and disruption in achieving net-zero retrofits by using industrialized, prefabricated systems.
Under the auspices of the PEER Project, NRCan undertook a proof-of-concept, pilot-scale field installation of a factory built, panelized retrofit of the above grade walls of a small building in 2017 to gather useful long-term thermal and moisture data. A building on NRCan’s Bells Corners Complex in Ottawa, Canada was selected for the pilot. The building was instrumented with temperature, relative humidity, and moisture content sensors to monitor the heat and moisture transfer in the existing wall assemblies and the two prototype retrofit panels used to overclad the building. The two panelized retrofit designs were (1) Nailbase and (2) Woodframe assemblies. The panel assemblies are further described in the following section and summarized in Table 1.

This paper presents the measured hygrothermal data collected in clear field sections of the panelized retrofits. The data collection period was from November 2017 to January 2021 (3 years). The hygrothermal performance of the above-grade wall assembly of the two different panelized approaches applied in two different conditions was compared, and the researchers found that all approaches showed sufficient resiliency based on high initial moisture conditions decreasing to satisfactory levels demonstrated by a peak mould index [4] of 0 on sensitive layers.

2. Existing Above Grade Wall and PEER Panel Designs
The proof-of-concept field installation was performed on a construction trailer, shown in Figure 1, on NRCan’s CanmetENERGY campus in Ottawa, Canada. The existing wall assembly construction from interior to exterior is described below:

- 3 mm fibreboard interior finish surface
- 0.2 mm polyethylene
- 38 x 89 mm studs 405 mm on-centre with fiberglass batts in the cavity
- 8 mm oriented strand board (OSB) sheathing
- Lapped asphalt building paper
- Prefinished profiled galvanized sheet steel cladding

Apart from the interior and exterior finishes, this construction was representative of typical Canadian residential construction from 1961-1983. These building types are prime candidates for PEER retrofits due to their below standard R-value, poor air sealing and simple geometry.

Panel A consisted of a premanufactured Nailbase panel comprised of 150 mm expanded polystyrene (EPS) with 19 mm OSB sheathing bonded to the exterior and 50 mm of 24 kg/m² mat-faced fibreglass batt adhered to the interior. The low-density fiberglass helped to plumb the panel and conformed to irregularities of the existing profiled steel siding. The fiberglass also provided dimensional tolerance at panel corners during installation and its high vapour permeability allowed for vertical drying. The EPS core was factory cut to receive continuous structural members at the top and bottom of the panel. These members served to connect several sub-panels and provide strength and stiffness for transportation and hoisting. New windows and doors were installed in the EPS layer and supported by a wood perimeter buck. Vertical strapping was installed over a self-adhered, vapour permeable air and weather resistive barrier membrane to give a rainscreen cavity and to support new cladding installed in the factory. A thicker EPS core layer could be specified to achieve higher R-values.

Panel B was a prefabricated 2x4 wood stud frame and dense-pack blown-in insulation system. The framing was sheathed with 11 mm OSB. A self-adhered, vapour permeable air and water resistive barrier membrane, furring strips to maintain a rainscreen cavity, and cladding were installed in the factory. The prefabricated stud wall was stood-off from the existing cladding. A 90 mm stand-off gap was specified to achieve the target thermal resistance. Dense pack fibrous insulation was blown-in at the top and bottom of the panel after they were in place on the building to fill both the stud cavity and the stand-off gap space.

The Nailbase (A) and Woodframe (B) panels are described from interior layer to exterior layer in Table 1 and schematically in Figure 3. Both panels were supported on brackets anchored into the existing floor system. Further information about the detailing, support, construction, and thermal performance has been published [5].
### Table 1 Retrofit Panel Descriptions [5]

|   | Panel A                                                                 | Panel B                                                                 |
|---|-------------------------------------------------------------------------|-------------------------------------------------------------------------|
| 1 | 50 mm low-density (24 kg/m$^3$) fiberglass or mineral wool batt          | 90 mm continuous cellulose insulation (56 kg/m$^3$)                       |
| 2 | 150 mm Type-II expanded polystyrene (EPS) core with continuous let-in structure | 38 mm x 89 mm studs @ 405mm O.C. c/w cellulose insulation (56 kg/m$^3$) |
| 3 | 11 mm OSB sheathing                                                      | 11 mm OSB sheathing                                                      |
| 4 | Self-adhered vapour permeable air and weather resistive barrier          | Self-adhered vapour permeable air and weather resistive barrier          |
| 5 | 19x89 mm strapping @ 405 mm OC                                          | 19 x 89mm strapping @ 405 mm OC                                         |
| 6 | Prefinished engineered wood siding                                      | Prefinished engineered wood siding                                      |

**Figure 1** PEER proof-of-concept building before (left) and after (right) the retrofit.

3. Evaluating PEER Prototypes

Construction took place from November to December 2017. In-situ hygrothermal monitoring began afterward. The building was outfitted with temperature [6, 7], relative humidity [8], and moisture content sensors [7]. The wire leads from sensors installed in the panels were run to the interior and terminated at data loggers [9]. The interior, exterior, and material interfaces were monitored.

3.1. Interior and Exterior Conditions

The interior conditions were monitored using the onboard temperature and relative humidity sensors of the data loggers. The data loggers were placed in an enclosure near the ceiling, out of the reach of occupants but remained open to the interior conditions. Over the three years, interior relative humidity was maintained by a humidifier with analog control. The heat was initially supplied by electric resistance heaters before being replaced by a heat pump (which also provided cooling and dehumidification) with a digital thermostat. The building was moved in September 2018 and the orientation of the monitored façade changed from North-East to South-East. After being moved, the building became a meeting room and fluctuations in interior conditions were observed. Figure 2 shows the interior temperature was maintained between 18°C and 25°C for most of the monitoring period; temperatures peaked due to overheating resulting from prolonged occupancy or solar exposure. The dips in interior temperature were caused by ajar windows and low thermostat setpoints during pandemic lockdowns (March 2020-March 2021).

The exterior conditions were measured from a nearby weather station from Environment Canada’s database. The exterior temperature and the vapour pressure difference between the interior and exterior were plotted in Figure 2. The vapour pressure difference between the interior and exterior was plotted below; the moisture drive was towards the exterior when the difference is above zero. The building was exposed to all climatic conditions in Ottawa, CA since 2017.
3.2. Moisture Performance Evaluation Criteria

The mould index for each timestep was calculated using the measured temperature and surface humidity of sensitive materials. This was the principal performance criterion. A maximum mould index of 3.0 was established, consistent with ASHRAE-160 [10]. To be conservative, a secondary mould index threshold of 1 or greater would require more investigation. To be considered low risk, the mould index must remain less than 1.0 for the duration of the test. The mould index is an empirical relationship of the surface relative humidity and temperature to a number that represents the level of mould fungi that is possible under the measured conditions on a scale of 0 to 6 [4]. Each integer represents a level of fungal growth on the surface, where 0 would be no growth and 6 is heavy and tight fungal growth.

Additionally, a maximum value of 80% RH at the surface of the sheathing was used as an indicator for moisture related issues in the building enclosure. The maximum value represents the critical relative humidity for sensitive materials when the temperature is greater than or equal to 20°C. This is a conservative maximum value because the critical relative humidity increases as the temperature decreases. For this wall assembly and outdoor climate, it is known that the surface temperature at the sheathing (sensitive layer) will be colder than 20°C and makes the indicator especially cautious. If the measured relative humidity remains below 80% RH during the monitoring period, the wall assembly can be viewed as a safe assembly, otherwise, further analysis would be required to make an assessment.

The data collected during the monitored period was used to calculate the mould index, and to assess the durability and resilience of these retrofit wall assemblies for Ottawa, CA.

3.3. Instrumented Prefabricated Panels

The data collected through this project was used to assess the drying potential and risk of condensation and mould growth on the retrofitted wall assemblies. Temperature, relative humidity, and moisture content were measured at each material interface for both types of retrofit panels (as shown in the vertical
section in Figure 3). Thermistors were placed at various material interfaces to measure the temperature gradient through the assembly. Relative humidity sensors were placed on the inside face of the exterior sheathing, within the fiberglass batt layers and existing cladding, and on the interior face of the existing sheathing. Finally, moisture content sensors were installed in both the existing building sheathing and panel sheathing to measure the OSB moisture levels.

The project sought to investigate the effect of retaining the existing cladding versus removing it. As such, the steel cladding was removed from a portion of the trailer thereby creating 4 unique retrofit wall assemblies in a single project: Nailbase and Woodframe retrofits with and without existing cladding.

![Figure 3 Vertical section view of instrumented wall assemblies insulated with the Nailbase (Top) and Woodframe (Bottom).](image)

4. Monitored Data
The data was collected at 30-minute intervals during the monitored period. In all retrofit scenarios the existing sheathing was kept warm and did not experience high humidity levels during the monitored period, shown in Figure 4 and 5, and further represented in Table 2 with a peak Mould Index of 0. The exterior sheathing that faced the Nailbase and Woodframe panels were exposed to higher initial moisture content, likely caused by moisture from blowing snow and rain while the roof was being installed. This layer was the most likely location for mould growth to occur and required further investigation.

4.1. Nailbase Panel
The Nailbase panel was instrumented with moisture content, relative humidity, and temperature at the interior surface of the OSB sheathing. The sheathing was protected from bulk wetting and air infiltration by a vapour-permeable weather resistive barrier and exterior air barrier (WRB/AB) but vapour diffusion could occur in either direction.

The relative humidity was measured from November 2017 to February 2021 with some interruptions due to connectivity issues with the data collection system. During fabrication and prior to installation, the Nailbase Panel was stored inside to prevent wetting and excess moisture. The relative humidity at
the interior sheathing surface, plotted in Figure 4, suggests that the panel was able to remain dry during construction, which was consistent with handheld moisture content readings during the retrofit. During the first six months of monitoring, the relative humidity peaked over 70% as the temperature dropped in Ottawa, CA. The following 3 consecutive winters, the measured RH peaked below 80%, improving confidence that the wall would be durable throughout its lifetime.

**Figure 4** Measured relative humidity at the interior face of new sheathing in the Nailbase Retrofit.

4.2. **Woodframe Panel**
The Woodframe panel was exposed to the same conditions as the Nailbase panel and provided an interesting contrast. The measured relative humidity in the Woodframe panels with the existing cladding removed encountered problems. The high humidity measured over the first winter suggests that moisture may have been introduced during construction. The roof cavity was in communication with the wall cavity for the Woodframe panels. The Woodframe sheathing did not dry out below 80% RH until May 2018, about 8 months after construction was completed, spending approximately 6 months above 80% RH. While moisture levels were concernedly high over this period, the surface was too cold for optimal mould growth. Consequently, the mould index remained within acceptable ranges. The subsequent two winters peaked below 80% RH and indicated that there was sufficient drying potential with the assembly.

Through the monitoring, it was apparent that removing the cladding changed the cycle of relative humidity. The observation highlighted that without the cladding, the relative humidity was higher at the exterior sheathing than the same point in the wall with the existing cladding intact. The observation was consistent with observations from the Nailbase panel and could be an indication that when overcladding leaky buildings, impermeable steel cladding works as a vapour barrier to limit the vapour diffusion towards the exterior. However, after the initial dry-out period the relative humidity remained under the threshold for a durable wall for both cases.

**Figure 5** Measured relative humidity at the interior face of new sheathing in the Woodframe Retrofit.
4.3. Calculated Mould Indices of Prototypes
The Mould Index was the main criterion used to assess the moisture-related risk of the panelized retrofit pilot conducted. Using the measured relative humidity values and moisture content values converted to relative humidity with the corresponding temperature, the Mould Index for each measurement was calculated. The value and date of the peak mould index for each retrofit were compiled in Table 2.

For the Nailbase panel, there was no potential for mould growth. The relative humidity and temperature conditions did not accumulate any potential for mould growth as seen in Figure 6. The panels were applied to the existing building dry, and the moisture balance was maintained for the monitoring period. The measured relative humidity in the Woodframe panel was greater than 80% RH during the winter, especially during the first 8 months after construction was completed. Since the temperatures were cold, there was not a significant risk for mould growth as the critical value of relative humidity for mould growth increases as the temperature drops below 10°C. As such, the calculated mould index indicated that the riskiest period for the assembly is during the Spring, as temperature increased and the amount of moisture in the assembly was still high (due to exterior conditions and the moisture stored in the assembly). This was apparent in May 2018, when the mould index begins to grow rapidly because the temperature rises to allow for mould growth. However, there is enough drying over time and the mould index began to decline to 0 about 9 months later, indicating that the potential for mould growth on the sheathing was low.

Table 2 Evaluation Criteria for the 4 Retrofit Solutions.

| Status of existing cladding Sheathing | Status of existing cladding | Nailbase | Woodframe |
|-------------------------------|----------------------------|----------|------------|
| Intact                         | Removed                    | Intact   | Intact     |
| New                            | New                        | Existing | New        |
| New                            | New                        | New      | Existing   |

Peak Mould Index
Date of Peak Mould Index

5. Conclusions
In conclusion, both types of retrofit panels were not considered risky assemblies and passed the moisture durability evaluation criteria. They were applied to an existing building with steel cladding and an area...
with the metal cladding removed. During construction of the roof in the winter of 2017, moisture may have been introduced into the retrofit wall assemblies. Sheathing moisture content readings reflected this possibility, but both assemblies were able to dry out within the first year and showed acceptable relative humidity and moisture content for the following 2 years.

The Mould Index did not exceed 1.0 for either panel design. The threshold for acceptable performance was 3.0. It was therefore concluded that these panel designs are suitable for overcladding similar existing constructions with both vapour permeable and impermeable existing claddings in Ottawa, Canada. It is important to consider the existing cladding type and its moisture storage capacity before overcladding. Note that these conclusions pertain to the field of the panel only. Monitoring of panel joints is ongoing and will be the subject of a future paper. As with any high-performance building envelope assembly, bulk water control remains paramount for long-term durability. A retrofit panel with higher outward drying capacity may provide additional tolerance of bulk water control defects.

5.1. Future Work

The project will continue to be monitored to ensure that the general trends continue, as the building was moved during the monitoring period and boundary conditions changed. The data collected from this project will be compared to validate hygrothermal models. A full-scale pilot project of an occupied building is currently under construction. The pilot utilized a modified Nailbase panel design to overclad a woodframe building with a brick veneer that was retained. Hygrothermal monitoring of that project is underway.

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References

[1] Natural Resources Canada [Internet]. Comprehensive Energy Use Database c2018 [cited – 2021] Available from: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm [Accessed 6 April 2018].
[2] Natural Resources Canada [Internet]. PEER - Prefabricated Exterior Energy Retrofit c2018 [cited – 2021] Available from: https://www.nrcan.gc.ca/energy/efficiency/data-research-and-insights-energy-efficiency/housing-innovation/peer-prefabricated-exterior-energy-retrofit/19406
[3] Energiesprong [Internet]. Energiesprong [cited – 2021] Available from: energiesprong.org
[4] A Hukka and H A Viitanen 1999 Wood Science and Technology 33 475-485
[5] S Brideau, M Carver, A Parekh, B Conley 2018 Healthy, Intelligent, and Resilient Buildings and Urban Environments Syracuse, NY
[6] RDH Building Science Laboratories 2019 Temperature Sensor
[7] Structure Monitoring Technology 2012 Point Moisture Measurement Sensor
[8] RDH Building Science Laboratories 2019 Relative Humidity Sensor
[9] Structural Monitoring Technologies 2021 SMT-A3 Datasheet
[10] ANSI/ASHRAE 2016 Criteria for Moisture Control Design Analysis in Buildings