RDH BUILDING SCIENCE

Six-Year Conventional Roof Monitoring Report | Project 6230.020/.030






Submitted to:
Mr. Blair Bennett
Soprema Inc.
#101 - 18651 52nd Avenue
Surrey, BC V3S 8E5

SOPREMA

Mr. Dave Lawlor
Rockwool Group
8024 Esquesing Line
Milton, Ontario L9T 6W3

ROCKWOOL

Submitted February 22, 2022,
by RDH Building Science Inc.
#400 – 4333 Still Creek Drive,
Burnaby, BC V5C 6S6

Executive Summary

A conventional roof research and field monitoring study was initiated by RDH Building Science Inc. (then RDH Building Engineering Ltd.) in partnership with Soprema and ROCKWOOL (then Roxul) in 2012. The purpose of this study was to better understand the performance of conventional roof assemblies and to evaluate the impact of roof membrane colour and insulation strategies. This final report presents a complete analysis of data collected over the course of six years, periodic field investigation findings and laboratory material testing results.

The in-service reflectance of roofs was measured for black, grey and white roof membranes. In the three-year interim report, it was assumed that degrading reflectance of the white and grey membrane had been caused by soiling and weathering; however, after the sensors were cleaned in March 2015 and December 2016, the reflectance values were shown to have increased in 2015 to nearly the initial installation levels from 2012. A visual comparison of roof membrane samples from 2012 and 2019 suggested that the aged white and grey membranes have darkened over time. Lab test results in 2019 confirmed that solar reflectance of the aged white membrane sample has decreased from 0.58 to 0.40 (~31%) and 0.33 (~44%) at high low points of the roof slope respectively. The solar reflectance of the grey membrane sample did not significantly decrease (less than 2%). Interestingly, the aged black membrane sample increased in solar reflectance from 0.04 to 0.06 (~53%) as a result of surface oxidation and degranulation, though this change is likely to have negligible practical implications.

How membrane colours affect solar absorption was examined using the field monitoring data acquired over the monitoring period. Consistent with previously reported results, roofs with darker membrane cap sheets were generally found to experience higher maximum temperatures and faster changes in temperature. For example, roof temperature measurements for black membrane cap sheets were found to exceeded ambient air temperatures by up to 50°C in some instances. The impact of membrane colour is greatest during sunny and warm periods, and, consequently, the impact of the membrane colour on cooling degree days was found to be much greater than on heating degree days. In many cases, absorption of solar energy will create more additional cooling demand than it will reduce heating demand in the winter, potentially leading to a net energy penalty for using a dark colour membrane (dependant on geographic location). However, this result is not applicable if the interior space is not actively cooled, as is the case for the building on which the monitoring was performed.

The monitored measurements reinforced previously reported findings with regards to factors affecting peak temperatures and temperature lag effects. The data showed a trend of increasing inward heat flow for all insulation arrangements over the course of the monitoring period and this trend is most significant for roofs with polyisocyanurate (polyiso) insulation. This trend for the roofs with polyiso insulation is likely due to aging resulting in decreased thermal resistance, which is consistent with the laboratory measurements of insulation thermal performance.

For all three insulation arrangements, a slight overall annual increase in the relative humidity below the insulation was observed from the end of 2012 to mid-2015. However, the relative humidity levels appear to have reached an annual equilibrium from mid-2015 to the end of 2018. It is worth noting that these roofs reached equilibrium not at entirely

dry conditions, and that through daily variation from solar driven moisture, relative humidity levels of 100% (i.e., condensation) were measured within the assemblies in some cases, suggesting some presence of liquid water. However, exploratory openings and moisture content field measurements in 2014 and 2019 showed that the roof insulation for all assemblies was generally dry and no liquid water was observed.

Movement within the roof assemblies was examined and gaps between the insulation boards were found to typically widen in the winter and narrow in the summer, resulting in a net-increase in gap width over time. It was also found that upper layers typically experienced more displacement than the lower insulation layer, likely due to thermal contraction and expansion of the SBS roof membrane. Field observations suggest that gaps in insulation are more likely to develop parallel to the roof slope, which was also reinforced by further post-field investigation data analysis. Based on the measurements, the correlation between insulation layer and displacement was strongest, followed by roof slope.

In all, this study used the combination of long-term monitoring with periodic field investigation and laboratory testing provides significant insight in to understanding how the hygrothermal (heat and moisture) and physical properties of conventional roof assemblies can change over time. The findings clearly demonstrate the ways in which cap sheet membrane colour and insulation arrangement can both significantly affect roof performance.

Table of Contents

1	**Introduction**	**1**
1.1	Background	1
2	**Field Monitoring Results**	**5**
2.1	Overview of Boundary Conditions	5
2.2	In-Service Reflectance of Membrane Cap Sheets	6
2.3	Effects of Membrane Colour	9
2.4	Effects of Insulation Arrangement	14
2.5	Moisture Movement in Roof Assemblies	22
2.6	Insulation Dimensional Stability	26
3	**Site Visit & Exploratory Investigation**	**34**
3.1	Infrared Thermographic Scanning	35
3.2	Exploratory Openings and Sampling	35
3.3	Field Displacement Measurements	40
3.4	Review of Monitoring Displacement Data	43
4	**Laboratory Testing**	**50**
4.1	Physical Properties of Aged Membranes	50
4.2	Thermal Performance of Aged Insulation	53
5	**Key Findings**	**55**

Appendices

Appendix A Aged Membrane Laboratory Testing by Soprema

Appendix B Methodology – Annual HDD/CDD Based on Membrane Colour & Insulation Arrangement

Appendix C ASTM C518 – Measured Thermal Performance Polyisocyanurate and Stone Wool Insulation Over Time

Appendix D 2015 Interim Report Update – Insulation Dimensional Stability Analysis

1 Introduction

1.1 Background

Conventional roof assemblies (low-slope roof assemblies in which the waterproof membrane is located above the insulation) constitute the majority of the low-slope roof assemblies in North America. The design of these exposed roof membrane assemblies can have significant impacts on the thermal performance of the roof assembly and consequently on building energy consumption, occupant comfort, membrane durability, and assembly service life. Therefore, a conventional roof research and field monitoring study was initiated by RDH Building Science (then RDH Building Engineering Ltd.) in partnership with Soprema and ROCKWOOL (then Roxul) in 2012. This conventional roof research and field monitoring study analyzes the performance of nine unique roof assemblies with different membrane colours (white, grey, or black) and insulation arrangements (polyisocyanurate, stone wool, or a hybrid of both) with a large roof with relatively few obstructions located on an industrial building in the Lower Mainland of British Columbia. This final report provides a summary update and data analysis of the six-year study from the beginning of September 2012 to the end of October 2018 and is an update to previously published analyses.[1,2,3]

The three membrane colours and their respective solar properties as specified by the manufacturer are provided in Table 1.1. The three insulation arrangements of near equivalent specified R-values (R-21 to R-22) consist of polyisocyanurate (polyiso), stone wool, and hybrid of both (stone wool on top of polyiso) as shown in Figure 1.1.1, Figure 1.1.2, and Figure 1.1.3, respectively. The combined roof assemblies cover an approximate area of 12 m x 12 m (144 m²). Figure 1.1.4 shows the arrangement of the roof assemblies on the study building.

TABLE 1.1 ROOF MEMBRANE CAP SHEET PROPERTIES SPECIFIED BY MANUFACTURER

Cap Sheet Colour	Solar Reflective Index (SRI)	Solar Reflectance	Thermal Emittance (Infrared)
White	70	0.582	0.91
Grey	9	0.138	0.85
Black	-4	0.040	0.85

[1] Graham, M.S., 2010. Revised R-values. Professional Roofing, May 2010. Available at: http://www.professionalroofing.net/

[2] Dell, M. and Finch, G., 2013. Monitored Field Performance of Conventional Roofing Assemblies – Measuring the Benefits of Insulation Strategy. Proceedings from the 2013 RCI Symposium on Building Envelope Technology, November 13-14, 2013, Minneapolis, Minnesota.

[3] Finch, G., Dell, M., and Ricketts, L., 2014. Conventional Roofs: Measuring Impacts of Insulation Strategy & Membrane Color in Canada. Proceedings from the 14th Canadian Conference on Building Science and Technology, 2014, Toronto, Ontario.

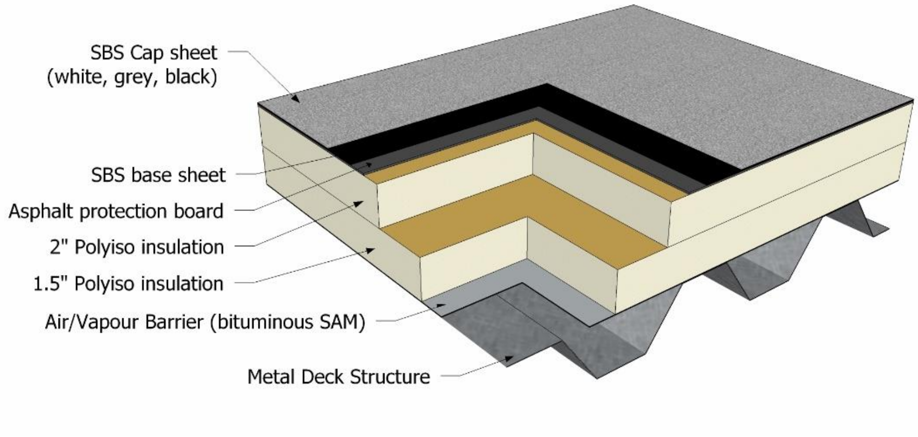

Figure 1.1.1 Polyiso Roof Assembly – Two layers of polyiso insulation.
Total R-value = R-21.0 hr·ft²·°F/Btu (R-6/inch)
Top Layer = R-12.0; Bottom Layer = R-9.0

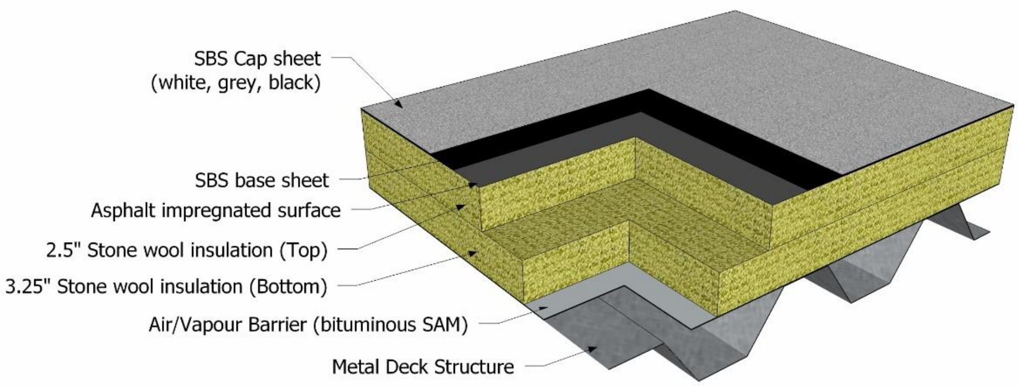

Figure 1.1.2 Stone Wool Roof Assembly – Two layers of stone wool insulation.
Total R-value = R-21.9 hr·ft²·°F/Btu (R-3.8/inch)
Top Layer = R-9.5; Bottom Layer = R-12.4

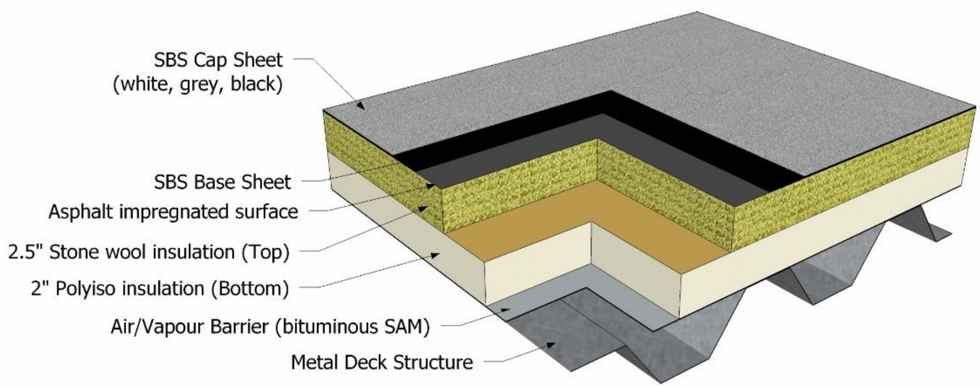

Figure 1.1.3 Hybrid Roof Assembly – Base layer of polyiso insulation and top layer of stone wool insulation.
Total R-value = R-21.5 hr·ft²·°F/Btu (Polyiso = R-6/inch; Stone Wool = R-3.8/inch)
Top Layer = R-9.5, Bottom Layer = R-12.0

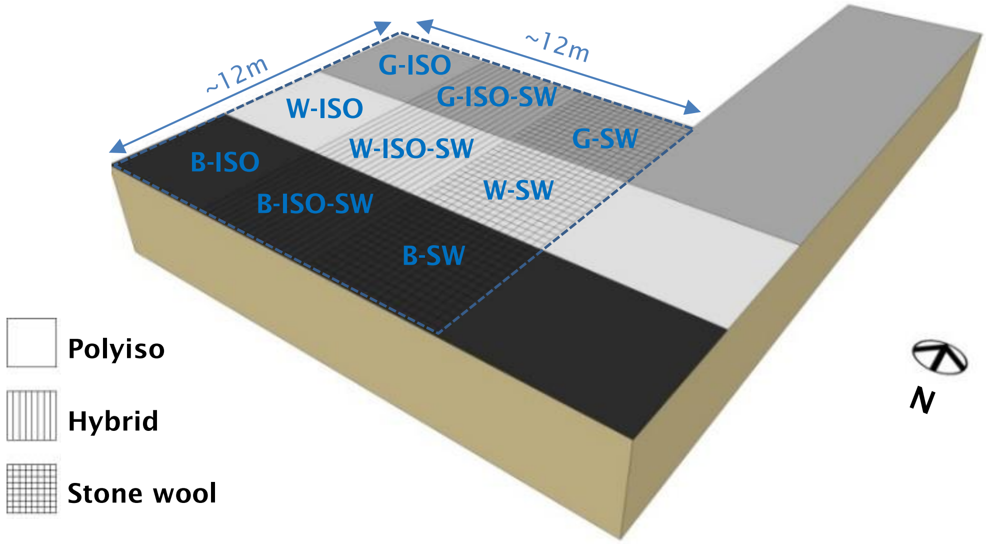

Figure 1.1.4 Layout of the nine test roofs on the study building.

Various sensors were installed within each of the different roof assemblies to measure indicators of their performance including material temperatures, relative humidity, heat flux, and dimensional stability of the insulation. The monitoring equipment and sensors were supplied and installed by SMT Research Ltd. (SMT) under the direction of RDH. A schematic roof cross-section is provided in Figure 1.1.5 which illustrates the typical layout of the sensors in each roof assembly. The naming convention for the sensors installed in the roof assemblies is provided in Table 1.2. Note that this report is largely intended for an audience familiar with the original report by RDH *Study of Conventional Roof Performance*, dated September 14, 2014, which was written after two years of data collection and includes a detailed methodology and description of the study.

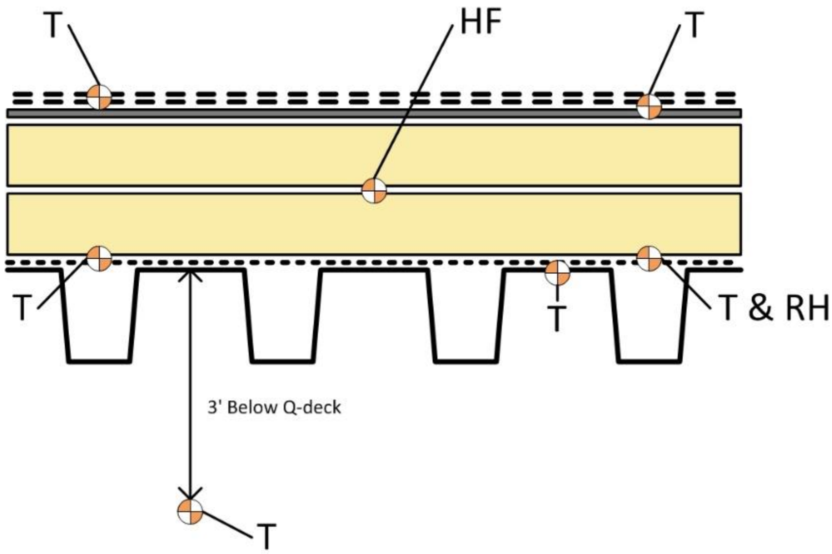

Figure 1.1.5 Schematic roof cross-section showing typical arrangement of sensors installed in each roof assembly.

TABLE 1.2 SENSOR NAMING CONVENTION									
Membrane Colour		-	**Insulation Arrangement**		-	**Sensor Type**		-	**Optional Descriptor**
B	Black		ISO	Polyisocyanurate		T	Temperature		Additional descriptors of sensor positioning
G	Grey		ISO-SW	Hybrid (stone wool on top of polyiso)		RH	Relative Humidity		
W	White		SW	Stone Wool		HF	Heat Flux		

2 Field Monitoring Results

The data presented in this report covers the period from installation in October 2012 through to October 2018. In some cases, data from some sensors were not available due to intermittent malfunctioning of the monitoring equipment, but these instances do not significantly affect the findings and are discussed where appropriate.

2.1 Overview of Boundary Conditions

The exterior conditions provided in this section were obtained from Environment Canada's weather station at Agassiz Airport, located approximately 35 km from the building, whereas interior conditions were obtained from on-site monitoring equipment. Both the exterior and interior conditions provided in this section were used for analysis throughout this report. The average exterior monthly temperature, exterior dew point temperature, and interior temperature are provided in Figure 2.1.1. Monthly heating degree days (HDD) and cooling degree days (CDD)[4] are provided in Figure 2.1.2. and the plotted average monthly relative humidity is provided in Figure 2.1.3.

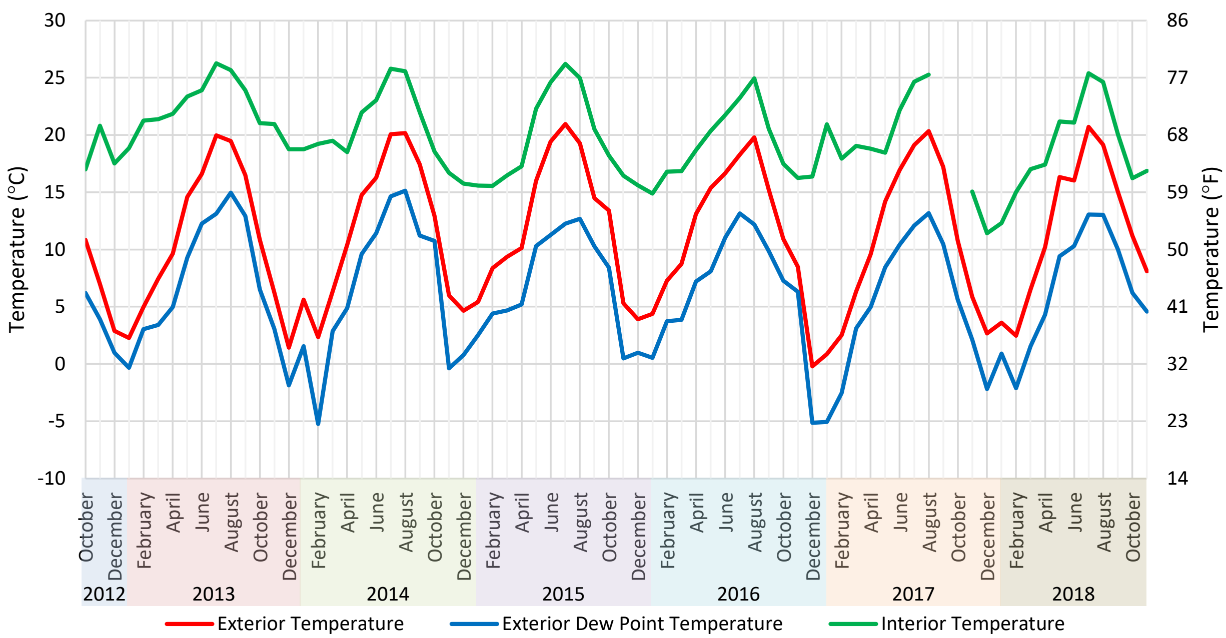

Figure 2.1.1 Graph of monthly average temperature and dew point temperature during the monitoring period from October 2012 to October 2018.

[4] HDD and CDD represent the cumulative degree difference when the measured surface temperatures are either below 18˚C or above 10˚C, respectively (ASHRAE 90.1-2016).

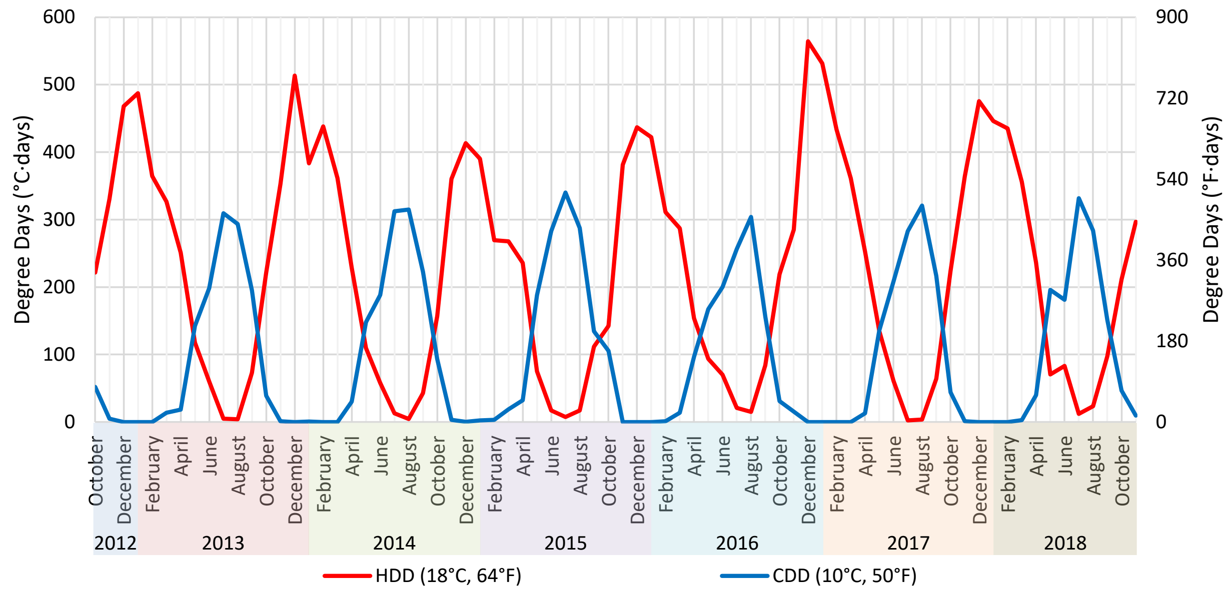

Figure 2.1.2 Graph of monthly average HDD and CDD during the monitoring period from October 2012 to December 2018.

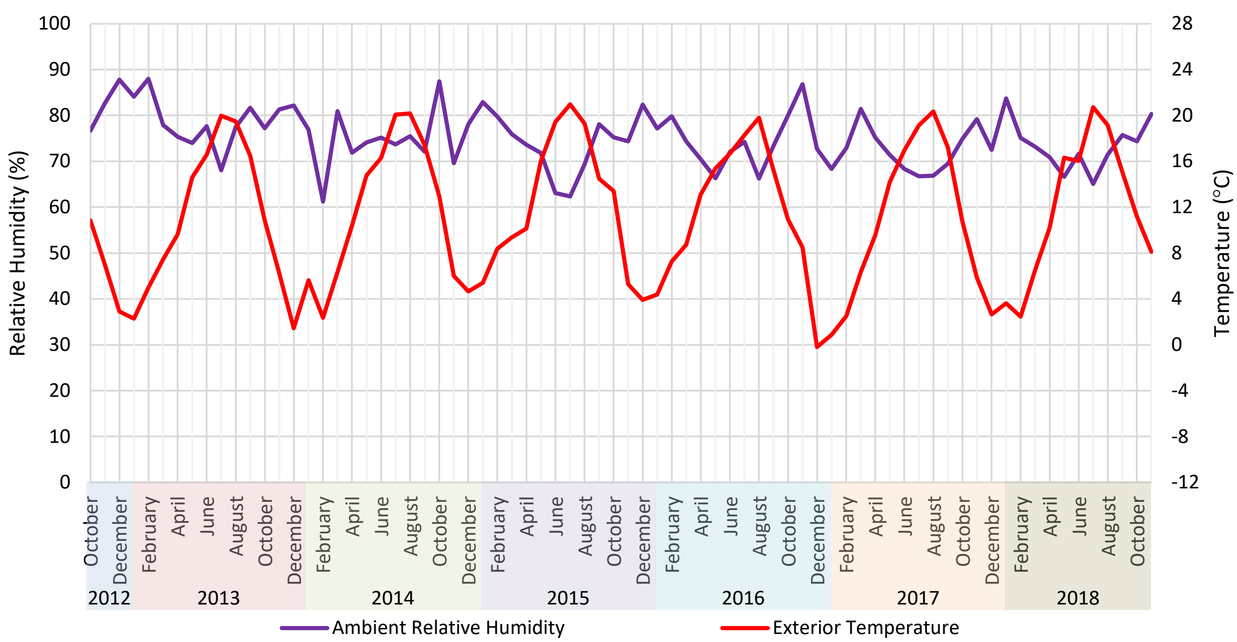

Figure 2.1.3 Graph of monthly average exterior relative humidity during the monitoring period from October 2012 to December 2018.

2.2 In-Service Reflectance of Membrane Cap Sheets

This section evaluates the in-service reflectance of the roof membrane cap sheet over time. Note that laboratory testing of aged membrane samples collected in 2019 was also conducted and results are discussed in Section 4.1.

The studied roof area included three colours of cap sheet membrane (white, grey and black), each with differing reflectance values ranging from high to low. Styrene-butadiene-styrene modified bituminous roof membrane (or SBS roof membrane) cap sheet colours varied to understand the effect of their solar absorptivity and long-wave emissivity properties on membrane durability, roof assembly movement, component temperatures and net heat flows. Reflected solar radiation from the roof cap sheets was measured using solar radiation sensors (pyranometers) mounted approximately 1m above the roof surface and pointed downwards as shown in Figure 2.2.1.

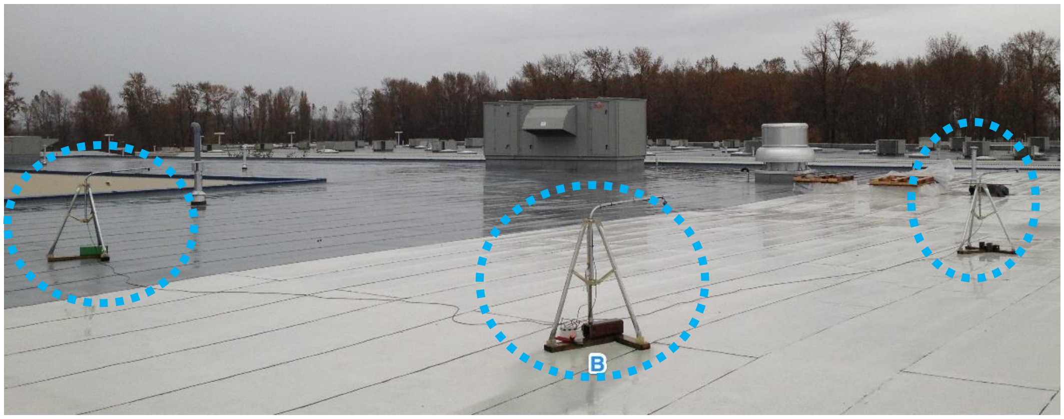

Figure 2.2.1 Three solar radiation sensors were installed to measure reflected solar radiation from the roof membranes.

Note that reflected solar radiation was measured at two locations for the white roof membrane and 'B' designates the higher point of the two.

The total horizontal solar radiation from the sun was measured as well as the reflected solar radiation from the white (at a high and a low point on the roof surface) and grey roofs to estimate their in-service solar reflectance over time. Note that this testing was not performed in accordance with ASTM reflectance measurements typically used for rating of roofing membranes. Instead, the technique used in this study is intended to provide a relative measure of reflectance to allow for comparison of the in-service performance of the roofs in the study. This was done by orienting one sensor towards the sky while the other three sensors were oriented towards the membrane. As a result, the reflectance at each location is represented as a fraction of the total (e.g., 1 being the theoretical maximum reflectance).

Figure 2.2.2 shows unfiltered reflectance values, black cap sheet membrane temperature, and ground snow cover for an eight-day period during December when there was significant snowfall (December 20) and snow accumulation (December 21 and 22). In the plot, a reflectance significantly greater than 1.0 is indicated on December 20 followed by days with reflectance values at or near 1.0. This finding is likely either due to the sky-oriented sensor being partially covered by snow (i.e., reduces the measured total horizontal solar radiation), due to fresh white snow on the roof membrane (i.e., improves the reflectance), or both. For these reasons, calculated reflectance values greater than 1 were filtered out of the final data set used for the analysis, in addition to reflectance values from days with recorded ground snow cover in the region[5]. The effect of frost cover on the reflectance of the roof membrane was also considered; however, while frost may occur more frequently, its presence on the roof surface is typically limited to early mornings when the sun is closer to the horizon. Therefore, much less radiation is being measured or reflected during these periods and would have marginal effect on the overall

[5] Ground snow cover data obtained from https://chilliwack.weatherstats.ca/ which provides information combined from multiple Environment and Climate Change Canada data sources

reflectance values. Interestingly, the cap sheet membrane temperature remains relatively stable around 0˚C to 2˚C during snow ground coverage, likely due to the insulative properties of snow.

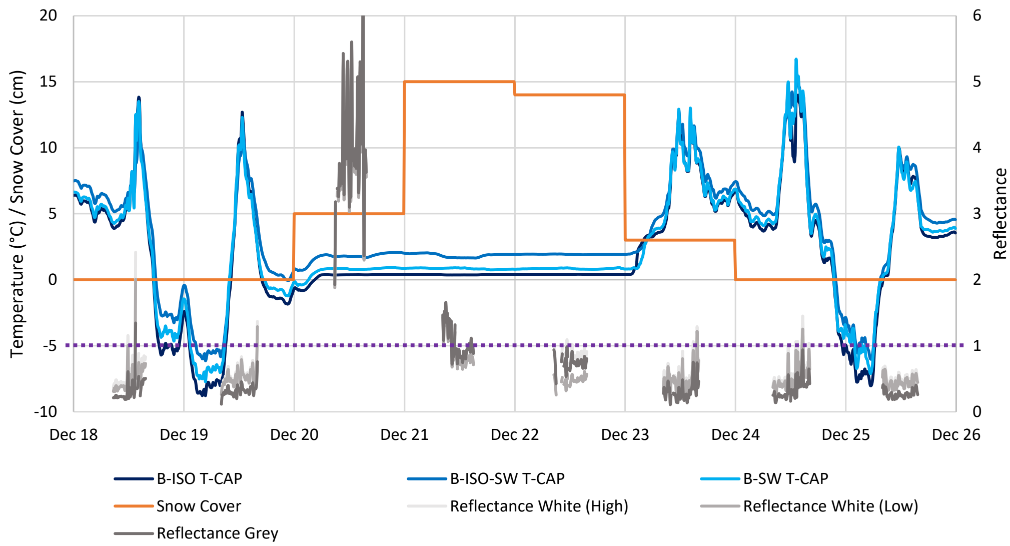

Figure 2.2.2 Black cap sheet membrane temperatures (ISO, ISO-SW, and SW) are plotted with ground snow cover in the region (Chilliwack), and unfiltered relative reflectance values. Ground snow cover data obtained from chilliwack.weatherstats.ca.

Figure 2.2.3 compares the average winter solar reflectance of the roof membranes between December 21st and March 20th from 2013 to 2018, including manufacturer solar reflectance ratings for context. The comparison was made for winter due to periods of data loss in spring, summer and fall of 2014 and summer of 2017.

In the 2015 interim report, data after three years of monitoring suggested a declining trend in the white and roof membrane reflectance, assumed to be caused by soiling and weathering of the cap sheet surface over time. However, near the beginning of winter 2016, the measured reflectance of the white membrane cap sheet had returned to roughly the original values that were measured in winter 2013. It was later confirmed that this was a result of the monitoring equipment having been cleaned in March 2015 and December 2016. Therefore, the trend found in the first three years was likely caused by soiling of the sensor rather than soiling and weathering of the membrane. Measurements from the full monitoring period did however show that the reflectance of the white membrane at the higher point of the roof slope had not reduced significantly over the six-year service life.

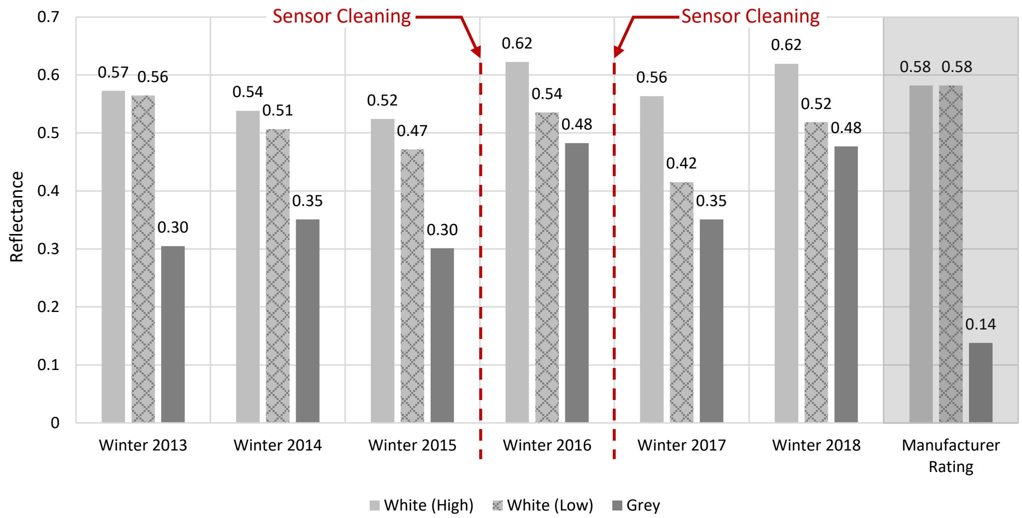

Figure 2.2.3 Average reflectance of membrane between December 21 and March 20 over the six-year monitoring period. Note that two cleaning periods (March 2015 and December 2016) are indicated with red dashed lines.

It is important to note that the discrepancies between the field measured values and manufacturer's rated values are expected and as discussed, are largely due to the difference in measurement techniques. For example, the measured reflectance of the white membrane in winter 2013 is similar to the manufacturer's rated reflectance, whereas the measured grey membrane reflectance is significantly higher than the rated value. This is potentially a result of the sensor on the grey roof being located relatively closer to the white roof or that the sensor is measuring some reflected radiation from the adjacent white roof. It is also possible that the grey membrane is more reflective compared to its rated value. For the white membrane, the measurement of the reflectance at a low point of the roof slope is less than the membrane at a high point, a result of the low point being dirtier (which was later confirmed visually on site). Results from laboratory testing of membrane samples collected in 2019 are discussed in Section 4.1.

2.3 Effects of Membrane Colour

This section evaluates the impact of membrane cap sheet colour (i.e., reflectance) and its effect on membrane temperature and heat flow through the assembly.

Figure 2.3.1 shows the measured monthly average membrane temperature by membrane colour, where the dots indicate the maximum and the minimum temperature that the membrane experienced each month. The values provided for each membrane colour are averages of all of the different insulation arrangements (i.e., "white" represents the average of all three insulation arrangements with white roof membrane cap sheet).

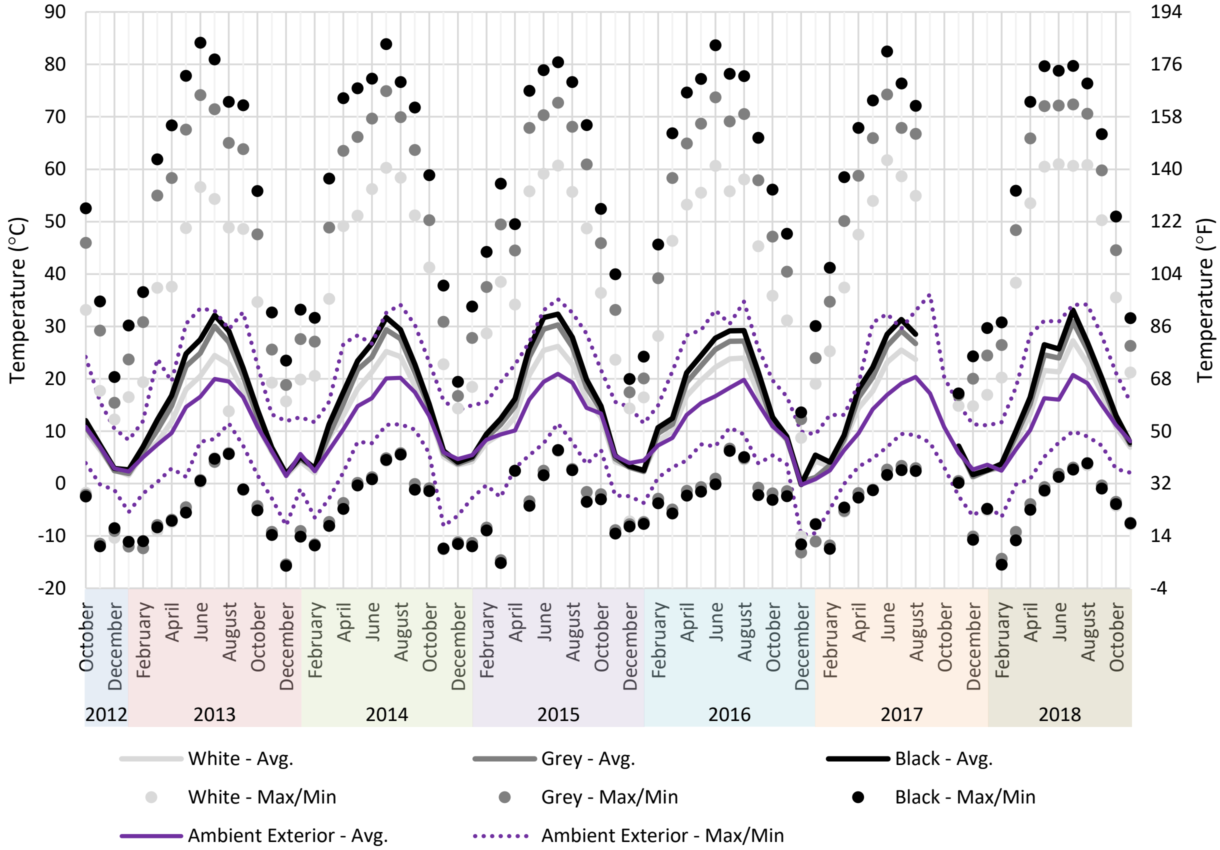

Figure 2.3.1 Graph of monthly average membrane temperatures and maximum/minimum membrane temperature for each month by membrane colour.

Figure 2.3.1 illustrates how differences in roof membrane colour can have a significant impact on roof membrane temperatures. As expected, this impact is greatest during the summer months. For example, in July 2014, the maximum surface temperature of the black membrane was observed to be roughly 50˚C above the maximum ambient temperature, while the maximum temperatures of the grey and white roofs were 42.3˚C and 27.7˚C higher. In contrast, recorded minimum surface temperature in December 2014 for the black, grey and white membrane roofs were 5.5˚C, 5.1˚C and 5.2˚C, respectively. Note that these winter values are colder than the minimum ambient air temperature, and that the similarity between the temperatures is likely due to their long-wave emittance properties, which is largely independent of their colour.

To provide an understanding of what is occurring on a daily basis, Figure 2.3.2 through Figure 2.3.5 present the hourly cap sheet membrane temperatures by membrane colour for the hybrid insulation assemblies over a three-day period in the winter of 2014/2015, winter of 2017/2018, summer of 2015 and summer of 2017.

In the plots, the daily fluctuations in the roof membrane temperatures show that membrane colour has a significant impact during the day and can vary due to differences in short-wave solar reflectance/absorptivity values. The figures also show that overnight temperatures are relatively similar for each of the three membrane cap sheet colours. In all, the trends found in the daily data are generally similar to those found in the seasonal analysis.

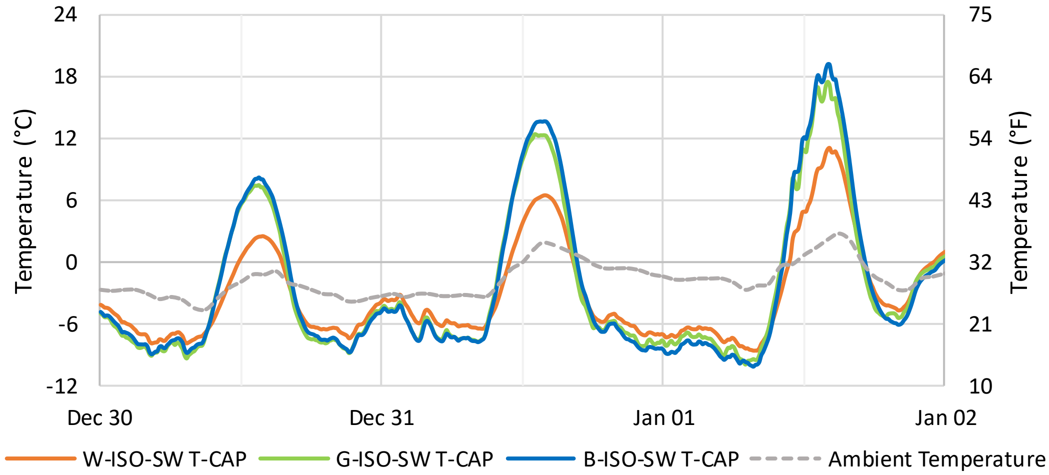

Figure 2.3.2 Graph of roof membrane cap sheet temperature for the three hybrid roof assemblies from December 30 to January 2, 2015.

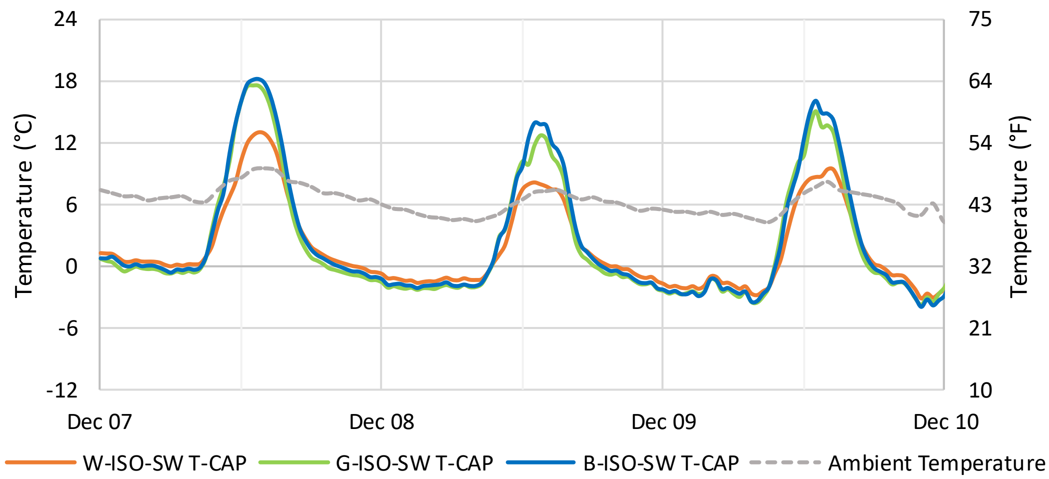

Figure 2.3.3 Graph of roof membrane cap sheet temperature for the three hybrid roof assemblies from December 7 to 10, 2017.

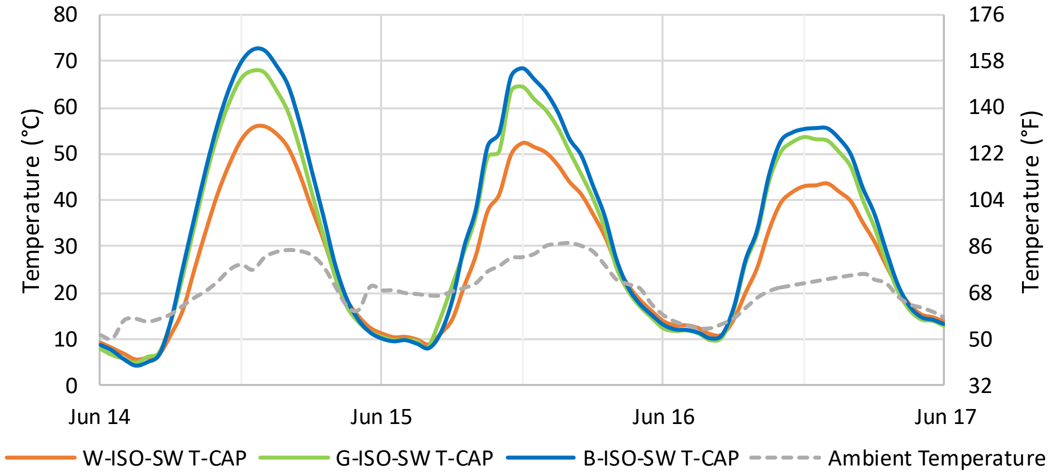

Figure 2.3.4 Graph of roof membrane cap sheet temperature for the three hybrid roof assemblies from June 14 to 17, 2015.

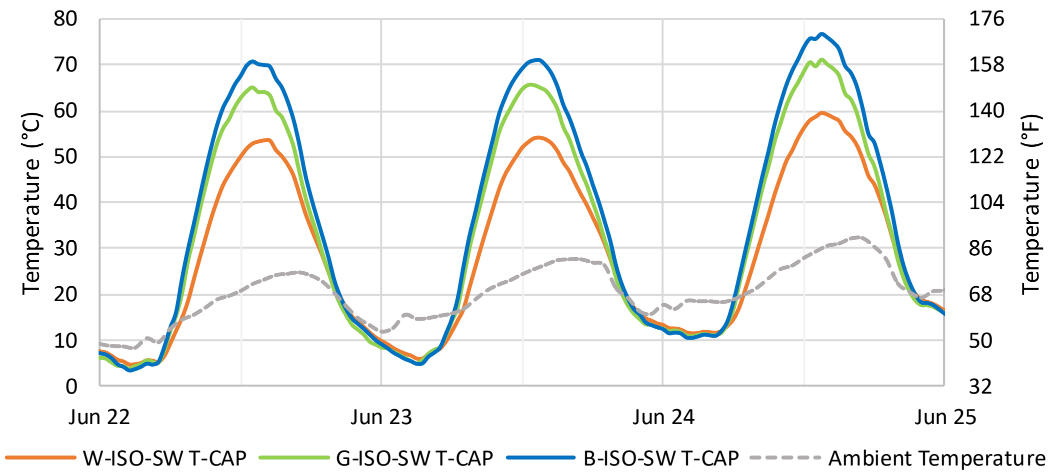

Figure 2.3.5 Graph of roof membrane cap sheet temperature for the three hybrid roof assemblies from June 22 to 25, 2017.

The inward and outward heat flux through the roofs for each of the different roof membrane colours is presented in Figure 2.3.6. The chart shows that the black roof membrane area experiences greater inward heat flow compared to the white and grey as a result of the relatively higher temperatures experienced on the surface of the dark membrane. The figure also shows a slight trend of increasing inward heat flow for all membrane colours over the course of the six-year monitoring period. While the cause of this trend is not immediately apparent based on roof membrane weathering and degradation of solar reflectance, the trend is still thought to be (as proposed in the 2015 interim report) due to the gradual decrease in thermal performance of the polyiso insulation as it ages. See Section 4.2 for the laboratory material testing results of thermal performance of aged polyiso insulation.

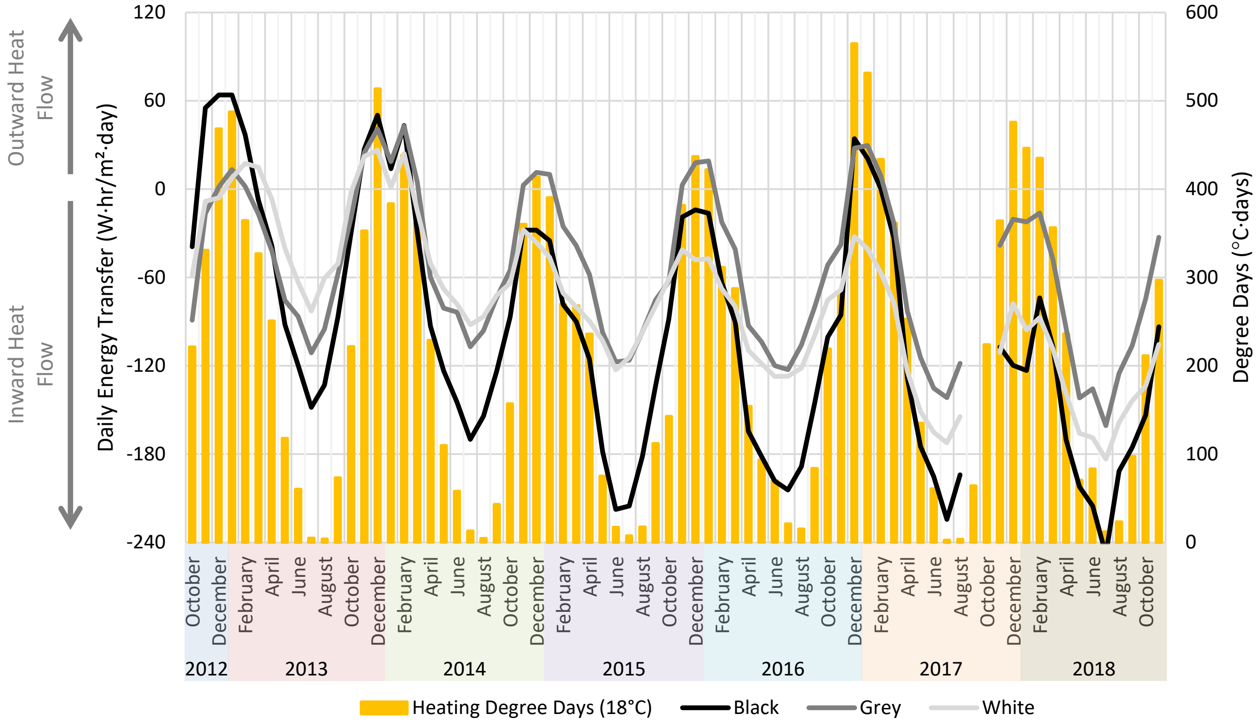

Figure 2.3.6 Graph of monthly average daily energy transfer by roof membrane colour. Note: HDD values are for the ambient air temperature.

In addition to heat flux, another way to assess the potential energy implications of different roof membrane colours is to calculate the HDDs and CDDs using roof surface temperatures and compare them with calculated HDDs and CDDs using ambient exterior air temperatures; the latter being standard practice. A comparison between degree days calculated using ambient temperature and roof surface temperature is presented in Figure 2.3.7. Note that CDDs are presented as negative values in this report.[6]

The chart shows HDDs are slightly reduced, particularly for the black and grey roof membranes when considering the increased solar heat gain. For cooling, there is a significant increase in CDDs for all membrane colours, when considering solar heat gain. The difference is much more pronounced for the CDD where the darker coloured membranes significantly contribute to overall heat gain. The figure shows that in some cases, the CDDs have more than doubled.

Based on these results, HDDs and CDDs using the roof surface (sol-air) temperature instead of ambient (exterior air) temperature should offer a more accurate estimate of degree days. Interestingly, this illustrates how standard energy modelling of buildings, based on ambient air temperatures that do not account for solar absorption on surfaces such as roofs can create significant inaccuracy as a result. In particular, the results show that the balance between heating and cooling demand for a building can be significantly affected by the colour of the membrane.

[6] See Appendix B for HDD/CDD methodology.

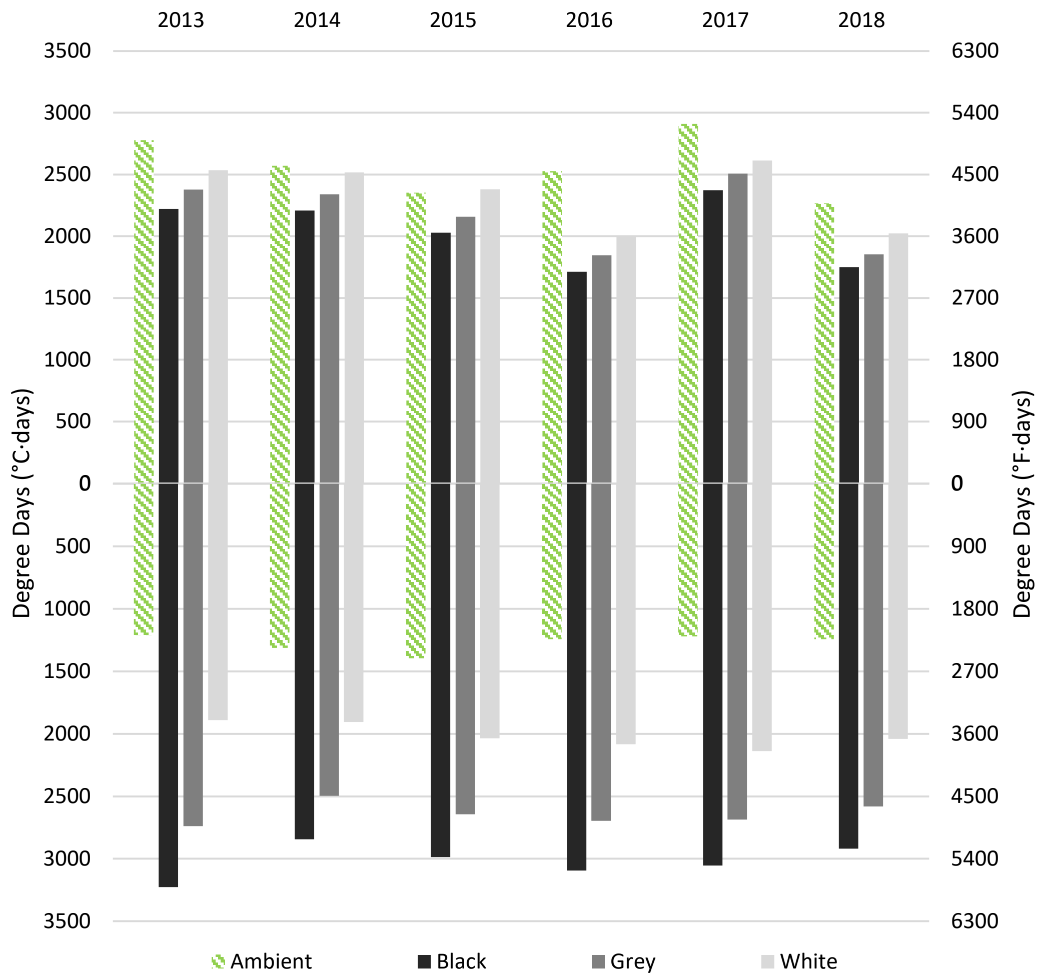

Figure 2.3.7 Adjusted annual HDD and CDD from 2013 to 2018 based on membrane colour.

Note that the roof surface temperature used to determine the degree days for each membrane colour was averaged for different insulation arrangements with the same roof membrane colour.

2.4 Effects of Insulation Arrangement

This section evaluates the impact of insulation arrangements on membrane temperature, interior metal deck temperature, and heat flow through the roof assemblies.

Figure 2.4.1 shows the measured monthly average membrane temperatures by insulation arrangements, where the dots indicate the maximum and the minimum temperatures that the membrane experienced each month. The values provided for each insulation arrangement are averages of the different roof membrane colours with similar insulation arrangements. (i.e., “ISO” is the average of polyiso-only roof assemblies with black, grey and white roof membrane cap sheet). Note that, to ensure all nine unique roof assemblies were equal from a thermal performance perspective, they were each installed with roughly the same nominal R-value (R-21.0 to R-21.9).

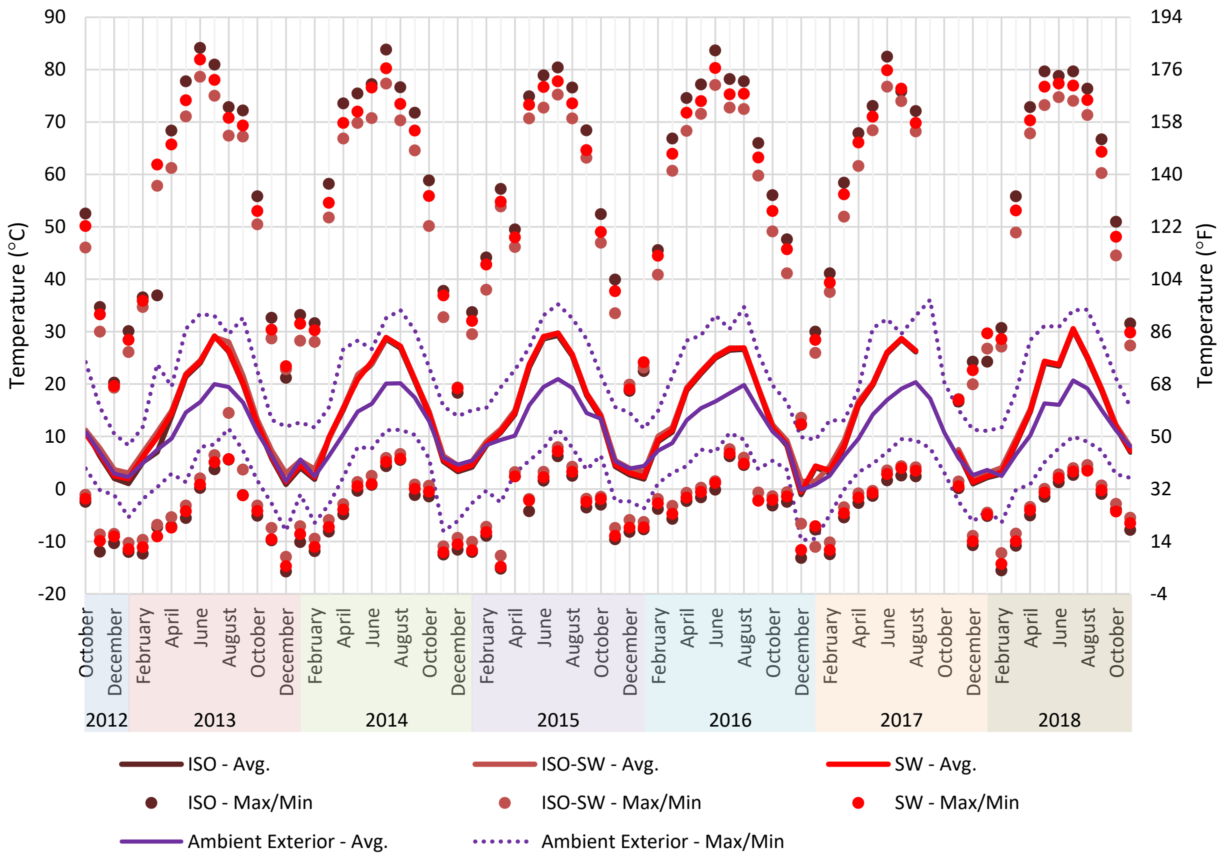

Figure 2.4.1 Graph of monthly average membrane temperatures and maximum/minimum membrane temperature for each month by insulation arrangement.

While the impact of insulation arrangement on the roof membrane temperature is less significant than the colour of the membrane, insulation arrangement does influence the roof membrane temperature. The most significant impact with respect to insulation arrangement is observed in the maximum monthly temperatures. Though it was anticipated that stone wool insulation would have the lowest maximum temperature, generally, the hybrid insulation arrangement had the lowest maximum temperatures throughout the year, while polyiso insulated roofs had the highest maximum membrane temperatures. Again, the minimum membrane temperatures are similar for all different roof types, but typically the polyiso insulated roofs also experienced the coldest temperatures. Other insulation behaviour is discussed further below and within the laboratory testing in Section 4.2.

Separated by insulation arrangement, roof membrane cap sheet temperatures for five consecutive days are presented in Figure 2.4.2 through Figure 2.4.5 for winter 2014/2015, winter 2017/2018, and five consecutive days for summer 2015 and 2017.

The roof membrane temperatures plotted from Figure 2.4.2 to Figure 2.4.5 show that the roof membrane with polyiso insulation experiences both the highest and the lowest temperatures over the course of a day. The polyiso roof assemblies experienced more extreme roof membrane temperatures when compared to the hybrid and stone wool roofs, likely due to the differences in the thermal mass (heat capacity), latent energy transfer, and temperature dependent thermal performance of the insulation types. The hybrid roof also appears to experience relatively higher temperatures before and after daytime solar exposure. These reduced maximum and minimum temperatures in the hybrid and the stone wool roofs are consistent with our previous findings[7] and will have a positive impact on the durability and service life of the roof membrane and insulation itself. The daily roof membrane cap sheet temperature trend for the three insulation arrangements from 2017 appears to be consistent with the results from the 2015 interim report.

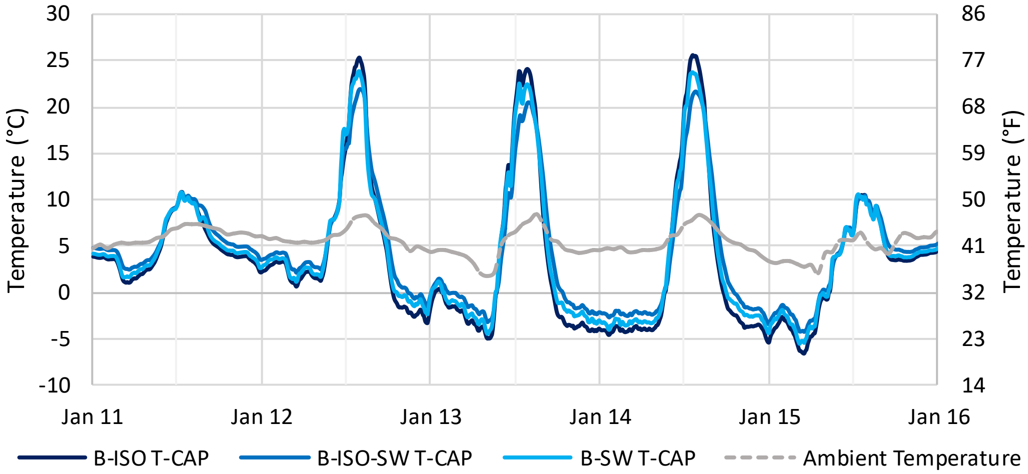

Figure 2.4.2 Graph of Roof membrane cap sheet temperature for the three insulation arrangements from Jan 11 to 16, 2015.

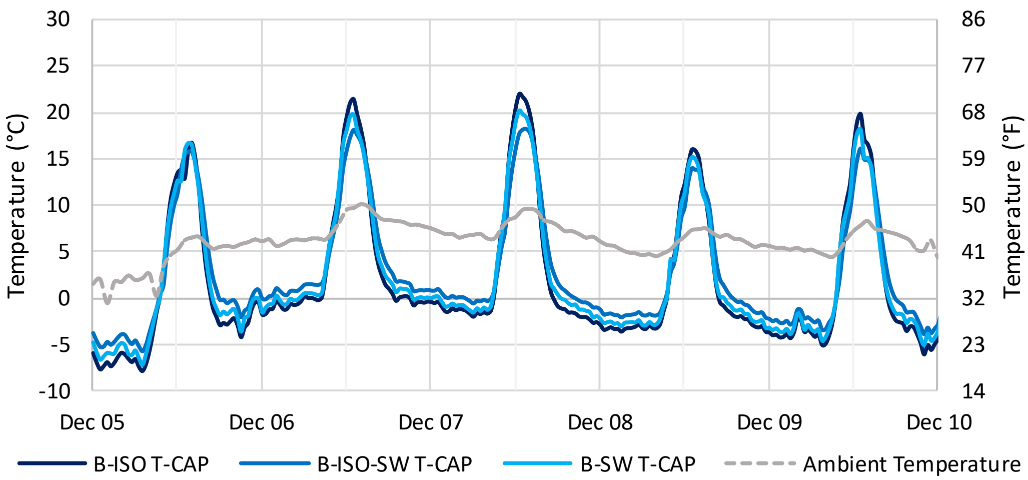

Figure 2.4.3 Graph of roof membrane cap sheet temperature for the three insulation arrangements from Dec 5 to 10, 2017.

[7] Finch, G., Dell, M., and Ricketts, L., 2014. Conventional Roofs: Measuring Impacts of Insulation Strategy & Membrane Color in Canada. Proceedings from the 14th Canadian Conference on Building Science and Technology, 2014, Toronto, Ontario.

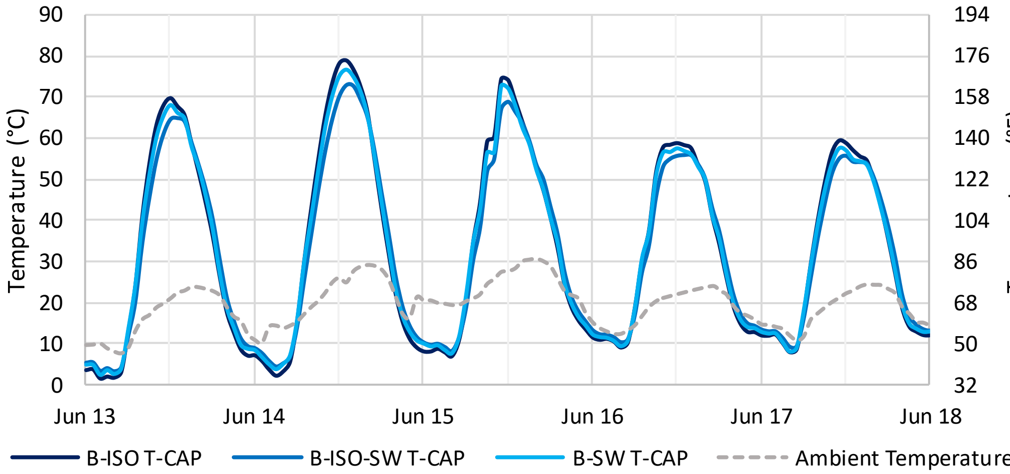

Figure 2.4.4 Graph of roof membrane cap sheet temperature for the three insulation arrangements from June 13 to 18, 2015.

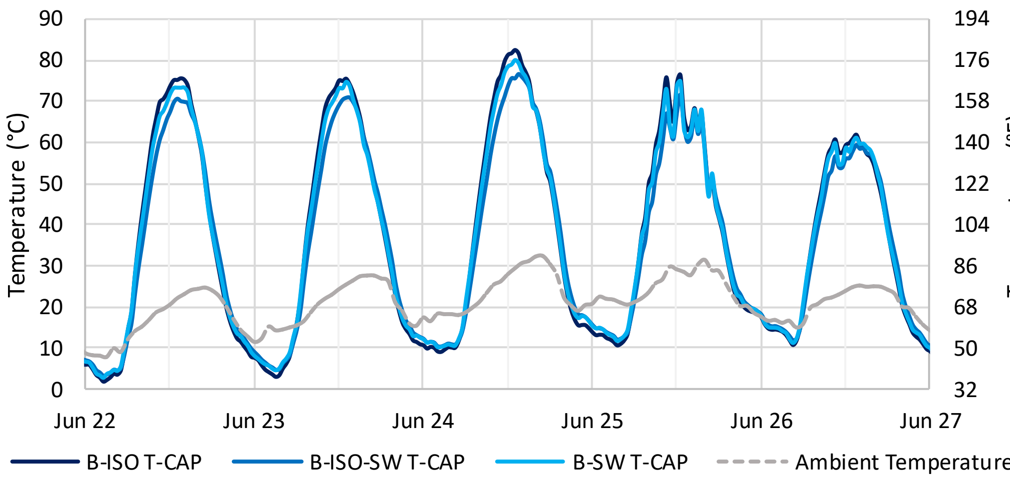

Figure 2.4.5 Graph of roof membrane cap sheet temperature for the three insulation arrangements from June 22 to 27, 2017.

Lag in temperature swings were observed during and noted in the 2015 interim report. To explore the previous findings in more detail, Figure 2.4.6 to Figure 2.4.9 show the effect of the insulation strategy over the course of a day. Roof membrane temperature for June 27th, 2015 (Figure 2.4.6) and June 29th, 2017 (Figure 2.4.7) and interior deck temperature during June 27th, 2015 (Figure 2.4.8) and June 29th, 2017 (Figure 2.4.9) for the black roofs were compared, given that they experienced the largest temperature variations.

A typical lag observed in the roof maximum temperatures for the hybrid assemblies in 2015 (Figure 2.4.6) became less apparent in 2017. Figure 2.4.7 shows the hybrid assemblies reaching daily maximum temperature at the same time as other assemblies. While not provided in this report, the monitoring data does show lag in hybrid assemblies' daily maximum temperature, though this occurrence was not as frequent as in 2015. Additionally, these lags are less significant (typically from ~1.0 hours in 2015 to ~0.5 hours in 2017) and have become increasingly difficult to observe given the monitoring equipment's sampling interval.

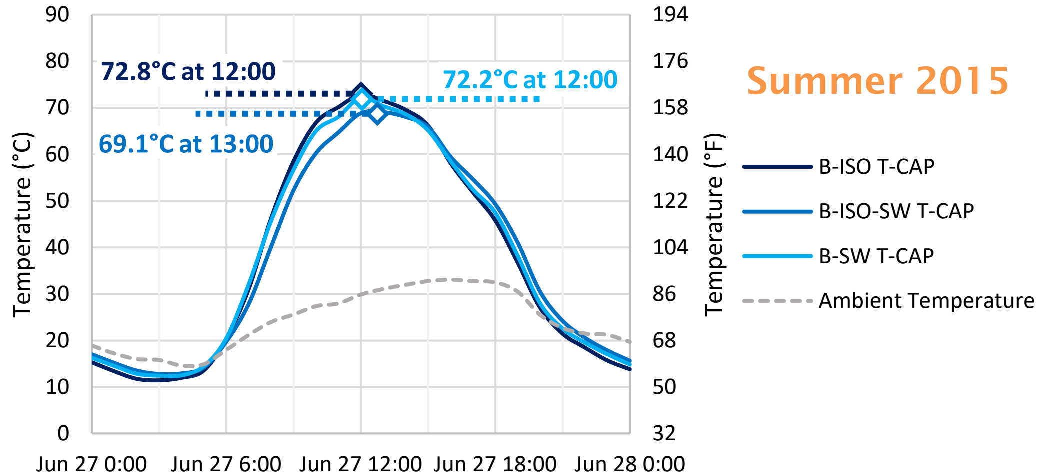

Figure 2.4.6 Graph of Roof membrane temperatures for roof assemblies with a black cap sheet on June 27, 2015.

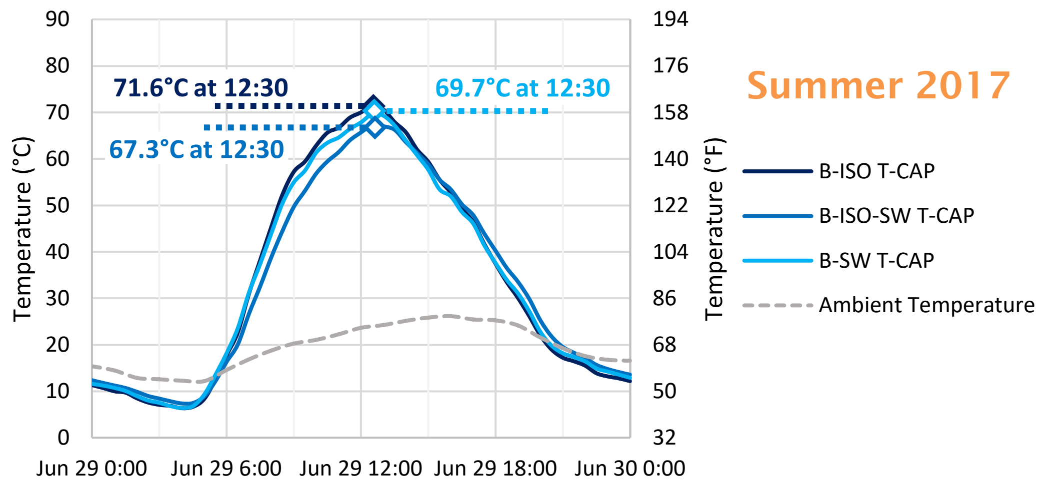

Figure 2.4.7 Graph of Roof membrane temperatures for roof assemblies with a black cap sheet on June 29, 2017.

Figure 2.4.8 and Figure 2.4.9 show similar lag in the maximum interior metal deck surface temperature. When compared to polyiso, the hybrid assembly experienced a thirty-minute to one-hour lag in the occurrence of the maximum temperature, and the stone wool assembly experienced an approximate three-hour lag. While the figures illustrating this lagging effect are only providing a snapshot for a single day, the effect is consistently noticeable during the monitoring period and is consistent with findings discussed in the two-year interim report.[8]

[8] Finch, G., Dell, M., and Ricketts, L., 2014. Conventional Roofs: Measuring Impacts of Insulation Strategy & Membrane Color in Canada. Proceedings from the 14th Canadian Conference on Building Science and Technology, 2014, Toronto, Ontario.

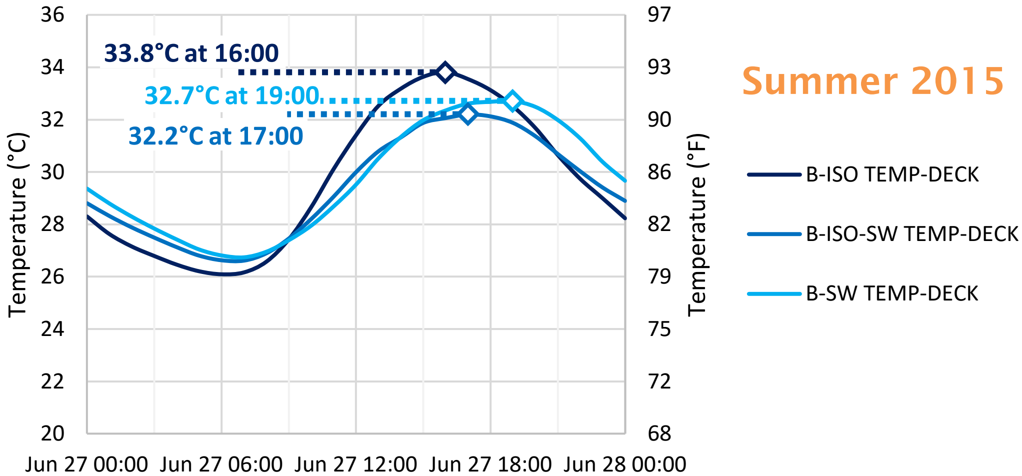

Figure 2.4.8 Graph of Interior metal deck temperature for the black roof assemblies on June 27, 2015.

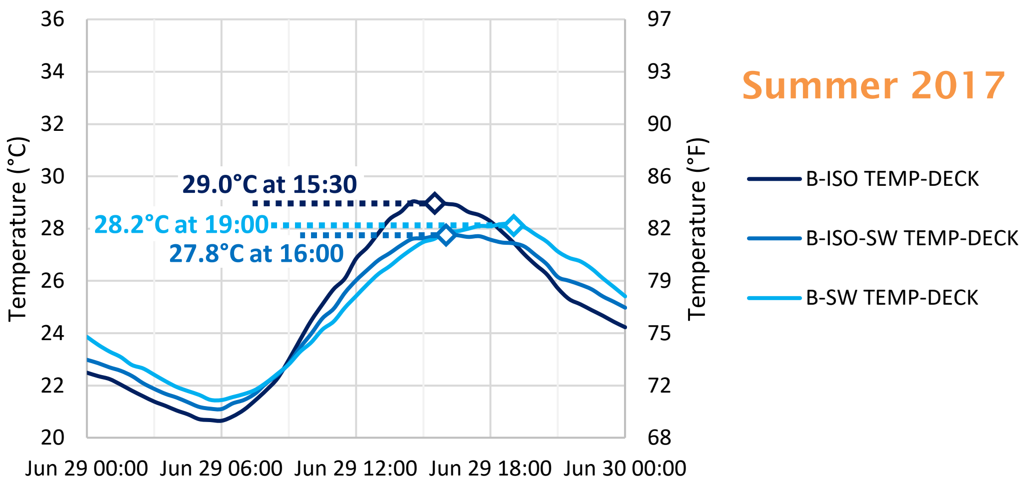

Figure 2.4.9 Graph of Interior metal deck temperature for the black roof assemblies on June 29, 2017.

To further assess the impact of insulation arrangement on the heat flow through the assemblies, the inward and outward heat flow through the different insulation arrangements was averaged for each month during the monitoring period and presented in Figure 2.4.10.

The figure shows a slight trend of increasing inward heat flow for both the polyiso and the hybrid insulation arrangements over the course of the monitoring period. The stone wool arrangement also indicates some increase in heat flow, though noticeably less than the other two arrangements. This trend for the polyiso arrangements likely indicates that the thermal resistance of polyiso is decreasing as it ages, which again is consistent with previous findings.[9,10,11]

[9] Graham, M.S., 2010. Revised R-values. Professional Roofing, May 2010. Available at: http://www.professionalroofing.net/

[10] Dell, M. and Finch, G., 2013. Monitored Field Performance of Conventional Roofing Assemblies – Measuring the Benefits of Insulation Strategy. Proceedings from the 2013 RCI Symposium on Building Envelope Technology, November 13-14, 2013, Minneapolis, Minnesota.

[11] Building Science Corporation (BSC). 2013. BSC Information Sheet 502: Understanding the Temperature Dependence of R-values for Polyisocyanurate Roof Insulation. Available at: http://www.buildingscience.com

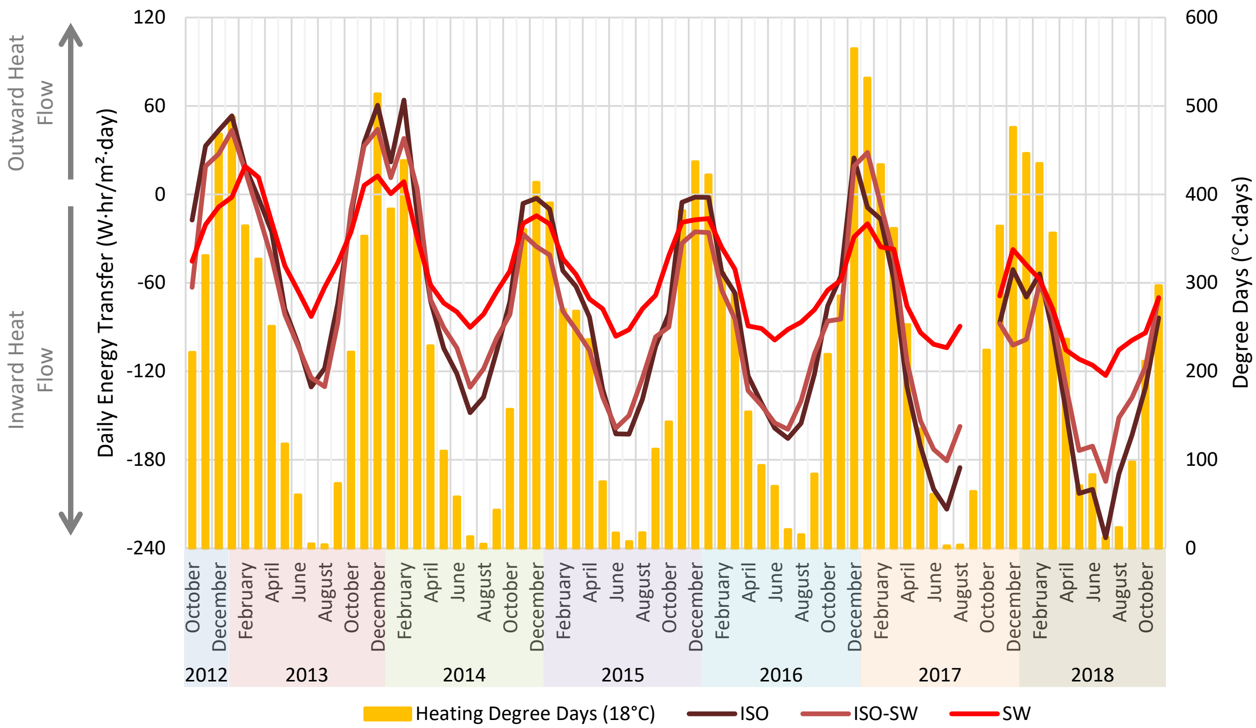

Figure 2.4.10 Graph of monthly average daily energy transfer by insulation arrangement.

Note HDD values are for the ambient air temperature.

Figure 2.4.11 compares percentage increase of daily energy transfer by insulation arrangement during the month of June and July for each year (2014 to 2018) relative to the first monitoring period (2013) to further examine the trend of increasing inward heat flow. As the inward heat flow depends largely on solar exposure, it is likely that roof would receive more energy during dry, sunny periods or during particularly hot summer months. Therefore, change in inward energy transfer for each insulation arrangement is provided along with percentage increase in CDD, as change in energy gained by the roof should have a strong correlation with observed CDD. For example, a relatively large increase in the heat flow for all insulation arrangement in June and July of 2015 can be explained by a greater than 20% increase in CDD. While inward heat flow increased in all assemblies, the increase is most significant in roofs with polyiso insulation as a result of its gradual decrease in thermal performance over time (discussed further in Section 4.2).

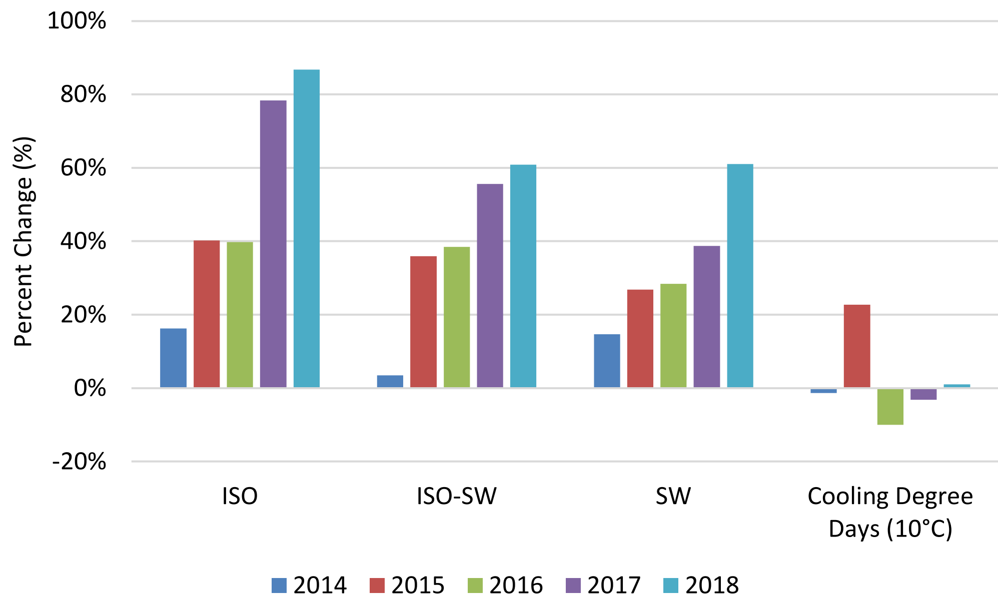

Figure 2.4.11 Percentage increase of daily energy transfer by insulation arrangement during the months of June and July since 2013 compared to percentage increase of CDD during the same period.

The impact of insulation arrangements was also assessed based on calculating degree days. HDD and CDD were compared when calculated using roof surface temperatures versus values calculated using ambient exterior air temperatures, similar to the analysis of energy implications of membrane cap sheet colour in Section 2.3.

Figure 2.4.12 shows that, for all assemblies, the calculated HDD using the roof surface temperatures is slightly less than the HDD using ambient conditions. The HDD is also consistently lower for the hybrid (ISO-SW) roof assembly, a result of the hybrid experiencing the warmest minimum temperatures. For cooling, the CDDs using roof temperatures are significantly higher than the CDDs using ambient conditions in all insulation arrangements, with slight differences for each arrangement. These slight differences in annual HDD and CDD between the insulation arrangements is likely due to combination of thermal mass and latent heat transfer. Again, these results illustrate how HDDs and CDDs should be calculated using the roof surface (sol-air) temperature instead of ambient (exterior air) temperature to offer a more accurate estimate of degree days.

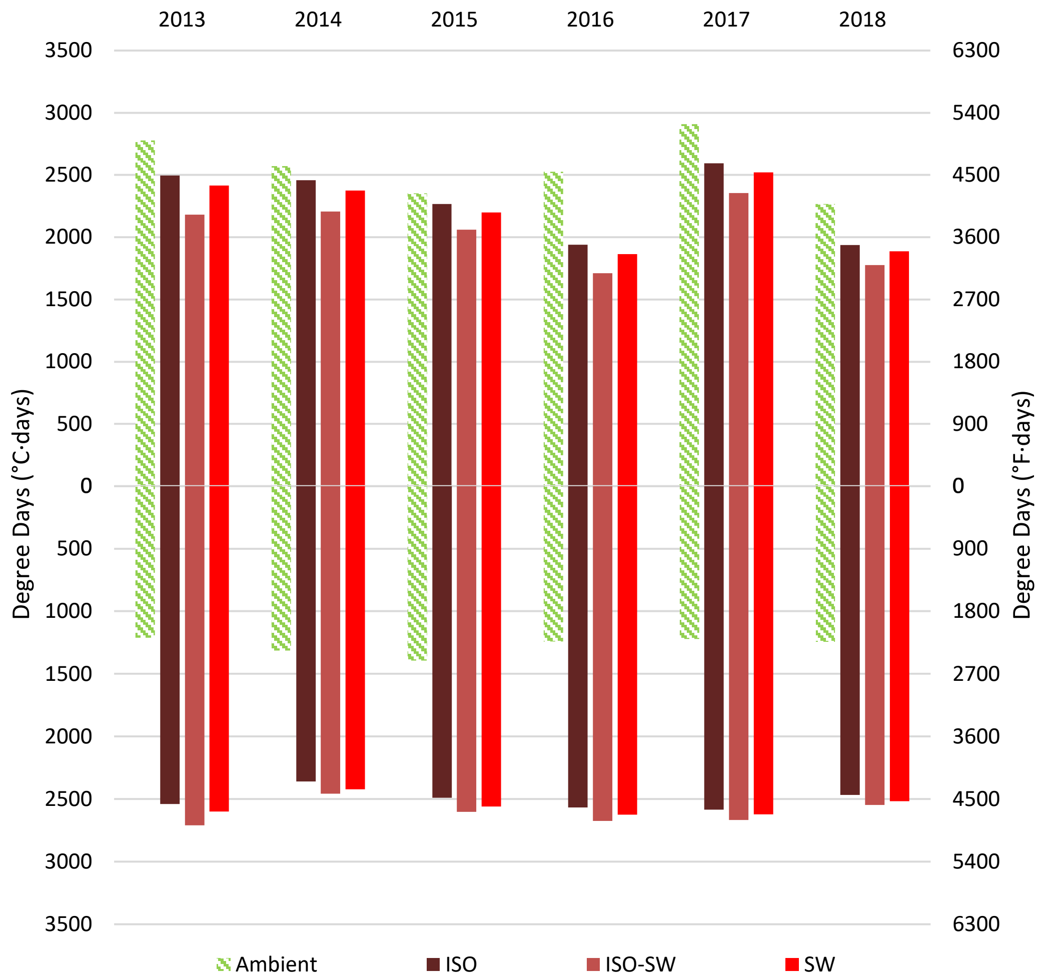

Figure 2.4.12 Adjusted annual HDD and CDD from 2013 to 2018 based on insulation arrangement.

2.5 Moisture Movement in Roof Assemblies

Moisture movement impacts heat transfer within a roof assembly by carrying latent energy with it as it moves through the insulation layers. Therefore, section evaluates the impact on the roof membrane temperature on moisture movement throughout the insulation layers of the monitored roof assemblies.

The measured average relative humidity levels within the roofs, sorted by insulation arrangement over the course of the monitoring period are provided in Figure 2.5.1. The plot shows a seasonal trend that is the result of change in the predominant direction of the seasonal vapour drive. During the summer, the top of the insulation is being heated, which drives vapour towards the bottom of the insulation where relative humidity sensors are located. During winter, the vapour drive reveres direction (upwards) as a result of relatively warmer interior conditions. The daily movement of vapour is more apparent with the stone wool insulation because stone wool has higher vapour permeability, whereas polyiso is relatively impermeable and consequently restricts the movement of moisture within the insulation. Note that vapour drive is most significant during sunny and hot days in the summer.

Figure 2.5.1 also reveals that for all three insulation arrangements, a slight overall year-to-year increase in the relatively humidity occurs over the course of the first three years that appears to stabilize from 2015 onward. This finding suggests that it took the roof assemblies approximately three years to reach equilibrium conditions and confirms leaks (water or air) are not present within the monitored locations of the roof. It is important to note that, generally the amount of moisture within a roof assembly is largely dependant on both the specific climate (i.e., relative humidity) where the roof is construction and the absolute moisture content of the roofing materials at the time it was constructed.

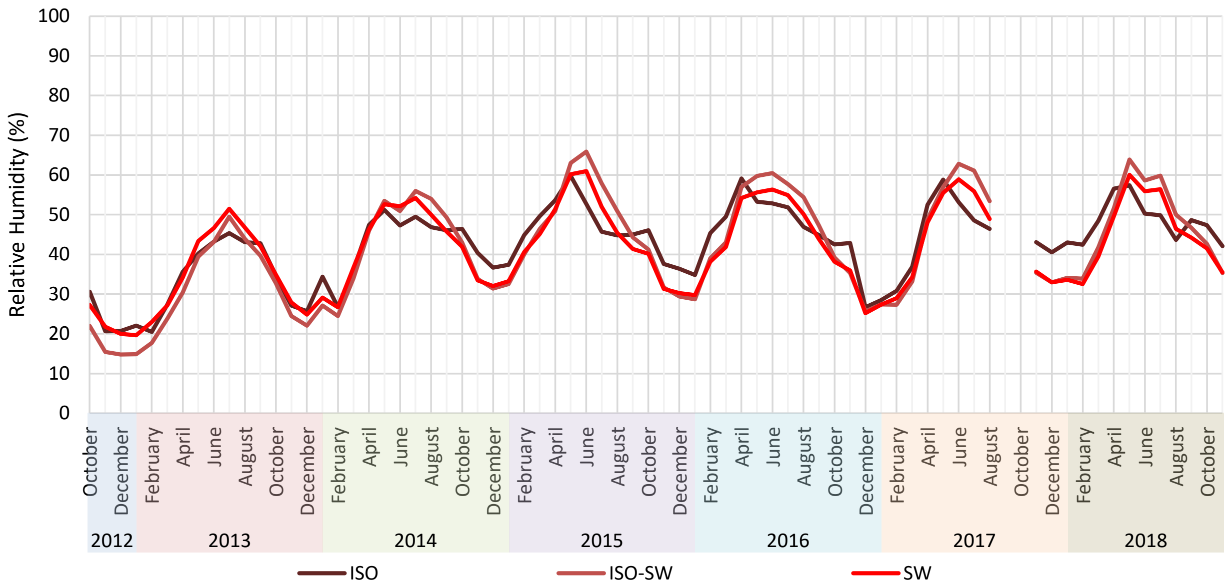

Figure 2.5.1 Monthly average relative humidity levels below insulation for each insulation arrangement.

To provide a clearer understanding of what is occurring on a daily basis, the measured relative humidity within the assembly was plotted over the course of two days in Figure 2.5.2 through Figure 2.5.7 for winter 2013/2014 and 2017/2018, spring 2014 and 2017, and summer 2013 and 2017 for the roof assemblies with black roof membrane cap sheet. See Section 3.2 for measured moisture levels of insulation samples measured during exploratory openings. Generally, daily trends with respect to moisture movement and membrane temperature are consistent with the seasonal findings, most notably during the spring and summer when membrane temperatures are most extreme.

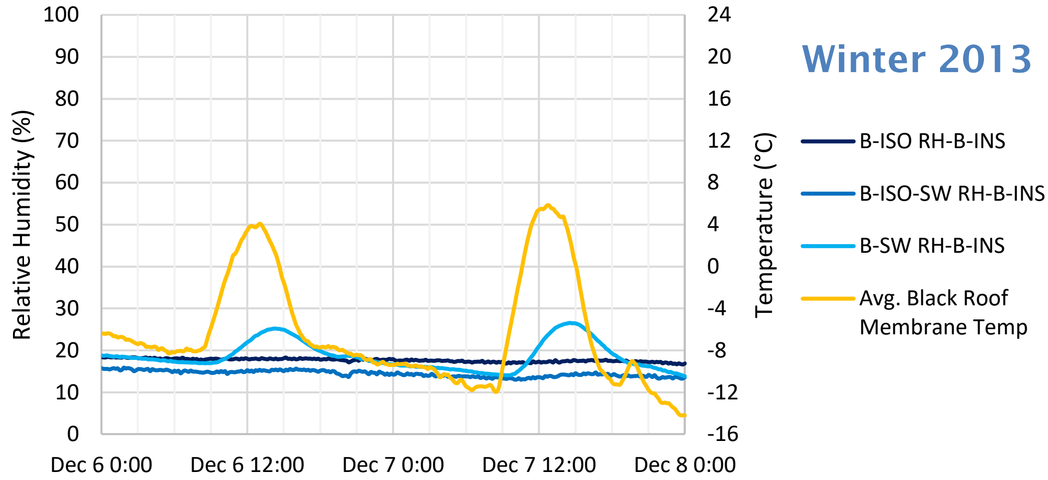

Figure 2.5.2 Relative humidity levels below insulation by insulation arrangement, and average black roof membrane temperature between December 6 to 8, 2013.

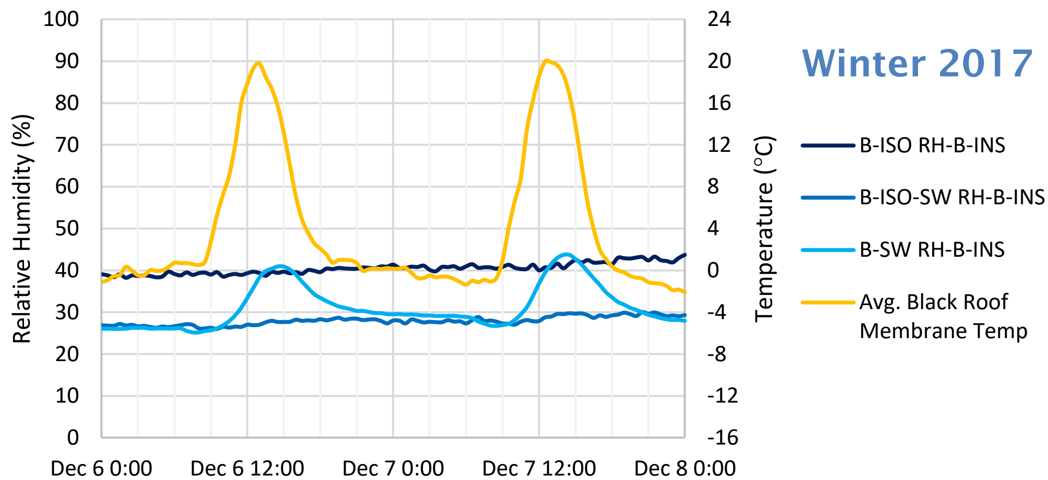

Figure 2.5.3 Relative humidity levels below insulation by insulation arrangement, and average black roof membrane temperature between December 6 to 8, 2017.

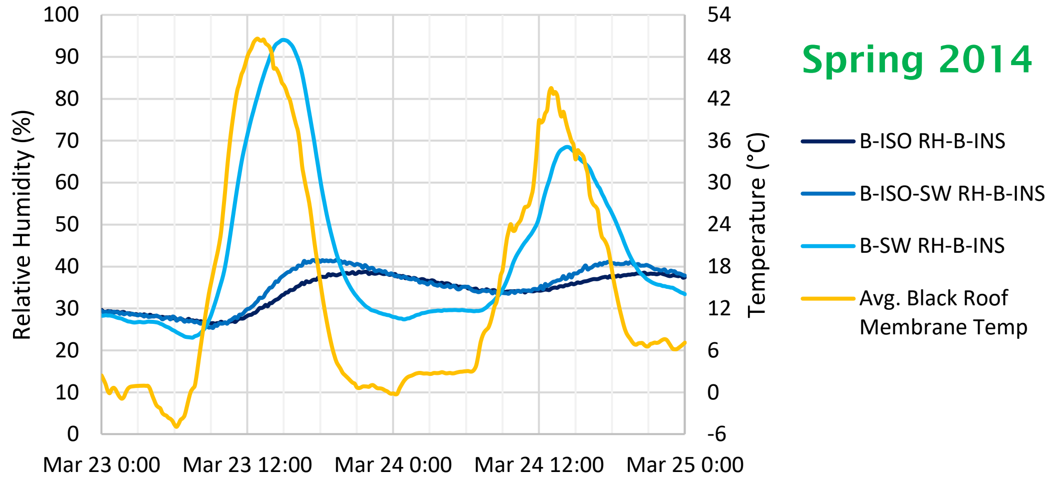

Figure 2.5.4 Relative humidity levels below insulation (sorted by insulation arrangement) and average black roof membrane temperature between March 23 and 25, 2014.

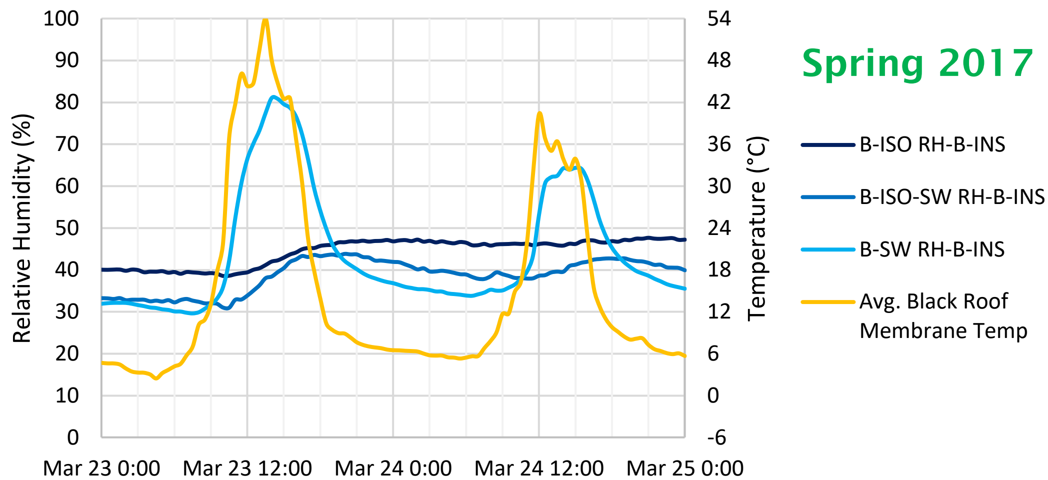

Figure 2.5.5 Relative humidity levels below insulation (sorted by insulation arrangement) and average black roof membrane temperature between March 23 and 25, 2017.

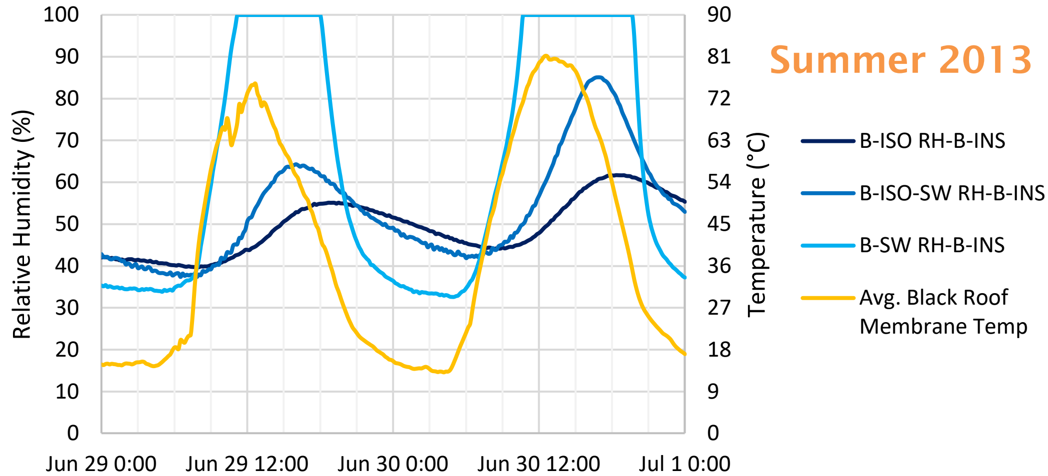

Figure 2.5.6 Relative humidity levels below insulation (sorted by insulation arrangement) and average black roof membrane temperature between June 29 to July 1, 2013.

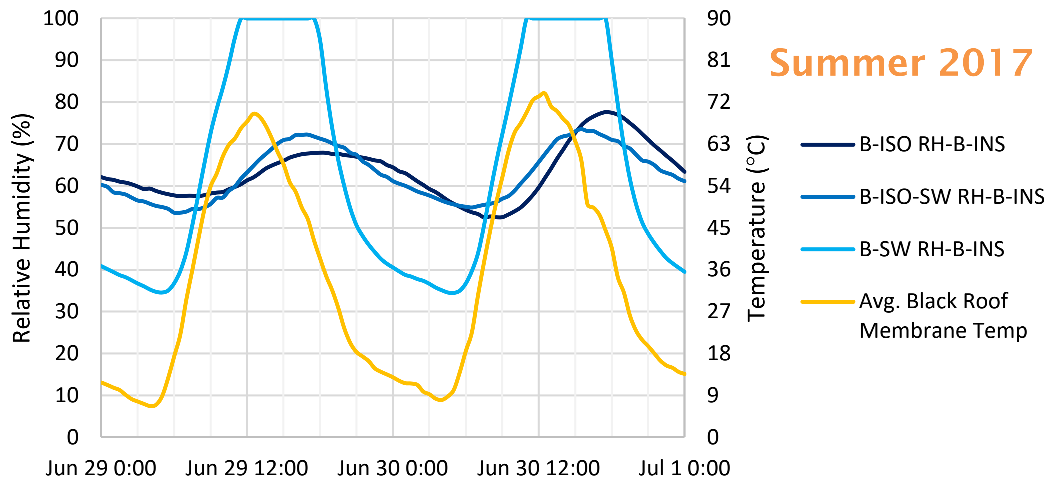

Figure 2.5.7 Relative humidity levels below insulation (sorted by insulation arrangement) and average black roof membrane temperature between June 29 to July 1, 2017.

2.6 Insulation Dimensional Stability

This section examines the displacement data obtained throughout the six-year monitoring period. Note that the analysis in this section, based on monitoring data, is an update to the plots and hypothesized trends provided in previous interim reports. The monitoring data is further analyzed and compared with our field observations and exploratory openings made in October 2019 in Section 3.4.

Previous investigations by RDH and others have found that short and long-term dimensional movement of roofing insulation, causing gaps in insulation boards to form and distortion or stresses in the roof membrane, can negatively affect the durability of conventional roof assemblies. To investigate relative dimensional stability and potential shrinkage of the insulation products used in this study, plunger-type displacement sensors were installed in the edges of the insulation boards with the plunger against an adjacent insulation board. The sensors were installed in all three insulation arrangements for white and black roofs in both the north-south and east-west directions as shown in Figure 2.6.1.

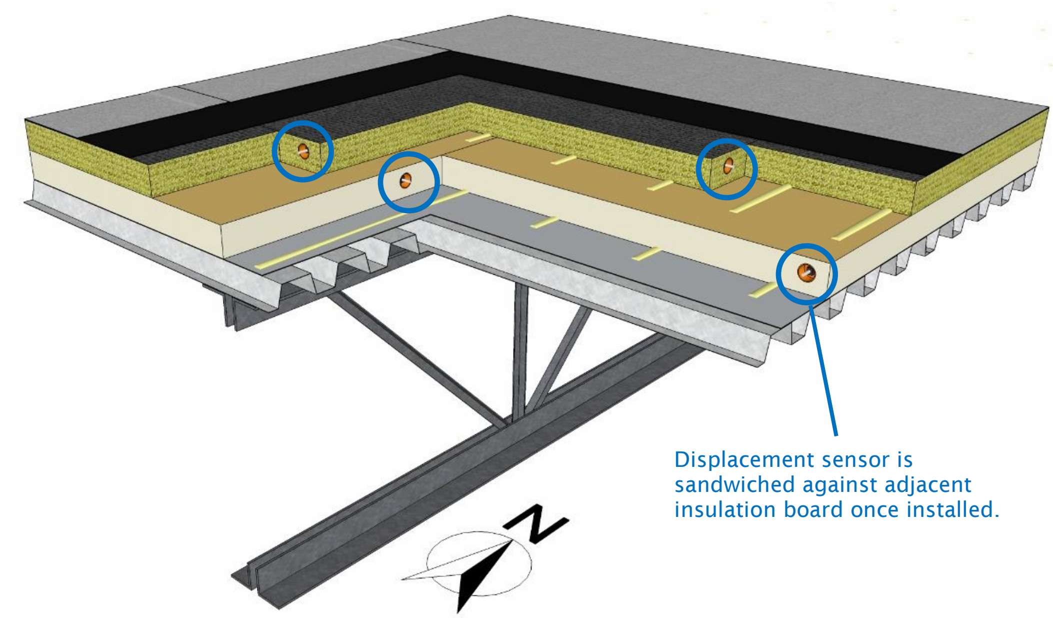

Figure 2.6.1 Typical roof assembly with locations of displacement senor indicated with blue circles (roof assembly with fully adhered hybrid insulation).

Previous laboratory investigation by RDH has indicated that temperature affects the physical dimension of material in the roof assembly differently. To provide some context to the movement that was observed in the roof assembly, Figure 2.6.2 plots the change in dimension for different types of materials commonly found in a conventional roof assembly when exposed to conditions between -20˚C and 90˚C. Materials including polyiso and stone wool insulations, composite reinforced SBS roof membranes (un-torched, new), and cover board.[12] It should be noted that the tested SBS roof membrane samples were un-torched whereas torch-applied membranes will likely undergo some of this dimensional change when being heated and installed during construction. Furthermore, the measurements of the dimensional movement of the SBS membrane were made using a plunger type gauge. Due to the relatively soft nature of the membrane, particularly at high temperatures, the plunger gauge in some cases would indent the membrane. As a result, the measured expansion of the membrane at high temperatures is likely understated.

As expected, stone wool insulation is relatively dimensionally stable within the tested temperature range, while polyiso experiences relatively more movement. Furthermore, the change in dimension for polyiso insulation is somewhat linear, with a noticeably accelerated changes in dimension both below 22˚C and above 70˚C.

Results also show that the dimensional stability of un-torched samples of SBS roof membrane in both the machine direction (MD) and the cross-machine directions (XMD) contracted at both extreme heat and extreme cold temperatures. Additionally, contraction in the MD appeared to be greater. This membrane contraction at elevated temperatures is likely due to a combination of the manufacturing process and its bitumen-based

[12] The data for the figure was obtained from several laboratory investigations performed by RDH. Other insulation types (i.e., EPS, XPS) and reinforcement types in SBS roof membrane (i.e., Fiberglass, Polyester) were also tested.

composition. For example, membrane reinforcement is typically stretched (i.e., pre-tensioned) in order to reduce any slack while being saturated in bitumen during the manufacturing process. This tension can either be released as the SBS roof membrane becomes softer at elevated temperatures during torch installation process or in service due to the viscoelastic nature of the bitumen-based membrane.

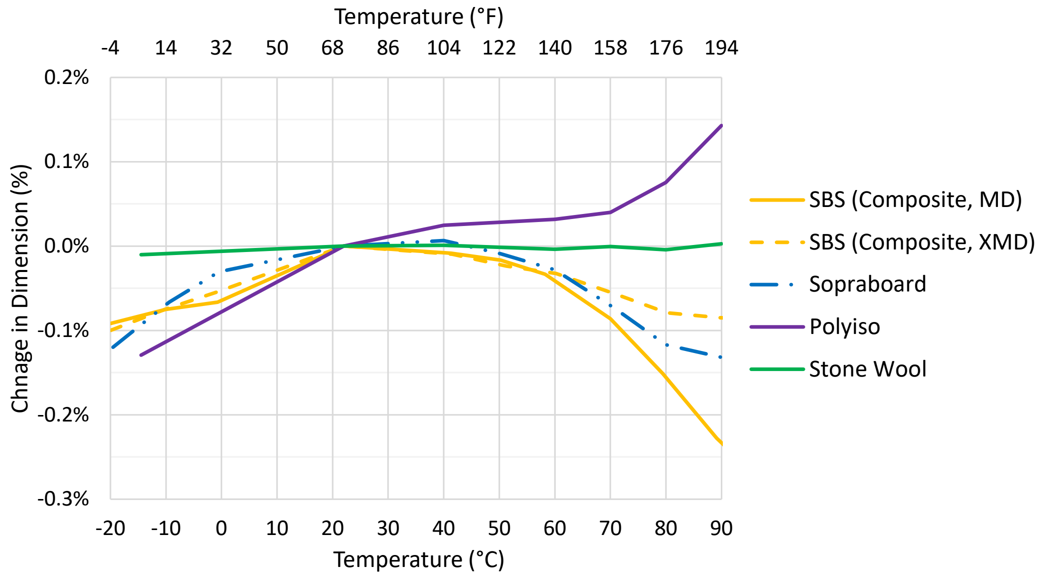

Figure 2.6.2 Dimensional change of common materials found in a conventional roof assembly.

Insulation specimens were 305 mm x 305 mm (12" x 12") where change in width and length were averaged.

SBS roof membrane specimens were un-torched (new), 51mm x 305mm (2" x 12") strips of membrane. Three specimens were tested in both machine direction (MD) and in cross-machine direction (XMD).

The data obtained from the displacement sensors were analyzed in the same manner as it has been in the previous interim reports[13] and comparisons were made between orientation (Figure D.1), membrane colours (Figure D.2 and Figure D.3), and insulation type and location (i.e., lower/upper; Figure D.4 and Figure D.5). Displacement is provided both in millimetres and as percent change in dimension. Negative displacement corresponds with an increase in gap between boards. Note that the percent change is intended for reference only and does not necessarily indicate actual change in the physical dimension of the insulation boards.

It is also important to note that the monitoring data does not indicate the direction of the movement since the sensors are not fixed to the structure. The displacement sensors are limited to measurements in gap size between the boards; therefore, changes in the gap size could be a result of either insulation expansion or contraction, shrinkage (i.e., permanent contraction), or movement of the insulation boards relative to each other. For example, movement of the insulation boards could be driven by thermal expansion and contraction of the SBS roof membrane or by movement of the structure (e.g., deflection of steel roof structure).

[13] See Appendix D for updated plots from the previous interim report, which includes additional data for the complete 6-year monitoring period.

As shown in Figure 2.6.3, when displacement data is averaged between orientation and membrane colour and comparisons are made between lower and upper layer by insulation arrangement, it becomes more evident that layers in the insulation arrangement experienced similar movement. This observation is true not only for SW-only and ISO-only assemblies but also for hybrid assemblies with different insulation types, which suggests that the correlation appears stronger between the location of the insulation layer (i.e., upper and lower) compared to the type of insulation.

Between the insulation arrangements, hybrid assemblies generally moved the most, followed by SW-only, then by ISO-only assemblies; however, the thermal stability of the insulation boards does not explain this observation. The difference in the movement may be due to other factors such as insulation boards being installed with small gaps, differences in compressive strength of insulation material, and/or effectiveness of the adhesive. Another key observation from the analysis is that the upper layers in these assemblies generally experienced greater movement overall compared to the lower layers.

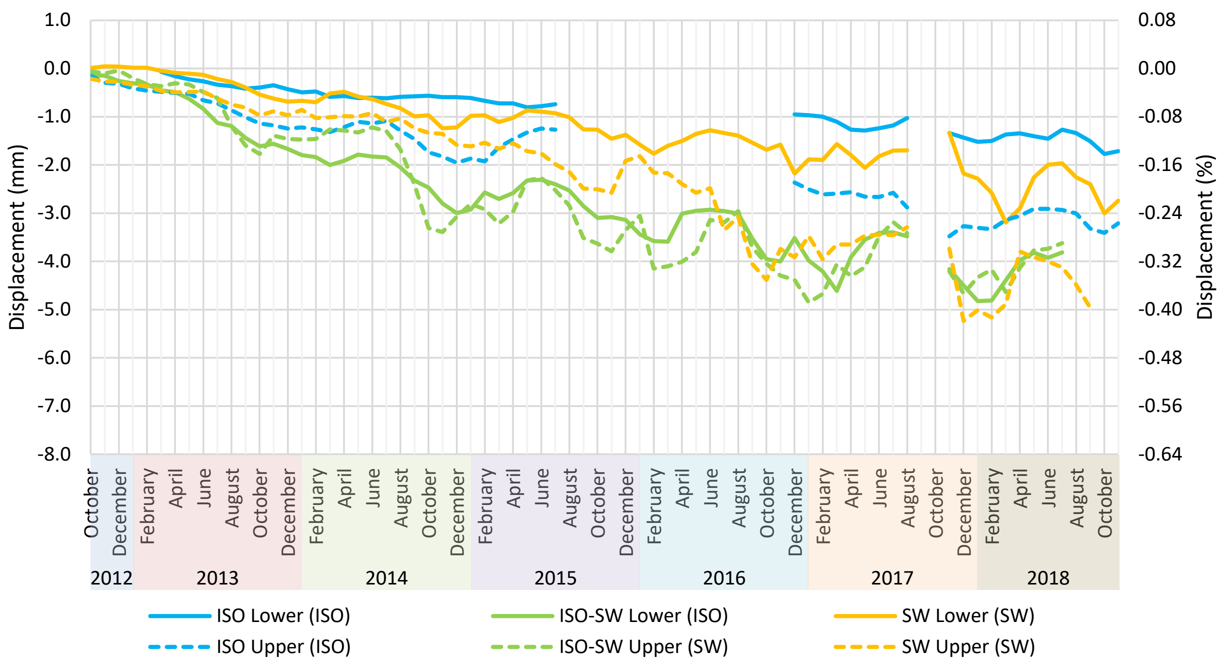

Figure 2.6.3 Monthly average displacement by insulation arrangements and by insulation layers averaged for both sensor directions and both membrane colours (parenthesis indicate insulation type).

A correlation was also identified between the amount of movement and the temperature of the roof assembly in Figure 2.6.4. The plot illustrates that an upper layer that experiences both larger temperature fluctuation and more extreme temperatures will experience more movement. The figure shows that during the first year and a half after construction (roof completed at the end of summer 2012), the gap between the insulation boards generally widens. However, around February 2014, movement within the roof begins to occur in the opposite direction (i.e., narrowing of gap). Note that the roofs appear to never return to their original location. Furthermore, the displacement appears to follow a seasonal trend, displaying greater movement during winter relative to summer.

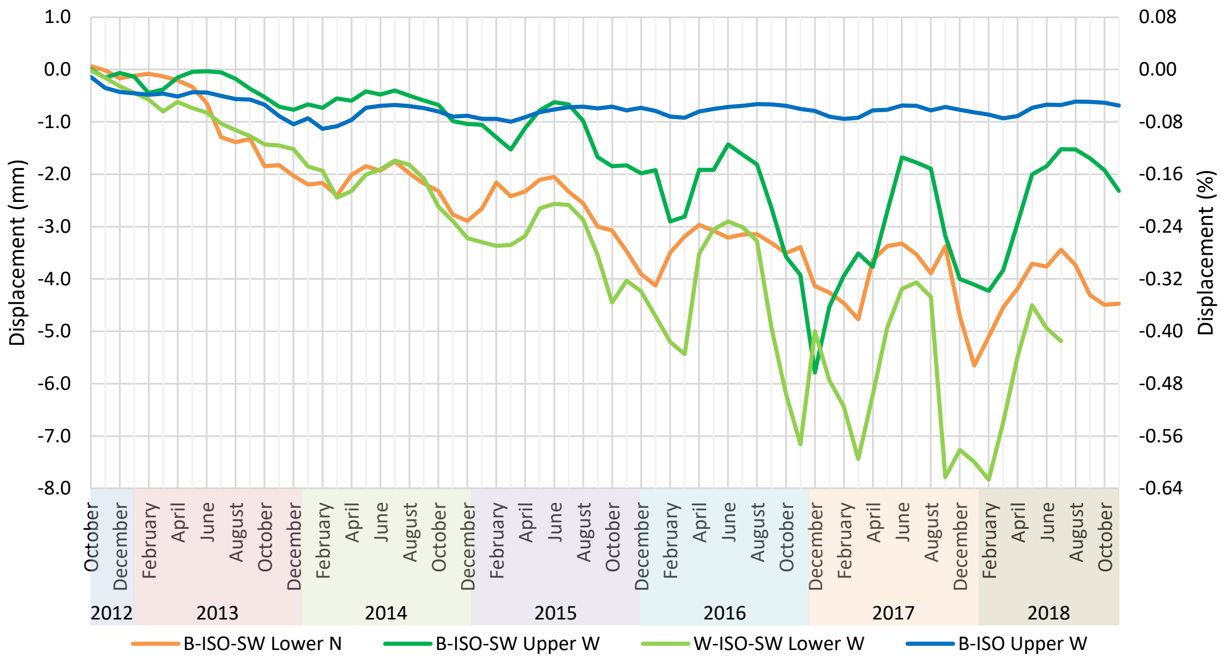

Figure 2.6.4 Monthly average displacement at four sensor locations

Note that four locations with complete data were selected where a single sensor was averaged on a monthly basis.

The data from Figure 2.6.4 was then averaged by season in Figure 2.6.5 to isolate periods during extreme temperatures. As a result, it becomes more evident that the gaps generally widen in the winter and narrow in the summer, and that movement is generally greatest in winter.

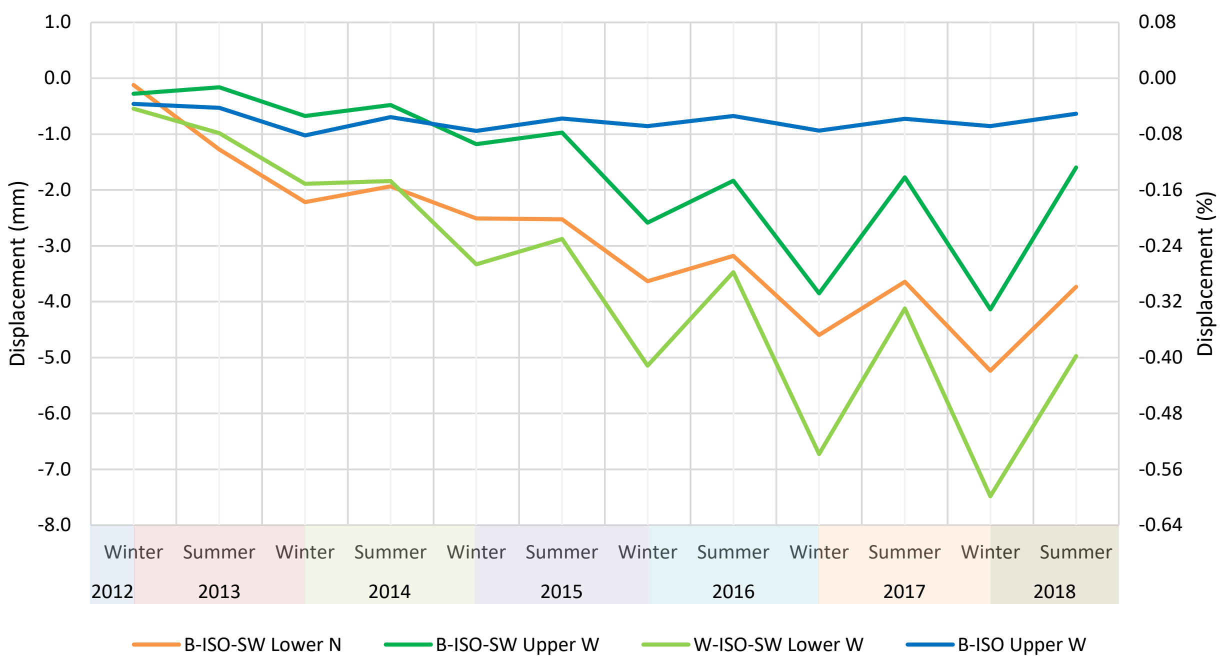

Figure 2.6.5 Seasonally averaged displacement data at four sensor locations

To understand daily change in the size of the gaps between insulation boards, the displacement data was reviewed on a shorter timescale. Figure 2.6.6 to Figure 2.6.9 show displacement data over a four-day period from June 24 to 28 in 2015 and 2017 when the roof experienced high summer heat exposure. Note that the figures plotting measurements in the east-west direction are taken from polyiso-only and stone wool-only roof assemblies with white membrane cap sheet.

The plots show that the movement in the upper insulation layer of the stone wool roof assembly is greater and appears to be increasing over time. Also, note that the movement of the stone wool tracks with the roof membrane temperature. For example, as the roof membrane temperature approaches the daily maximum, the gap between both layers of stone wool insulation board decreases. This observation is consistent with the seasonal movement discussed above. For polyiso, there is minor displacement in the upper layer and relatively insignificant change between 2015 and 2017. Results also show that the displacement in the lower layer of stone wool is slightly greater than polyiso. The movement in the lower insulation layer also tracks roof membrane temperature, similar to the upper layer.

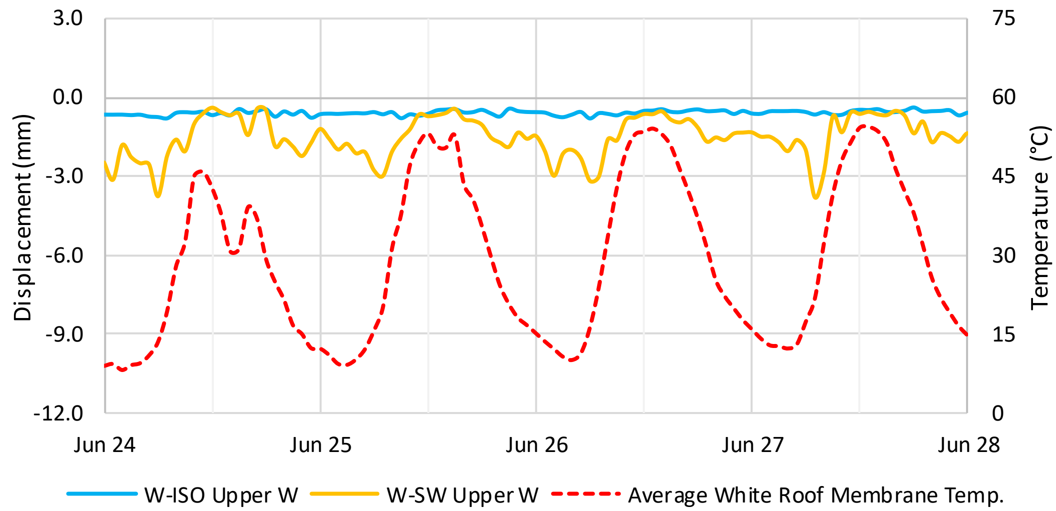

Figure 2.6.6 Daily displacement of upper polyiso and stone wool insulation in east-west direction and average white roof membrane temperature between June 24 to 28, 2015

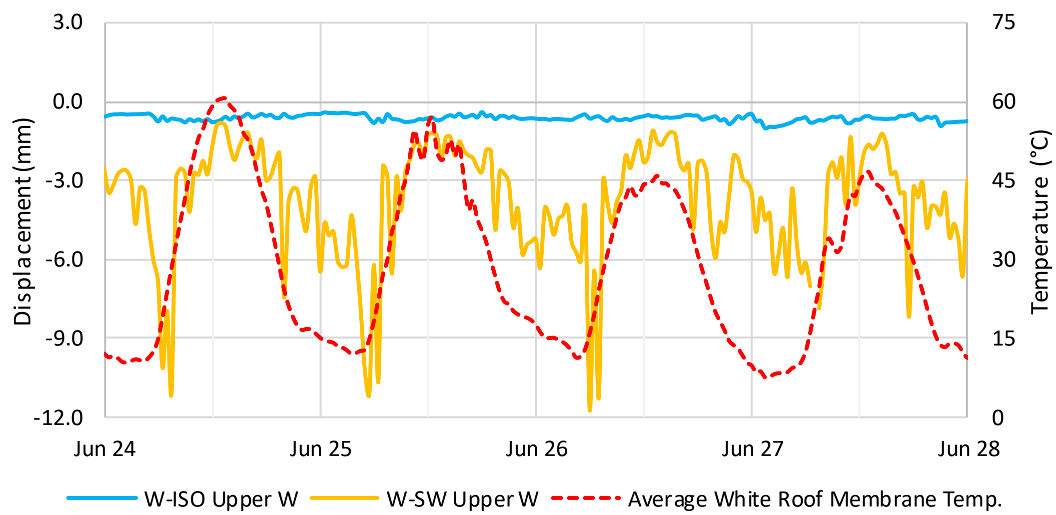

Figure 2.6.7 Daily displacement of upper polyiso and stone wool insulation in east-west direction and average white roof membrane temperature between June 24 to 28, 2017

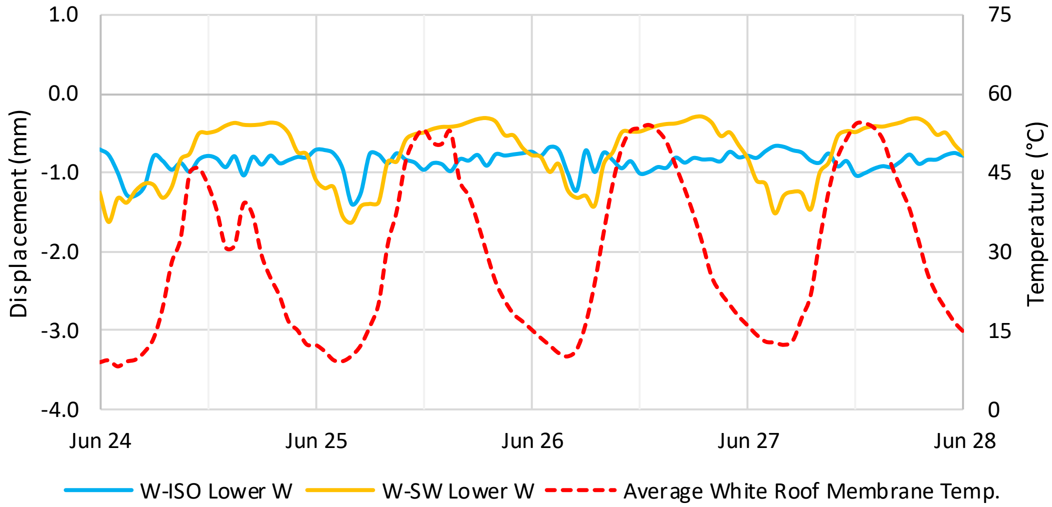

Figure 2.6.8 Daily displacement of lower polyiso and stone wool insulation in east-west direction and average white roof membrane temperature between June 24 to 28, 2015

Note that the scale has been reduced for these figures compared to Figure 2.6.6 and Figure 2.6.7.

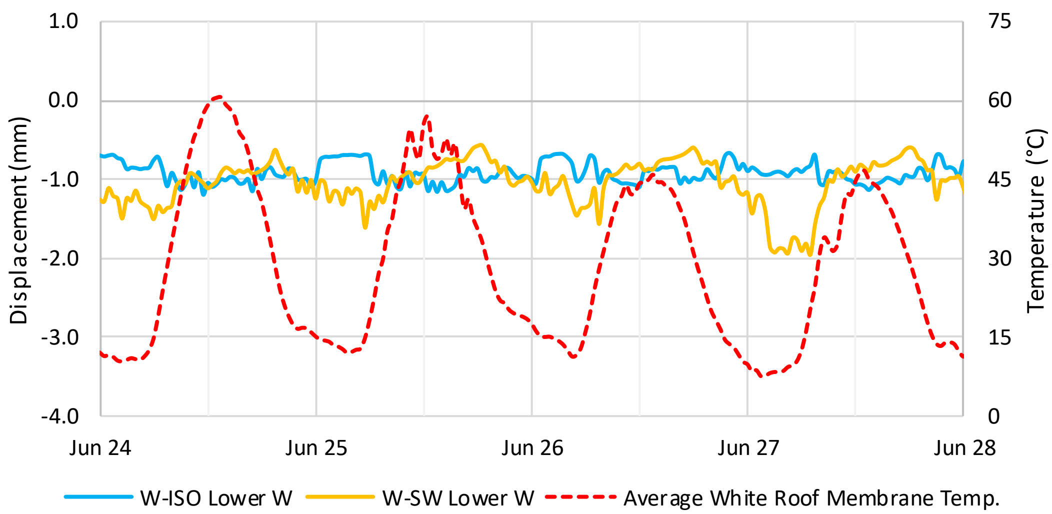

Figure 2.6.9 Daily displacement of lower polyiso and stone wool insulation in east-west direction and average white roof membrane temperature between June 24 to 28, 2017

Note that the scale has been reduced for these figures compared to Figure 2.6.6 and Figure 2.6.7.

In all, the insulation dimensional stability analysis based on monitoring data suggests that there is a correlation between the roof temperature and the movement within the assembly. While both the upper and the lower insulation layers appear to be influenced by roof membrane temperature, the upper insulation layer typically experienced more displacement. The seasonal analysis suggests that widening of gaps in cold weather exceeds shrinking of gaps in warm weather, leading to a net year-over-year increase in the gap widths. This cyclical movement, correlating to roof membrane temperature was also observed daily between day and night.

This movement occurs with all insulation types, including the stone wool insulation (which is quite dimensionally stable), suggesting that the movement may be largely attributable to the membrane, rather than the insulation products. When comparing insulation arrangements, hybrid assemblies generally experienced the most movement, followed by SW-only, then by ISO-only assemblies; however, thermal stability of insulation material does not explain this observation.

3 Site Visit & Exploratory Investigation

In October 2019, RDH conducted a final site visit at Soprema's manufacturing plant in Chilliwack as an update to the previous 2017 exploratory openings. The purpose of the site visit was to take samples of aged roof membrane and insulation, confirm the moisture content and insulation gap widths within the assembly, and review the roof for thermal anomalies using an infrared thermographic scanner. Figure 2.6.1 is a satellite image of Soprema Chilliwack plant and schematic roof plan indicating where sensors, cut openings and other relevant items (e.g., RTU, roof edge, slope, etc.) are located.

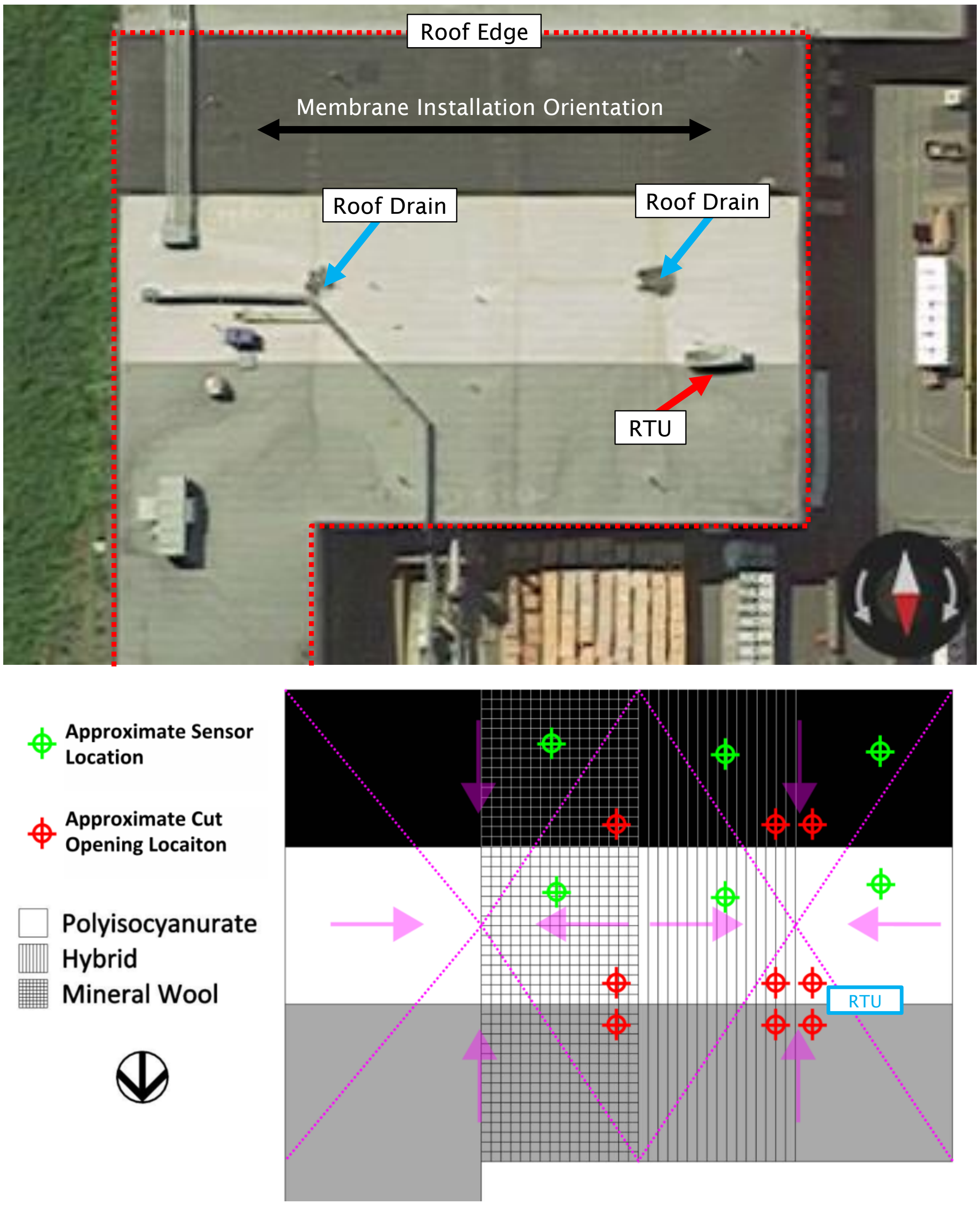

Figure 2.6.1 Google satellite image of Soprema Chilliwack plant roof (top) and schematic roof plan indicating sensor and cut opening location (bottom). Roof slope is indicated in purple dotted line and arrows.

3.1 Infrared Thermographic Scanning

An infrared thermographic scan was completed for the surface of the test roofs. This scan was completed prior to sunrise to avoid the impacts of solar radiation on the surface temperature of the roof. During this scan, no thermal anomalies were noted within the field of the test roof assemblies, indicating continuous insulation with minimal thermal bridging at board joints.

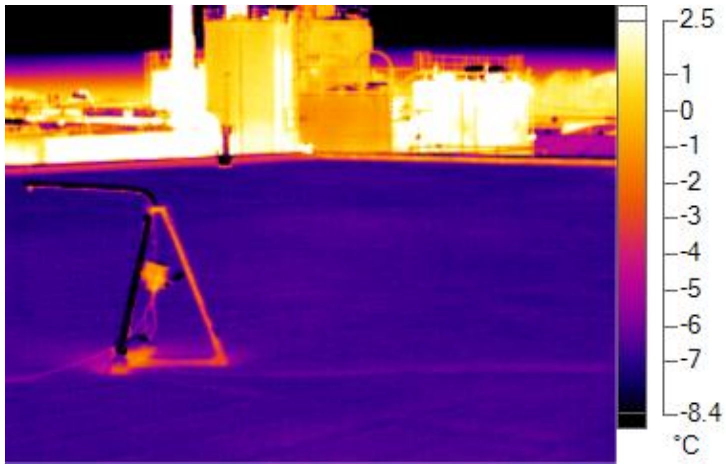

Figure 3.1.1 Thermal image of roof with no evident thermal anomalies.
This image was taken from G-SW/W-SW roof area, facing south-west corner of the roof.

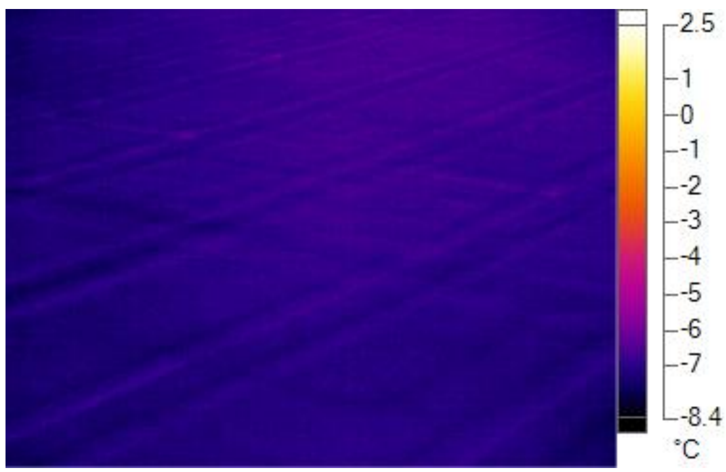

Figure 3.1.2 Thermal image of with no evident thermal anomalies.
This image was taken roughly in the centre of the roof (W-ISO-SW).

3.2 Exploratory Openings and Sampling

Following the thermographic scan, a general walkthrough of the monitored roof area was performed to identify nine approximately 30" x 30" exploratory opening locations. These opening locations were intentionally selected away from the middle of the insulation arrangements to avoid contact with the monitoring equipment.

As shown in Figure 3.2.1, no wrinkles or ridging of the SBS roof membrane were observed. Similar to observation from our past visit, dirt and debris has accumulated around the roof drains as show in Figure 3.2.2.

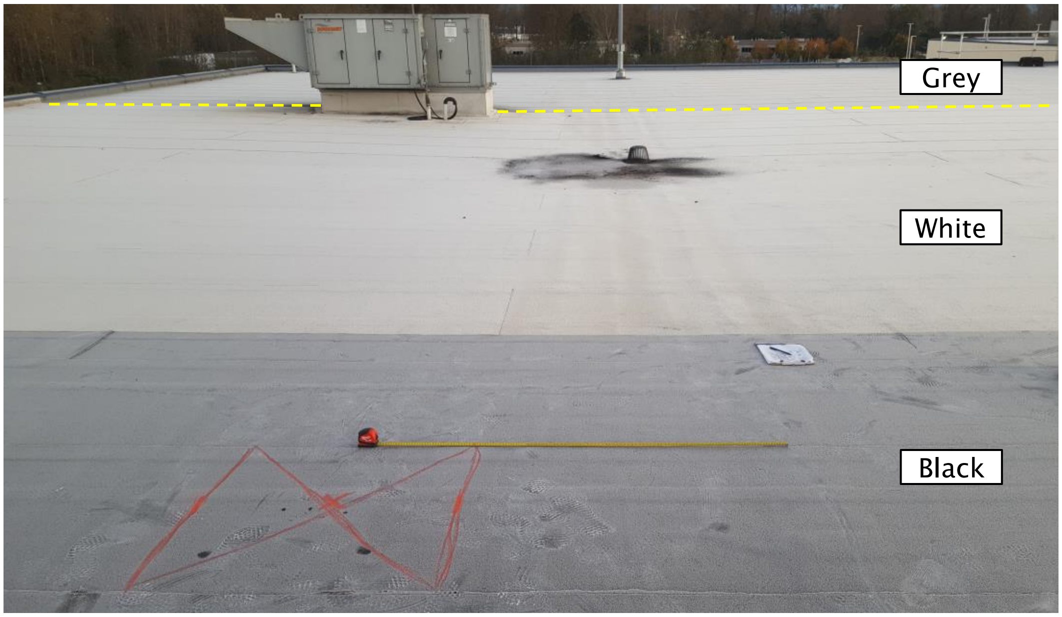

Figure 3.2.1 Photo taken from a roof area with black SBS roof membrane (frost covered) and polyiso (B-ISO), facing North toward west roof drain.

Note the roof top unit at the boarder of white and grey SBS roof membrane (yellow dash line) and soiled white membrane around the roof drain.

Figure 3.2.2 Close-up of west roof drain

After the removal of SBS cap and base sheet membrane (and coverboard used in polyiso-only assembly), insulation board joints were identified in the top layer and gap widths were measured using a tapered gap feeler gauge (see Figure 3.2.3).

Figure 3.2.3 Overview of an exploratory opening after SBS cap and base sheet have been removed (top, B-DD shown). Close-up of measurements being taken at the red dotted circle is provided at bottom, on the left and close-up at the white dotted circle on the right.

Note that asphalt impregnated surface of stone wool often delaminated from the insulation board as the base sheet was torched on to it.

Once the gaps in the top insulation layers were recorded, the top layer was removed to expose the bottom insulation layer. Given that the board layers are staggered, board joints in the lower layer were not always visible. Where accessible, the bottom insulation layer gaps (if any) were recorded. The obtained field displacement measurements are summarized in Section 3.3.

During the exploratory investigation, relative moisture content of insulation board was measured using a Delmhorst DB-10 moisture meter, as well as insulation core temperatures using a digital thermocouple with 5" probe as shown in Figure 3.2.4. These measurements were taken as soon as the sides of the insulation boards became accessible.

Figure 3.2.4 Relative moisture content of bottom insulation layer (polyiso) in B-ISO-DD assembly being measured using a Delmhorst DB-10 moisture meter (left) and core temperature of top insulation layer (polyiso) in B-ISO assembly being measured using a digital thermocouple with 5" probe (right).

Insulation board samples roughly 13" x 13" were then removed (top and bottom layers) from each assembly. As the insulation samples were being collected, the thickness of the insulation board was measured using a digital caliper (Figure 3.2.5). The obtained thickness measurements are provided in Table 3.1 along with relative moisture content and temperature measurements. Note that the insulation thicknesses measurements reported in the table are an average of four measurements taken for each insulation sample. Also, for stone wool insulation, an effort was made to measure thickness where asphalt surface treatment was undamaged.

Figure 3.2.5 Four thickness measurements were taken for each 13" x 13" insulation board sample using a digital caliper (polyiso sample from G-ISO shown).

Note that for stone wool insulation thickness, an effort was made to measure thickness where asphalt surface treatment was undamaged.

TABLE 3.1 INSULATION SAMPLE SUMMARY					
Roof Arrangement	Insulation Layer	Insulation Thickness [mm, (inch)]	Insulation Temperature [°C]	Ambient Temperature [°C]	Insulation Moisture
B-SW	Top	78 (3.1)	4.0	3.5	DRY
	Bottom	63 (2.5)	-	3.5	DRY
B-ISO-SW	Top	59 (2.3)	6.1	2.7	DRY
	Bottom	49 (1.9)	3.8	2.7	DRY
B-ISO	Top	38 (1.5)	3.4	2.5	DRY
	Bottom	48 (1.9)	-	2.5	DRY
W-SW	Top	81 (3.2)	5.0	4.6	DRY
	Bottom	62 (2.5)	8.2	7.8	DRY
W-ISO-SW	Top	58 (2.3)	7.2	10.2	DRY
	Bottom	51 (2.0)	8.8	10.2	DRY
W-ISO	Top	37 (1.5)	11.9	8.3	DRY
	Bottom	49 (1.9)	13.3	8.9	DRY
G-SW	Top	79 (3.1)	7.1	6.7	DRY
	Bottom	64 (2.5)	8.7	7.3	DRY
G-ISO-SW	Top	60 (2.4)	11.0	9.5	DRY
	Bottom	48 (1.9)	12.3	9.5	DRY
G-ISO	Top	37 (1.4)	14.9	11.2	DRY
	Bottom	49 (1.9)	16.6	11.6	DRY

The measured thickness of each top and bottom insulation layer, combined for each roof arrangement was compared with its manufacturer rated nominal thickness in Table 3.2. Interestingly, greater reductions in the thickness of the insulation layers were consistently experienced in the hybrid assembly, while no correlation with the membrane colour was observed. Based on the preliminary measurements, shrinkage of the insulation may have occurred through either compacting or off-gassing.

TABLE 3.2 COMBINED INSULATION THICKNESS (FIELD MEASURED VS. NOMINAL)			
Roof Arrangement	Combined Measured Insulation Thickness [mm, (inch)]	Combined Nominal Insulation Thickness [mm, (inch)]	% Measured vs. Nominal
B-SW	141 (5.56)	146 (5.75)	97%
W-SW	143 (5.63)		98%
G-SW	143 (5.63)		98%
B-ISO-SW	108 (4.25)	114 (4.50)	94%
W-ISO-SW	109 (4.29)		95%
G-ISO-SW	108 (4.25)		95%
B-ISO	85 (3.35)	89 (3.50)	96%
W-ISO	86 (3.40)		97%
G-ISO	86 (3.38)		97%

SBS roof membrane samples were also collected on site and later sent to Soprema's laboratory to test the physical properties of the field aged membranes. Collected insulation samples were tested in RDH's laboratory to measure the thermal performance of the aged insulation. The laboratory testing results of the aged SBS roof membrane and insulation samples are presented in Section 4.

3.3 Field Displacement Measurements

The intention of measuring insulation board gaps in the field was to identify the insulation board joint width in East-West and North-South orientation for both top and bottom insulation layer. However, as the insulation board joints did not always align with the opening (i.e., 30" x 30" opening centred in a 48" x 48" insulation board), only five of the nine exploratory openings revealed both a top and bottom layer joint.

With respect to insulation board gaps, a correlation was observed between both the slope of the roof and the roof membrane installation orientation (i.e., machine direction). Since the roof membrane was installed in east-west direction, it was relatively simpler to determine if the gaps were parallel or perpendicular to the machine direction. However, determining the insulation board gaps relative to roof slope is more complex, given the location of the exploratory openings relative to the roof drains (i.e., low points). Therefore, as a convention, the gap measurements parallel to the slope are presented throughout this section in red or indicated with red arrows, whereas gap measurements considered perpendicular to the slope are presented in green or indicated with green arrows.

An example of the gap orientation convention is provided in Figure 3.3.1, where gaps indicated with red arrows represent movement parallel to the roof slope and gaps indicated with green arrows represents movement perpendicular to the slope. Note that in this example, the gap indicated with red arrows has also occurred in membrane direction (as defined by the black arrow).

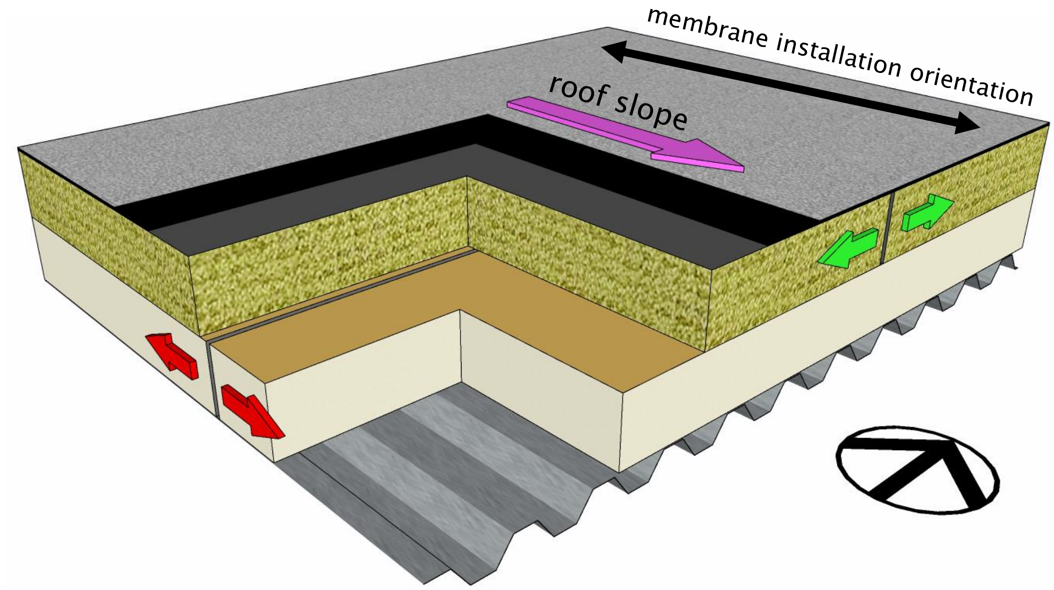

Figure 3.3.1 Example of gap orientation convention relative to roof slope, and membrane installation orientation.

Physical measurements of the gap width between the insulation boards taken from each insulation layer (where accessible) for each roof assembly are summarized in Table 3.3, and are also indicated on a roof plan in Figure 3.3.2 to better illustrate the observations in the context of the roof layout including roof elements that may have impacted the movement of the roof assemblies. Based on the analysis, the following was observed:

- → Shorter arrows near HVAC roof top unit (RTU), indicating relatively small amounts of movement occurred near these areas of fixation,
- → Arrows are typically longer in the east-west direction, indicating wider gaps parallel to the SBS roof membrane installation direction (i.e., gap running perpendicular to membrane installation direction was typically wider), and
- → Red arrows are typically longer, indicating wider gaps were measured parallel to the roof slope.

TABLE 3.3 FIELD INSULATION JOINT GAP MEASUREMENT				
Roof Arrangement	Insulation Layer	Gap Orientation	Measured Gap (mm)	Orientation Relative to Slope
B-SW	Top	EW	3.9	Parallel
		NS	2.5	Perpendicular
	Bottom	N/A		
B-ISO-SW	Top	EW	3.5	Perpendicular
		NS	0.0	Parallel
	Bottom	NS	3.9	Parallel
B-ISO	Top	EW	6.6	Perpendicular
		NS	0.0	Parallel
	Bottom	N/A		
W-SW	Top	NS	1.6	Perpendicular
	Bottom	EW	5.4	Parallel
W-ISO-SW	Top	N/A		
	Bottom	EW	1.1	Perpendicular
W-ISO	Top	N/A		
	Bottom	NS	0.4	Parallel
G-SW	Top	NS	0.0	Perpendicular
		EW	8.5	Parallel
		EW	2.9	Parallel
	Bottom	NS	0.0	Perpendicular
		EW	4.4	Parallel
G-ISO-SW	Top	NS	0.0	Parallel
	Bottom	NS	0.0	Parallel
		EW	1.5	Perpendicular
G-ISO	Top	NS	0.0	Parallel
	Bottom	N/A		

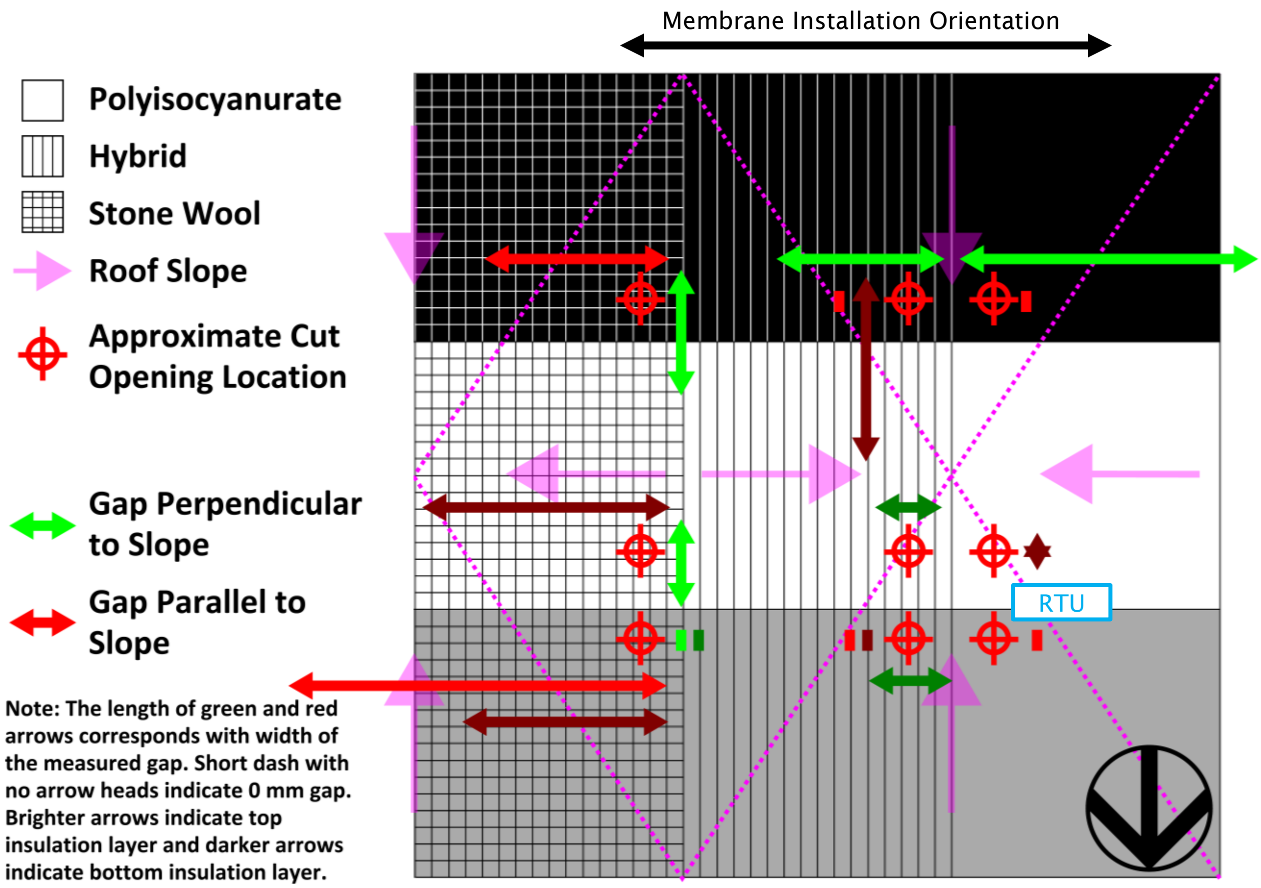

Figure 3.3.2 Field gap measurements provided in a schematic roof drawing (top) and a satellite image of the roof is provided to add visual context (bottom).

3.4 Review of Monitoring Displacement Data

In Section 2.6, the monitoring data analysis of insulation movement within the roof assemblies indicated a strong correlation between roof temperature and movement within the assembly. Generally, the top insulation layers that experiences larger temperature fluctuation and more extreme temperatures experienced more movement. However, this movement occurs with all insulation types, including stone wool insulation, which is relatively dimensionally stable. Results suggest then that movement may be largely attributable to the membrane rather than the insulation. Generally, scatter in the monitoring data made drawing this conclusions difficult, though in light of the findings and correlations observed during exploratory investigation and field displacement measurements (Section 3.3), the monitoring data was reviewed and reanalyzed to investigate whether additional parameters and considerations could help identify better correlations to help further explain the movement observed within the roof assemblies.

A graphical analysis, similar to field gap measurement approach in Section 3.3, was performed using collected monitoring data to investigate impact of following parameters:

- Fixed element on the roof (roof edges, HVAC roof top unit or RTU)
- SBS roof membrane direction (installed east-west)
- Roof slope

As shown in Figure 3.4.1, the displacement data from sensors installed near the RTU and the roof edge in the white polyiso roof (W-ISO, bottom right) shows noticeably small arrows, indicating small movement. These results are consistent with gap measurements taken during exploratory investigation near this sensor location. Considering that the insulation movement is likely influenced by SBS roof membrane movement, the RTU and the roof edge near the sensor location likely provided a fixed location and limited movement in the SBS roof membrane layer. This would also explain limited movement observed within the insulation layers.

During the field investigation, wider gaps were measured parallel to the SBS roof membrane installation direction, in the east-west orientation; however, as the monitoring data consistently showed poor correlation between the amount of movement and orientation, the longer arrows in the figures are distributed between east-west and north-south direction. This may be due to observed thermal expansion and contraction of the material discussed further in Section 2.6. While SBS roof membrane in machine and cross-machine direction contracts at different rates during exposure to extreme high temperatures, the difference is likely marginal. Furthermore, when the assembly typically experiences more movement in the winter, composite reinforced SBS roof membrane was shown to contract at a similar rate in both machine and cross-machine direction.

Roof slope was also analyzed where, similar to field gap measurement, longer red arrows were observed compared to green, which indicate that the gaps typically develop parallel to the slope and at greater magnitudes.

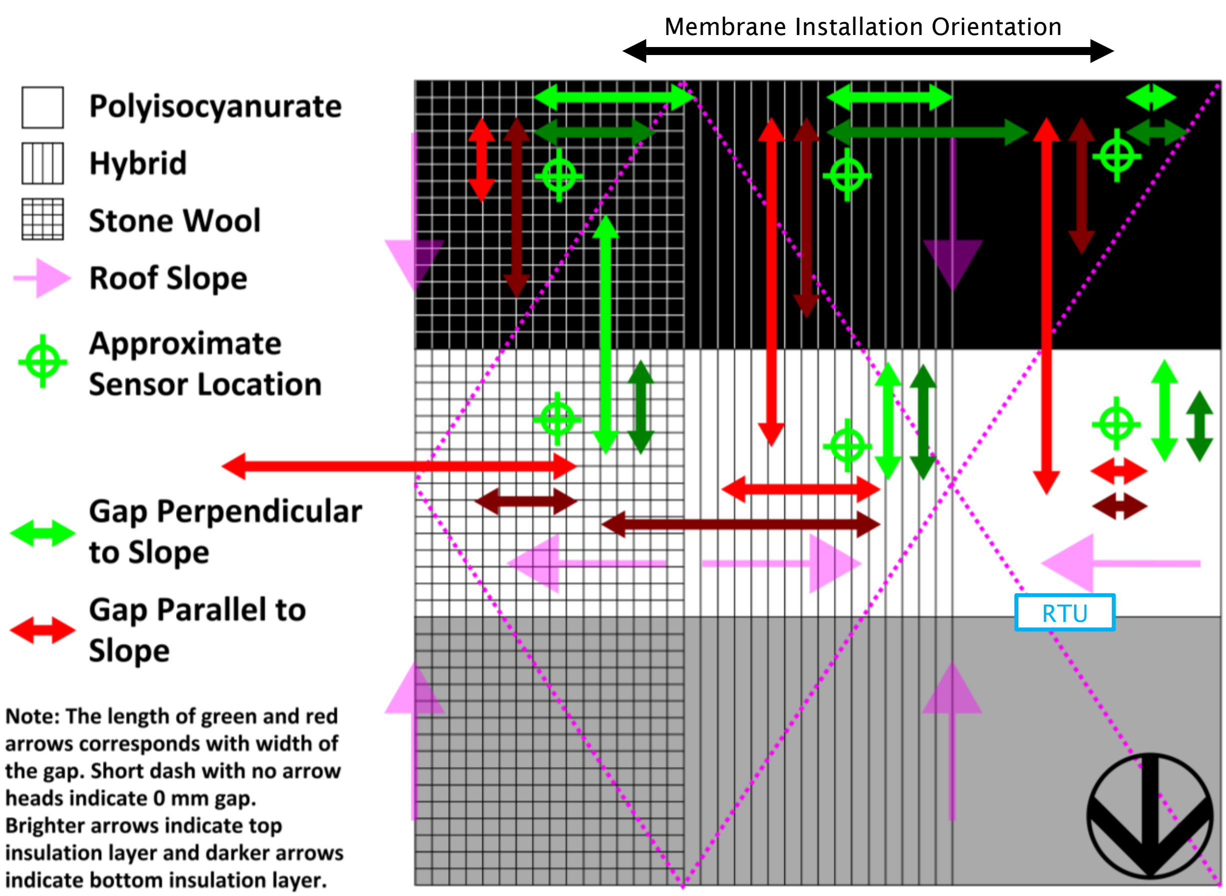

Figure 3.4.1 A Graphical analysis of displacement monitoring data (2018 yearly average used).

To illustrate the theory that more movement is experienced within the roof assembly away from SBS roof membrane securement or anchor points, displacement data obtained from the upper insulation layer along the centre line of the roof in the white SBS roof assemblies are provided in Figure 3.4.2. This plot compares movement nearest (W-ISO), mid (W-ISO-SW), and farthest (W-SW) from the roof edge and RTU. The data shows movement in the upper insulation layer is greatest where the SBS roof membrane is farthest from the parapet and RTU (i.e., farthest from membrane securement and anchor points). Displacement is provided both in millimetres (mm) and in % change in dimension of the 48" x 48" boards. Negative displacement corresponds with an increase in the gap between the boards.

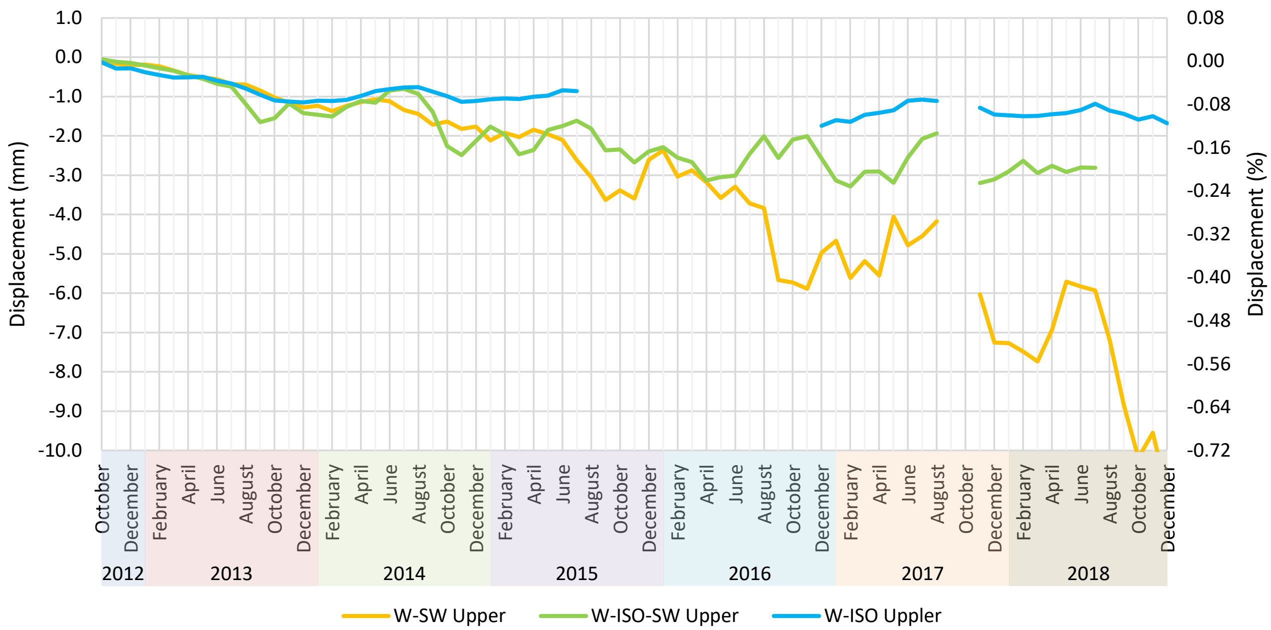

Figure 3.4.2 Displacement data obtained from the upper insulation layer along the centre line of the roof in the white SBS roof assemblies. This plot compares movement nearest (W-ISO), mid (W-ISO-SW), and farthest (W-SW) from the roof edge and RTU. The data provided is a monthly average of upper insulation layer for each respective roof arrangement.

Both the field investigation and graphical analysis of the monitoring data indicated a correlation between the amount of movement and the orientation of the gap relative to the roof slope. In order to analyze the relationship using the displacement data obtained during the monitoring period, the data that appeared to be outliers were first excluded from the analysis before the monitoring data was averaged by orientation (relative to the roof slope).

The roof schematic drawing provided in Figure 3.4.3 is the same drawing provided in Figure 3.4.1, yet includes data that was excluded from the analysis (grey arrows). The monitoring data excluded from this analysis includes:

- → Black, Stone Wool, Top layer North-South (B-SW Upper N)
- → White, Stone Wool, Top layer, North-South (W-SW Upper N)
- → White, Stone Wool, Bottom layer, East-West (W-SW Lower W)
- → White, Polyiso, Top layer, East-West (W-ISO Upper W)
- → White, Polyiso, Bottom layer, East-West (W-ISO Lower W)

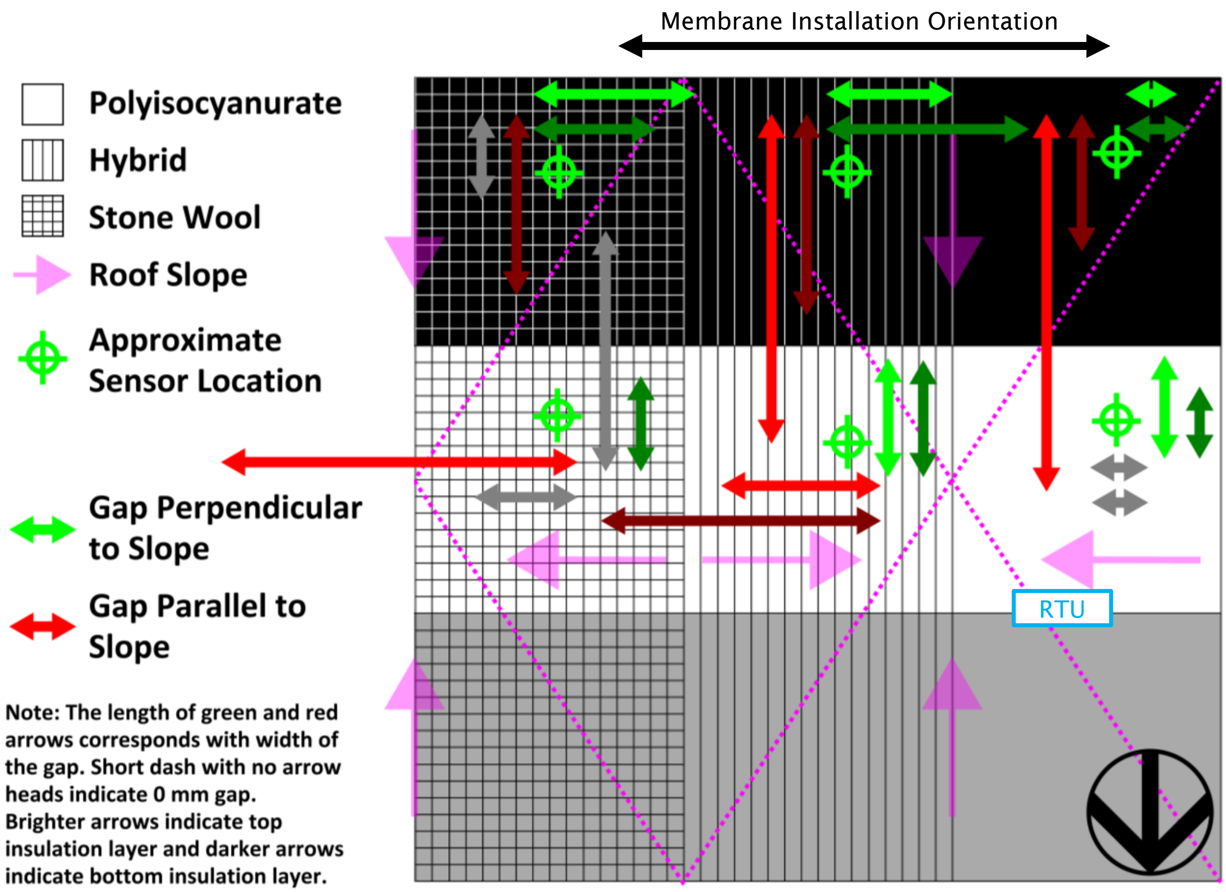

Figure 3.4.3 The same schematic roof drawing with displacement monitoring data provided in Figure 3.4.1.

Grey arrows indicate the data excluded from the subsequent analysis and they are displacement data from B-SW Upper N, W-SW Upper N, W-SW Lower W, W-ISO Upper W, W-ISO Lower W.

Since the roof slopes towards two roof drains along the centre line of the roof area, the gaps with the same compass orientation do not necessarily have the same orientation relative to the roof slope. In other words, because the gap orientation relative to the slope depends on their position relative to the roof drain, the gap measurements were provided in red or green in the graphical analysis to convey gap orientation clearly, and monitoring data was averaged following this convention.

Figure 3.4.4 provides all the displacement monitoring data averaged monthly based on gaps parallel to and gaps perpendicular to the roof slope (excluding the five cases previously mentioned). In all, the plots reinforce our field observation that a gap in the insulation is more likely to develop parallel to the roof slope.

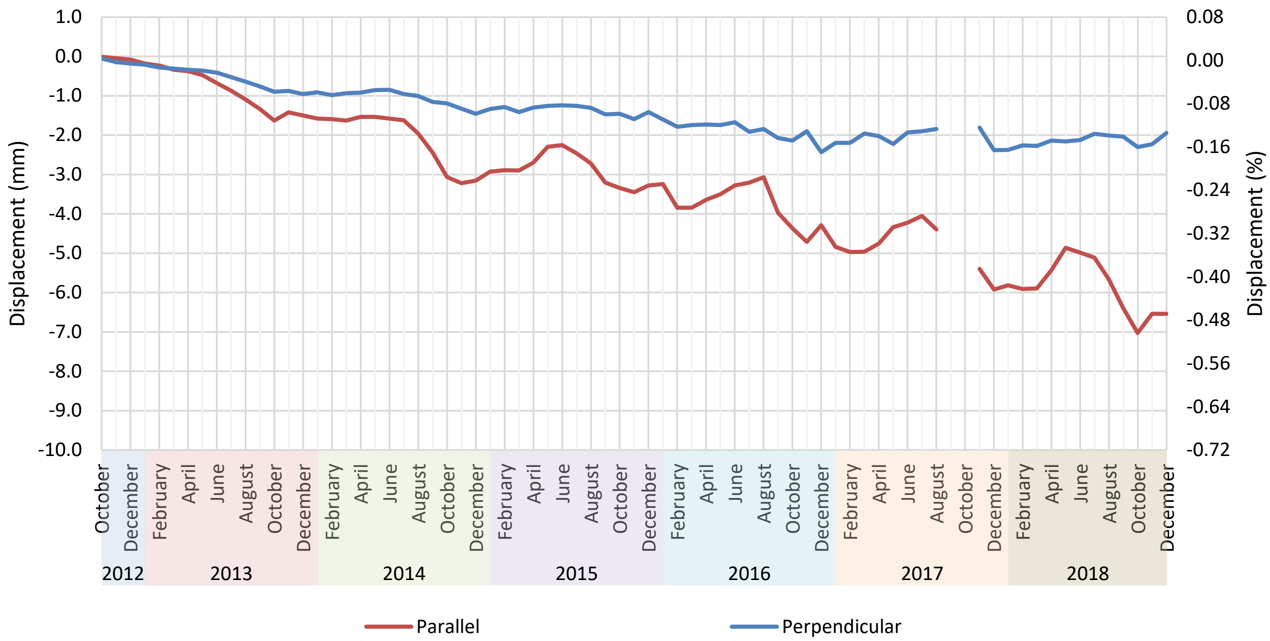

Figure 3.4.4 Monthly average displacement data averaged for measurement parallel to and perpendicular to the roof slope.

Note that the averaging excludes data from B-SW Upper N, W-SW Upper N, W-SW Lower W, W-ISO Upper W, W-ISO Lower W.

While no strong correlation was observed in the previous monitoring data analysis between the amount of movement and insulation types, the monitoring data was reanalyzed based on the roof slope orientation and reviewed. The data used to create Figure 3.4.4 was filtered by insulation types and provided in Figure 3.4.5 to see if any correlation can be observed. As a result, the figure illustrates and reinforces our previous analysis of the monitoring data, that the insulation type seems to have little impact on the movement in the insulation layer.

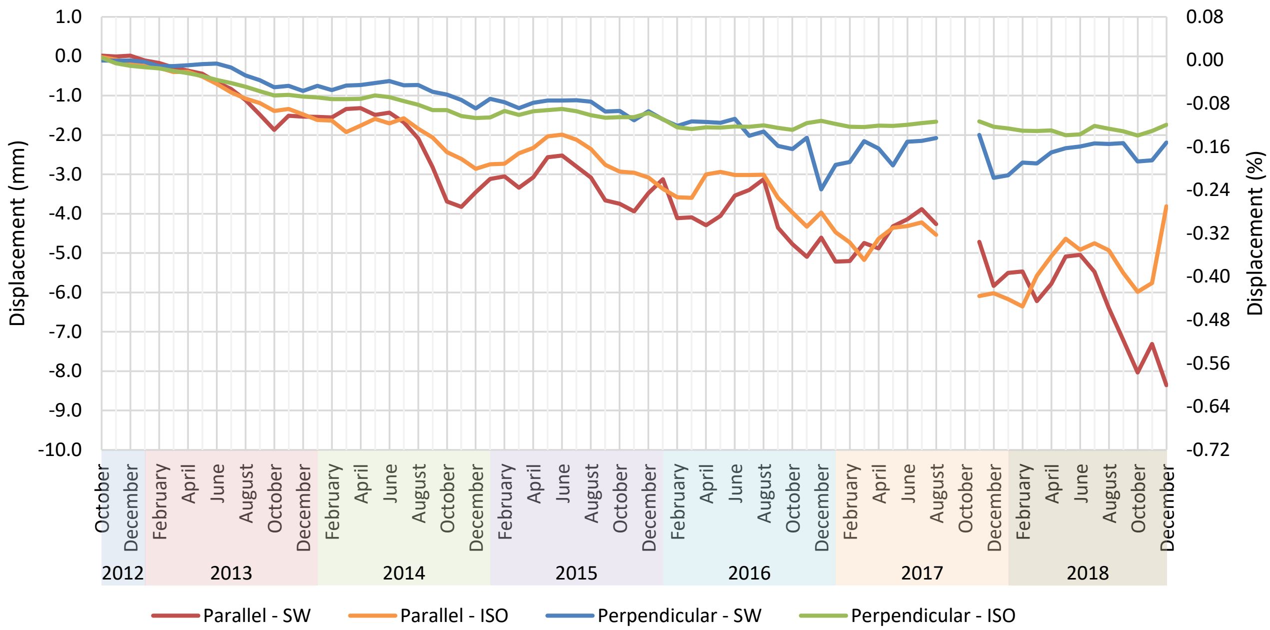

Figure 3.4.5 Monthly average displacement data averaged for measurement parallel to and perpendicular to the roof slope and <u>by insulation type</u>.

Note that the averaging excludes data from B-SW Upper N, W-SW Upper N, W-SW Lower W, W-ISO Upper W, W-ISO Lower W.

As previously reported, the amount of scatter presented in the data (especially in the upper layer) made drawing a strong conclusion about upper insulation movement difficult. However, the previous analysis did not account for the roof slope. Therefore, similar to Figure 3.4.5, the displacement monitoring data was averaged monthly by gaps both parallel and perpendicular to the roof slope, but in this case sorted by insulation layer location (i.e., upper or lower). Figure 3.4.6 illustrates that, while the impact of the gap orientation relative to the roof slope is more pronounced, the upper layers do appear to experience greater movement when parallel to the slope. Note that slope-averaged data was also averaged by membrane colour and membrane direction rather than by insulation type or insulation layer; however, the changes in trends were negligible. In all, second to roof slope, the relationship appears to be strongest between insulation layer and displacement measurements.

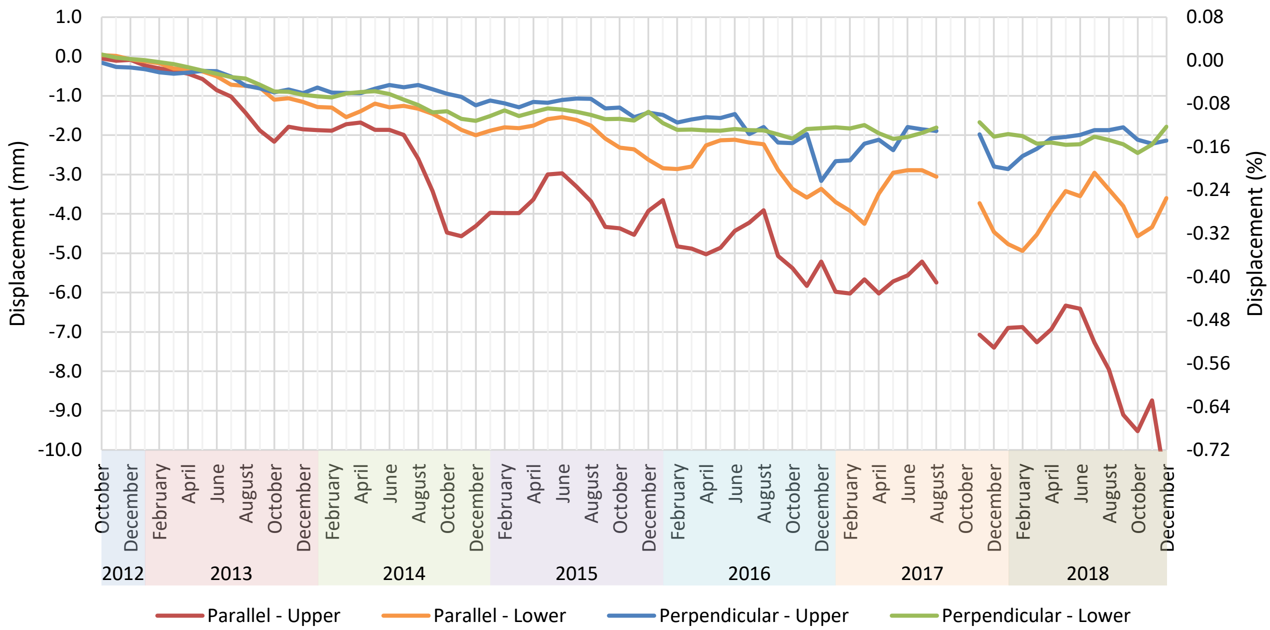

Figure 3.4.6 Monthly average displacement data averaged for measurement parallel to and perpendicular to the roof slope and by insulation layer.

Note that the averaging excludes data from B-SW Upper N, W-SW Upper N, W-SW Lower W, W-ISO Upper W, W-ISO Lower W.

In all, the field measurements indicated that minimal gaps were typically observed at the exploratory opening near the RTU while wider gaps were observed to have developed parallel to installed SBS roof membrane direction and the roof slope. Further analysis of the monitoring data was then conducted based on new information gathered during the field observations. As a result, the updated analysis of the monitoring data resulted in stronger correlation with displacement and roof geometry (fix points i.e., parapet, HVAC) and roof slope. The data showed that movement within the roof assembly is likely caused by movement of the SBS roof membrane and that where SBS roof membrane is fixed, less movement was observed. Also, the plots reinforce our field observation that a gap in the insulation is more likely to develop parallel to the roof slope. The plots illustrate and reinforces our previous analysis of the monitoring data that insulation type appears to have little impact on the movement in the insulation layer.

4 Laboratory Testing

Nine exploratory openings were made (30" x 30") where roofing membrane and insulation samples were collected from both the top and bottom insulation layers. SBS roof membrane samples were sent to Soprema's laboratory to test the physical properties of the field aged membrane and insulation samples were tested in RDH's laboratory to measure the thermal performance of the aged insulation.

4.1 Physical Properties of Aged Membranes

Collected aged membrane samples were sent for laboratory testing conducted by Soprema (see Appendix A for the full laboratory testing report). Testing of the samples included determining of the softening point on the top surface of the cap sheet, tensile and elongation of samples, and determining reflectivity of the granulated surfaces. Results of lab tested solar reflectance compared to manufacturer listed solar reflectance of new membranes are presented in Table 4.1.

TABLE 4.1 SOLAR REFLECTANCE OF MEMBRANE CAP SHEET AFTER SEVEN YEARS IN SERVICE

Cap Sheet Colour	Solar Reflectance (Data Sheet)	Solar Reflectance (Measured 2019)	% Decrease
White (high)	0.582	0.404	31%
White (low)	0.582	0.326	44%
Grey	0.138	0.141	-2%
Black	0.040	0.061	-53%

The laboratory testing report from Soprema states that tensile and elongation of the membranes, after seven years of exposure[14], are "similar to initial state". The membrane with black granules, however, had some variation in its softening point (132˚C) compared to grey (125˚C) and white (127˚C) granules, for which their softening point had not changed with exposure. The softening point of the black membrane is likely negatively impacted by the higher surface temperatures it experiences during the summer. Overall, the Soprema report concludes that roughly seven years of field exposure "seems to have no or just at little effect on the physical properties evaluated".

It is visually evident in the photograph samples in Figure 4.1.1 that the white and grey membrane have darkened over time whereas the black membrane appears to have lightened, perhaps due to oxidization. Interestingly, while changes in reflectance for the white membrane are often attributed to soiling, visual observation seems to indicate that degranulation is also a significant contributor to degraded surface reflectance of the membranes.

[14] Membrane was installed August 2012 and samples were cut in October 2019, one year after monitoring period was completed.

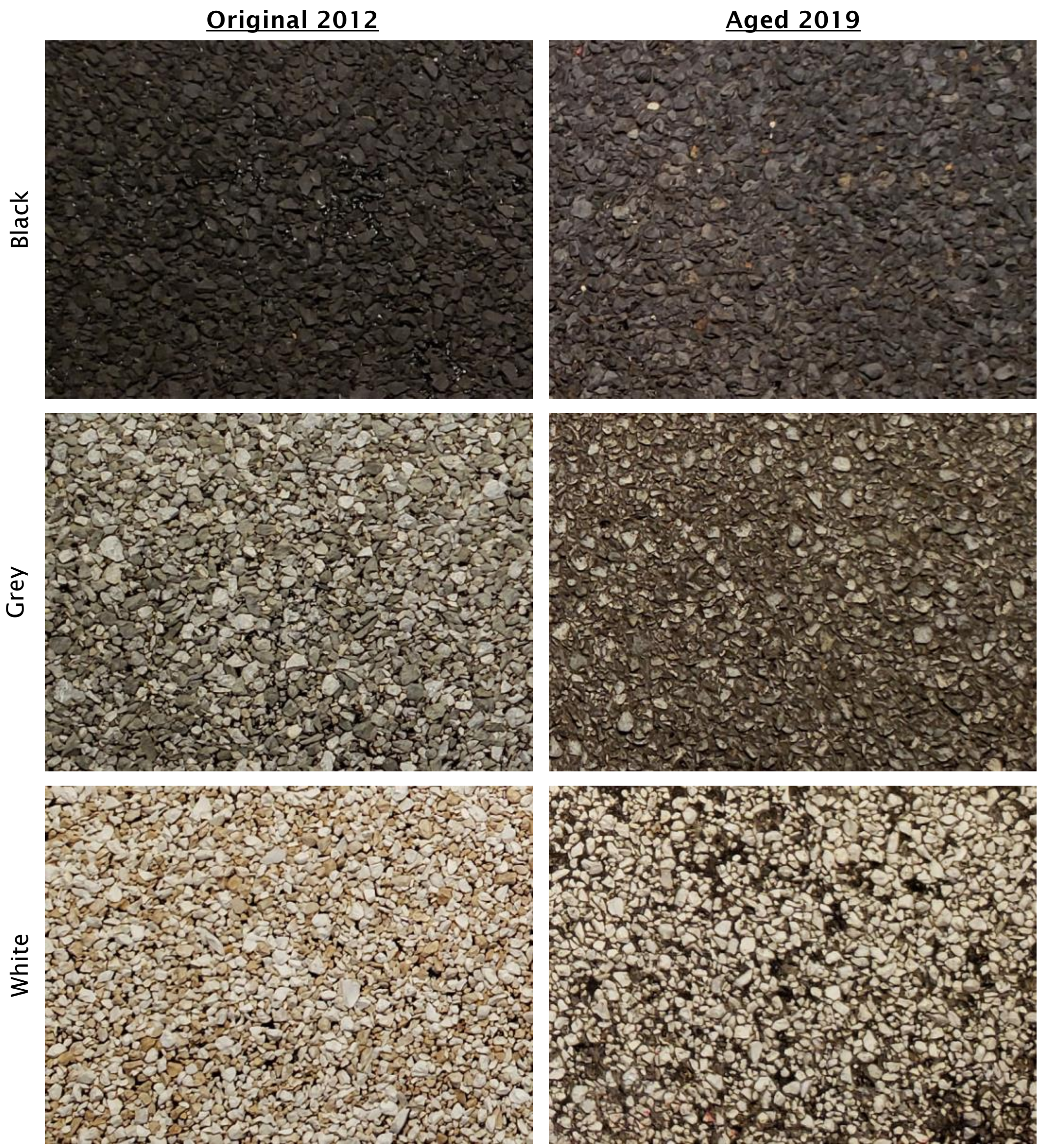

Figure 4.1.1 Roof membrane samples comparing the original 2012 vs. aged 2019 for the black, grey and white membranes.

For a clearer understanding of the change that has occurred to the SBS roof membrane over time, photographs of the original and aged samples were taken with a microscope and provided in Figure 4.1.2. These images show that while some degranulation can be seen, darkening of the grey and white SBS membrane is largely due to soiling and deposit of organic matter. The black SBS roof membrane is noticeably lighter due to combination of degranulation and soiling.

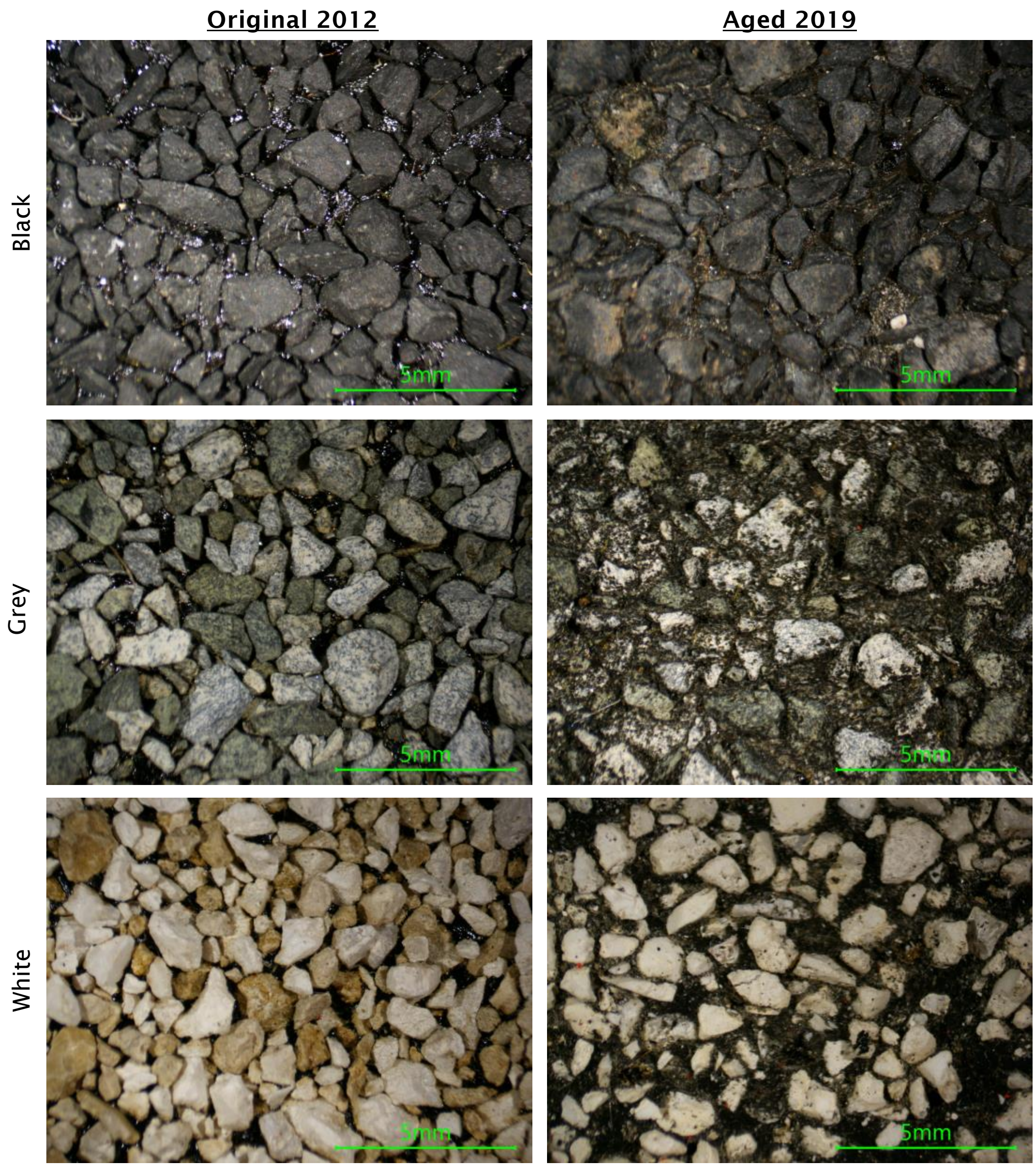

Figure 4.1.2 Microscopic photos of samples comparing original 2012 vs. aged 2019 for black, grey and white membrane.

The emissivity of the original and aged membrane was estimated using a longwave IR (LWIR) camera to observed if there were any significant change in the longwave emittance of the SBS roof membrane. The estimation method used an electrical tape as a reference, which is assumed to have emissivity of 0.95. The SBS roof membrane samples were conditioned to -12˚C with the electrical tape adhered to the granulated surface of each sample. Thermal images were then taken for radiometric analysis, where temperature of the tape was assumed to be the same as the SBS roof membrane sample and used as reference as shown in Figure 4.1.3.

The analysis estimated that all samples had emissivity in the high 0.90 range and while no significant change was observed, aged sample emissivity was typically 0.01 to 0.02 lower than the original.

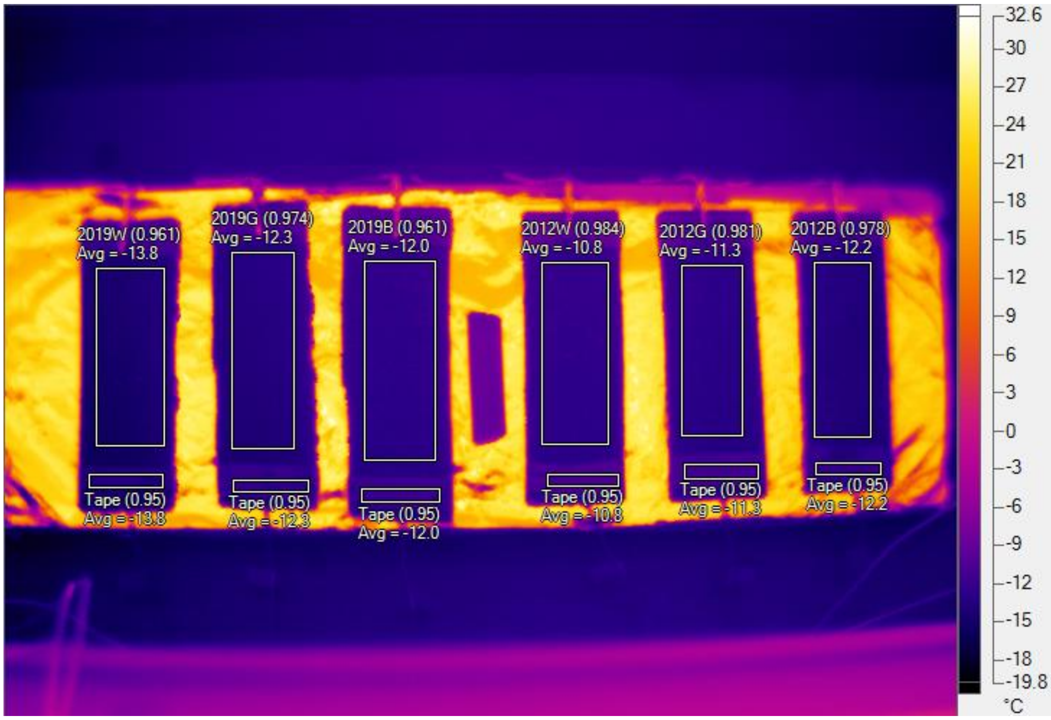

Figure 4.1.3 Thermal image of conditioned samples.

4.2 Thermal Performance of Aged Insulation

As discussed in the 2014 interim report, the thermal performance of the three insulation arrangements varies with temperature. Polyiso insulation in particular exhibits temperature dependent conductivity, generally leading to reduce thermal resistance at lower temperatures.[15] Additionally, ageing of polyiso has also been shown to reduce its thermal resistance as blowing-agents are off-gassed from the pores of the foam plastic insulation.[16,17,18] The thermal conductivity of in-service insulation samples was measured after three and eight years aged using a technique based on ASTM C 518-10 *Standard Test Method for steady-state thermal transmission properties by means of the heat flow meter apparatus* and modified to assess the thermal performance at a range of realistic temperature conditions independently from insulation thickness. The results of these measurements were converted to R-value per inch and are presented in Figure 4.2.1 and Appendix C.

[15] Dell, M. and Finch, G., 2013. Monitored Field Performance of Conventional Roofing Assemblies – Measuring the Benefits of Insulation Strategy. Proceedings from the 2013 RCI Symposium on Building Envelope Technology, November 13-14, 2013, Minneapolis, Minnesota.

[16] Graham, M.S., 2010. Revised R-values. Professional Roofing, May 2010. Available at: http://www.professionalroofing.net/

[17] Dell, M. and Finch, G., 2013. Monitored Field Performance of Conventional Roofing Assemblies – Measuring the Benefits of Insulation Strategy. Proceedings from the 2013 RCI Symposium on Building Envelope Technology, November 13-14, 2013, Minneapolis, Minnesota.

[18] Building Science Corporation (BSC). 2013. BSC Information Sheet 502: Understanding the Temperature Dependence of R-values for Polyisocyanurate Roof Insulation. Available at: http://www.buildingscience.com

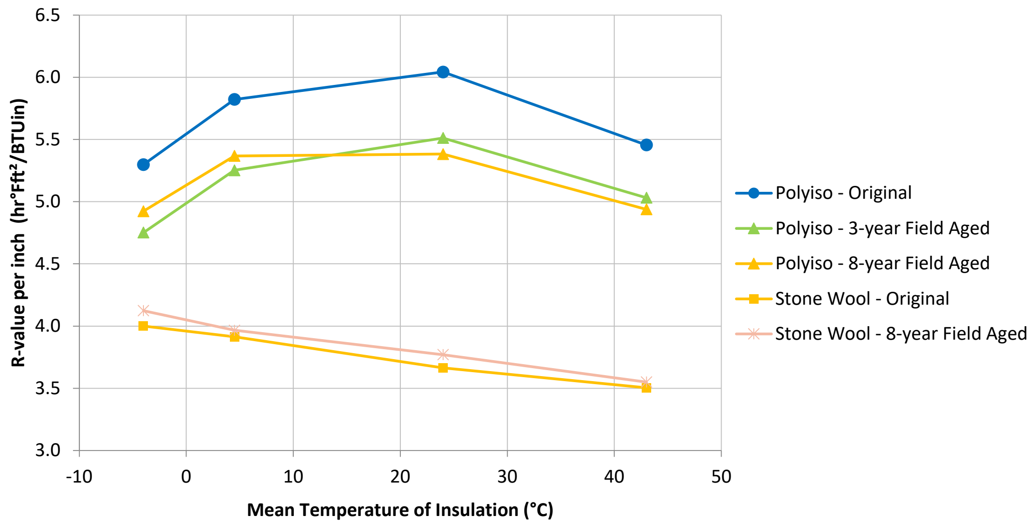

Figure 4.2.1 Measured temperature dependent R-value per inch of polyiso and stone wool insulation when new, field aged 3 years (polyiso) and 8 years.

Results from the measurements suggest that the thermal resistance of the polyiso insulation has decreased with age, compared to the stone wool which has retained its thermal performance over time. Interestingly, the three-year field aged polyiso insulation appears to have a relatively lower R-value per inch at lower mean temperatures, which has increased slightly after eight years of field aging. It is theorized that this phenomenon occurs as the blowing agent (largely pentane in these samples) initially diffuses out of the insulation and is replaced by air, which reduces the performance (e.g., three-year field aged). Over time, as more of the blowing agent has been replaced by air, the cold temperature performance improves somewhat due to less blowing agent condensing in the pores at colder temperatures. It is important to note that, in general, the blowing agents used in polyiso insulation products have been modified in recent years following the initial construction of the monitored roof assemblies in order to improve thermal performance at low mean temperatures.

5 Key Findings

Long-term monitoring studies offer a unique opportunity to expand our understanding of the performance of building enclosure materials and assemblies. The field monitoring data acquired over the six-year study period provides insight into the different performance of conventional roof assemblies depending on insulation arrangement and roof membrane colour, and these findings are supplemented with information collected through field investigations and laboratory testing. Key findings from this study include:

- → The impact of membrane colour is greatest during sunny and warm periods, and consequently, the impact of the membrane colour on cooling degree days was found to be much greater than on heating degree days. In many cases, absorption of solar energy can create more additional cooling demand than it will reduce heating demand in the winter, potentially leading to a net energy penalty for using a darker coloured membrane.
- → Roofs with higher solar reflectance were generally found to experience less extreme temperatures and slower changes in temperature.
- → Lab test results from Soprema confirmed that solar reflectance of the aged white membrane sample has decreased from 0.58 to 0.40 at the high point of the roof (~31%) and 0.33 at the low point of the roof (~44%), respectively, largely dependent on its location relative to roofing slope.
- → The aged black membrane sample increased in solar reflectance from 0.04 to 0.06 (~53%) as a result of degranulation, soiling, and likely surface oxidation.
- → The data showed a trend of increasing inward heat flow for all insulation arrangements over the course of the monitoring period, particularly roofs with polyiso insulation.
- → Movement within the roof assemblies was examined and gaps between the insulation boards were found to typically widen in the winter and narrow in the summer. Gap widening was generally greater than subsequent gap narrowing, resulting in a net-increase in gap width over time.
- → Upper layers of insulation typically experienced more displacement than the lower insulation layer (with the exception of the hybrid roof assembly), likely due to thermal contraction and expansion of the SBS roof membrane.
- → The correlation between insulation layer and displacement measurements seems to indicate that the strongest determining factor for insulation movement is which layer of insulation it is, with the second most important factor being roof slope.
- → Field observations and data analysis suggest that gaps in insulation are more likely to develop parallel to the roof slope.
- → An overall annual increase in the relatively humidity below insulation was observed for all insulation arrangements in first three years. After seven years in service, exploratory openings and moisture content field measurements showed that the roof insulation for all assemblies was generally dry and no liquid water was observed.

In all, this study used the combination of long-term monitoring with periodic field investigation and laboratory testing provides significant insight in to understanding how the hygrothermal (heat and moisture) and physical properties of conventional roof assemblies can change over time. The findings clearly demonstrate the ways in which cap sheet membrane colour and insulation arrangement can both significantly affect roof performance.

Recommendations for future studies include:

- → Monitor insulation dimensional stability using improved methods based on finding from this study (e.g., gauges fixed to the roof structure vs. insulation boards)
- → Confirm seasonal SBS movement exposed to extreme high and low outdoor ambient temperatures, and
- → Install new insulation products (e.g., polyiso insulation with new blowing agents) to monitor impacts on long-term heat flow.

We trust that this report meets your needs at this time. Please feel free to contact us with any questions or comments.

Yours truly,

Jun Tatara | Dipl.T
Building Science Technologist
jtatara@rdh.com
604 873 1181
RDH Building Science Inc.

Christopher Marleau | MASc
Building Scientist
cmarleau@rdh.com
604 873 1181
RDH Building Science Inc.

Reviewed by:
Graham Finch | Dipl.T., MASc, P.Eng
Principal, Senior Building Science Specialist

Marcus Dell | P.Eng,
Senior Principal, Senior Building Science Specialist

Lorne Ricketts | P.Eng, MASc
Principal, Building Science Specialist

Appendix A

Aged Membrane Laboratory Testing by Soprema

To:	Carl Houde	**Date:**	2019-12-20
From:	Émy Beauchemin	**Recipients:**	F. Paquette, B. Bennett.
		RDH:	C. Marleau, J. Tatara, L. Ricketts, G. Finch.

Project: ATA 2019
Task: 190 – Study with RDH on Chilliwack plant roof samples
(ref: ATA 2019-190)

Context:

RDH, a consulting company, has realized a study to compare 9 types of roof systems at our Chilliwack plant. In that study, 3 types of insulation system (polyisocyanurate, mineral wool and a combination of polyisocyanurate/mineral wool) and 3 colors of granules (black; grey and white) for the cap sheet were used. The systems were installed in August 2012 and samples have been cut in March 2015 and lately, in October 2019. In ASS 2015-148 tests were performed on the samples cut in 2015. In this task we will repeat the evaluation of ASS 2015-148; this time on samples exposed for about 7 years.

Objective:

- Measure the effect of aging on physical properties of various roofing systems installed on Soprema Chilliwack roof.

Manipulations:

On samples sent from RDH:
- Take pictures
- Determine the reflectivity of the granulated surface.
- Determine the softening point on the bitumen blend on the top surface of the cap sheet.
- Determine the tensile and elongation on samples according to ASTM D5147 at 23 °C

Observations:

- Tensile and elongation results, after 7 years of exposition, are similar to initial state for white and for black granules membranes installed on mineral wool.
- Surface bitumen of membrane with black granules has some variation in its softening point over time while surface bitumen of membranes with grey and white granules have their softening point unchanged after 7 years of exposition.

Conclusion:

- Aging seems to have no or just a little effect on the physical properties evaluated.

Regards,

Émy Beauchemin

Émy Beauchemin, R&D Technician

Research and Development, 1688 J.-B. Michaud, Drummondville, Quebec J2C 8E9 – Tel.: (819) 478-8166 Fax: (819) 478-8044

Results:

Table 1: System samples appearance and composition

Samples identification	White Low 2019	Black 2019[1]	White High 2019	Grey 2019
Visual appearance				
Sample composition	Mineral wool – Base sheet – White cap sheet	Mineral wool – Base sheet – Black cap sheet	SOPRABOARD – White cap sheet	Polyiso – SOPRABOARD – Base sheet – Grey cap sheet
Reflectance[2]	0.326	0.061	0.404	0,141

[1] The picture for the system identified as Black 2019 is the good picture. The granules look grey on the picture, but it is the membrane with the black granules shown.
[2] Reflectometer parameters B891

Research and Development, 1688 J.-B. Michaud, Drummondville, Quebec J2C 8E9 – Tel.: (819) 478-8166 Fax: (819) 478-8044

Table 2: Physical properties of systems

Samples description		Strain Energy (kN/m)	Max Load (kN/m)	Elongation at max load (%)	Softening point (°C)
SOPRASTAR FLAM HD GR & SOPRAPLY BASE 520 **initial**[3]	MD	22 ± 2	36 ± 2	70 ± 2	125[4]
	CMD	16 ± 3	29 ± 3	64 ± 6	
SOPRASTAR FLAM HD GR & SOPRAPLY BASE 520 **Aged 2.5 years** on mineral wool[5]	D1	22 ± 2	34 ± 1	75 ± 5	Not available
	D2	19 ± 2	28 ± 1	78 ± 4	
White Low 2019 **Aged 7 years** on mineral wool	D1	18 ± 3	36 ± 3	61 ± 6	127
	D2	17 ± 1	30 ± 1	68 ± 2	
SOPRAPLY TRAFFIC CAP 560 & SOPRAPLY BASE 520 – **initial**[3]	MD	20 ± 4	35 ± 2	67 ± 5	125[4]
	CMD	16 ± 2	26 ± 1	67 ± 6	
SOPRAPLY TRAFFIC CAP 560 black & SOPRAPLY BASE 520 **Aged 2.5 years** on mineral wool[5]	D1	20 ± 4	34 ± 2	66 ± 9	123.1
	D2	17 ± 4	26 ± 2	73 ± 12	
Black 2019 **Aged 7 years** on mineral wool	D1	16 ± 4	33 ± 3	54 ± 11	132
	D2	15 ± 3	28 ± 2	57 ± 9	
White High 2019 **Aged 7 years**	D1	9 ± 1	15 ± 1	65 ± 4	127
	D2	9 ± 1	20 ± 2	55 ± 5	
Grey 2019 **Aged 7 years**	D1	11 ± 3	25 ± 4	48 ± 8	125
	D2	13 ± 1	24 ± 1	65 ± 4	

Green: Initial state samples **Orange: 2.5 years of exposition** **Red: 7 years of exposition**

- Field samples could not be identified as MD or XD prior to testing. Both directions were tested but randomly identified D1 and D2.
- It was impossible to know if the samples having mineral wool as insulation is from a system composed of only mineral wool or a hybrid system composed of mineral wool and polyisocyanurate.
- The **SOPRASTAR FLAM HD GR and SOPRAPLY TRAFFIC CAP 560 black** systems exposed on a roof for 7 years demonstrate **tensile and elongation results similar to initial state** when installed on mineral wool.
- Both White High 2019 and Grey 2019 obtained weaker strain energy and maximum load results compared to the first two systems:
  - Those two systems were installed on SOPRABOARD; which has been removed prior to testing. This step may have damaged the base sheet of the Grey 2019 samples and could explain the weak results.
  - White High 2019 system seems to be a cap sheet installed directly on a SOPRABOARD, without base sheet. After the SOPRABOARD removal, sample is thinner than the Grey 2019 one's. The obtained results may correspond to the cap sheet alone, this could explain their weak value compared to the other samples which were composed of a base sheet and a cap sheet. The obtained results would be in line with the performance of a SOPRASTAR HD GR alone.
- After 7 years of exposition, the softening point of the bitumen binder is somewhat unchanged compared to initial state for most systems. The membrane with black granules is the system that shows the most important variation. Black being the color absorbing the most energy, it is plausible that black granules systems demonstrate in a more important manner fluctuations in their performances over time.

[3] Initial results are coming from ASS 2015-148, from membrane installed at our training facility in Drummondville in October 2015 and tested in November of the same year.

[4] Those are the nominal value of softening point.

[5] Results are coming from report ASS 2015-148, those samples were exposed for 2.5 years before being tested. The composition of those systems seems to match some of the systems received from October 2019 sampling. For this reason, *SOPRASTAR FLAM HD GR & SOPRAPLY BASE 520 aged on mineral wool* results will be compared to the *White Low 2019* ones. *SOPRAPLY TRAFFIC CAP 560 black & SOPRAPLY BASE 520 aged on mineral wool* results will be compared to *Black 2019* ones.

Research and Development, 1688 J.-B. Michaud, Drummondville, Quebec J2C 8E9 – Tel.: (819) 478-8166 Fax: (819) 478-8044

Appendix B

Methodology – Annual HDD/CDD Based on Membrane Colour & Insulation Arrangement

The following outlines the method for adjusting measured Heating and Cooling Degree Day values based on membrane colour and insulation arrangement given periodic monitoring equipment malfunctions.

Figure B.1 compares HDD calculated using measured data for the different membrane colours. Note that year 2013 to 2014, there's a visual trend of decreasing degree days as the roof membrane darkens; however, due to monitoring equipment malfunctioning, some loss in monitoring data were experienced in 2016 and 2017, and consequently, this figure does not fully represent the impact of membrane colour on the roof performance.

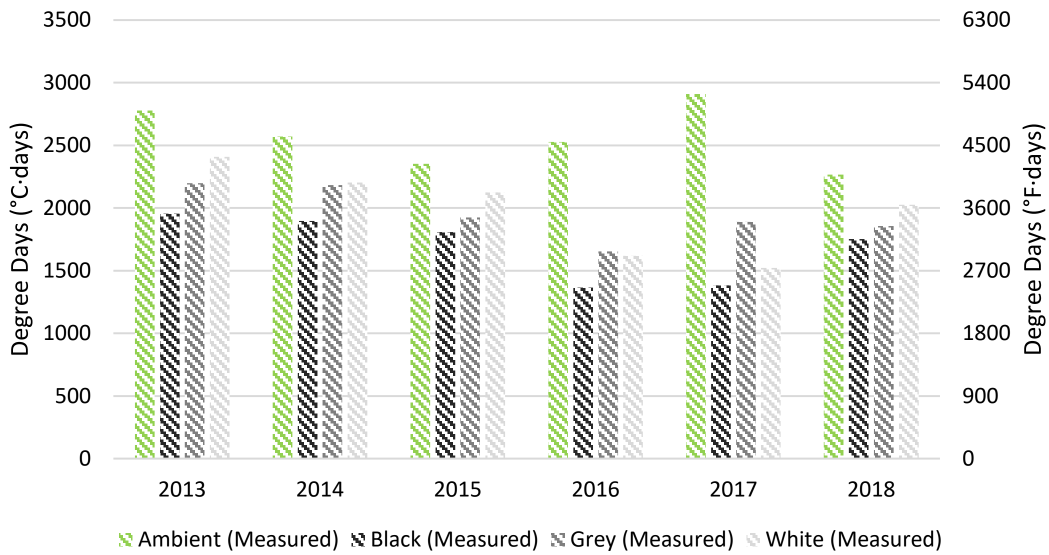

Figure B.1 – Annual HDD calculated using measured data from 2013 to 2018. Note that in some cases data points for surface temperature were available for some roofs and not others, which creates an inaccurate comparison. The data was filtered to address this in the following figure.

In some cases, data points are available for some sensors and not others, which means that comparing an average of these results can lead to an inappropriate comparison. To facilitate a more fair comparison, the data was filtered to remove data for all temperature sensors if one sensor failed to record. Figure B.2 shows the comparison of HDDs based on this filtered data. Note that because data points have been removed, the absolute number of calculated HDDs is no longer representative, so this analysis is meant solely for comparative assessment of the performance of the different roofs relative to each other. Nonetheless, this filtering of the data clearly indicates the difference in calculated HDDs based on the colour of the roof membrane, with white roofs typically having more HDDs than black roofs, and grey in between.

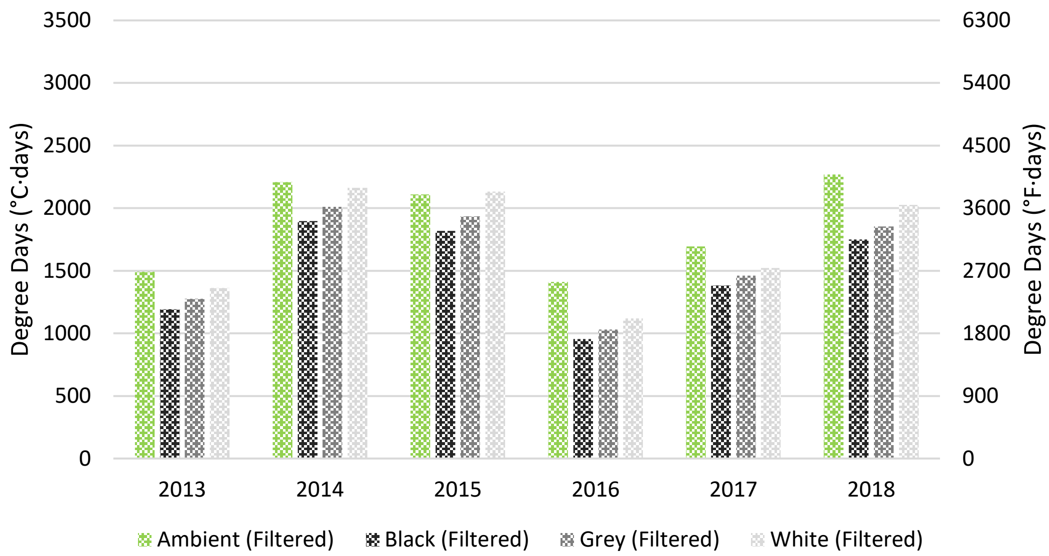

Figure B.2 – Annual HDD calculated using filtered data from 2013 to 2018. Note that the filtering removed data points; consequently, absolute calculated HDDs presented here are appropriate for relative comparison only.

While Figure B.2 allows for relative comparison, it does not allow for assessment of absolute heating degree days, as may be required if using this information as part of whole building energy modelling. Therefore, to provide information for this potential input, heating degree days based on weather data from Agassiz airport, which has the data integrity of nearly 100%, were used to scale the measured and filtered HDDs and CDDs. The adjusted degree days are provided in Figure 2.3.7, which compare annual HDDs and CDDs based on the ambient temperature and the roof surface temperature of the different membrane colours on a yearly basis.

Figure B.3 compares HDD calculated using measured data for the different insulation arrangements; however, due to monitoring equipment malfunctioning, some loss in monitoring data were experienced and consequently, this figure does not fully represent the impact of insulation arrangements on the roof performance.

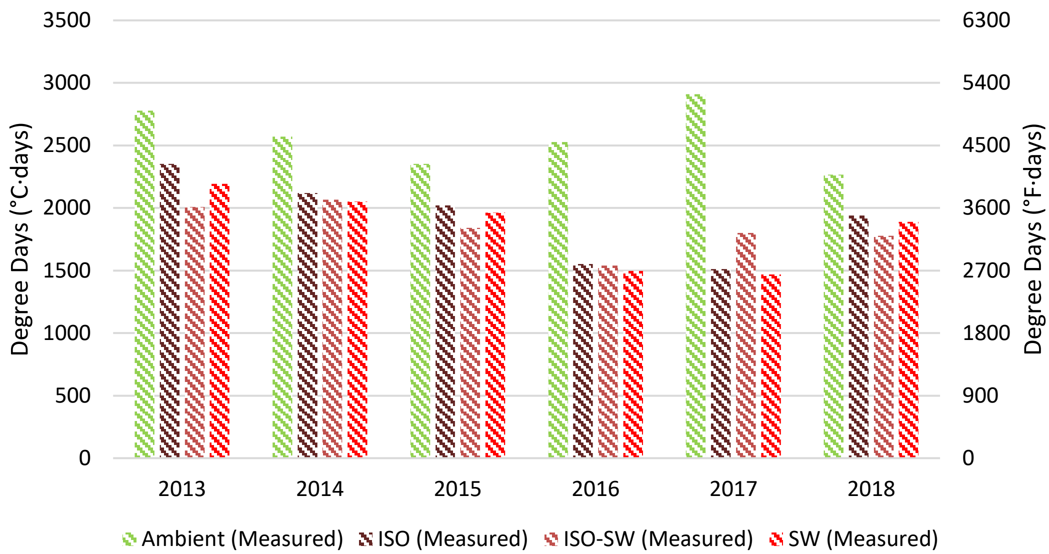

Figure B.3 – Annual HDD calculated using measured data from 2013 to 2018. Note that in some cases data points for surface temperature were available for some roofs and not others, which creates an inaccurate comparison. The data was filtered to address this in the following figure.

Similar to the analysis performed on impact of membrane colours on the roof performance, in some cases, data points are available for some sensors and not others, which means that comparing an average of these results can lead to an inappropriate comparison. To facilitate a fairer comparison, the data were filtered to remove data for all temperature sensors if one sensor failed to record. Figure B.4 shows the comparison of HDDs based on this filtered data. Note that because data points have been removed, the absolute number of calculated HDDs is no longer representative, so this analysis is meant solely for comparative assessment of the performance of the different roofs relative to each other. This filtering of the data clearly indicates the difference in calculated heating degree days based on insulation arrangements, with polyiso roofs typically having more HDDs than stone wool roofs, and hybrid roofs having the least.

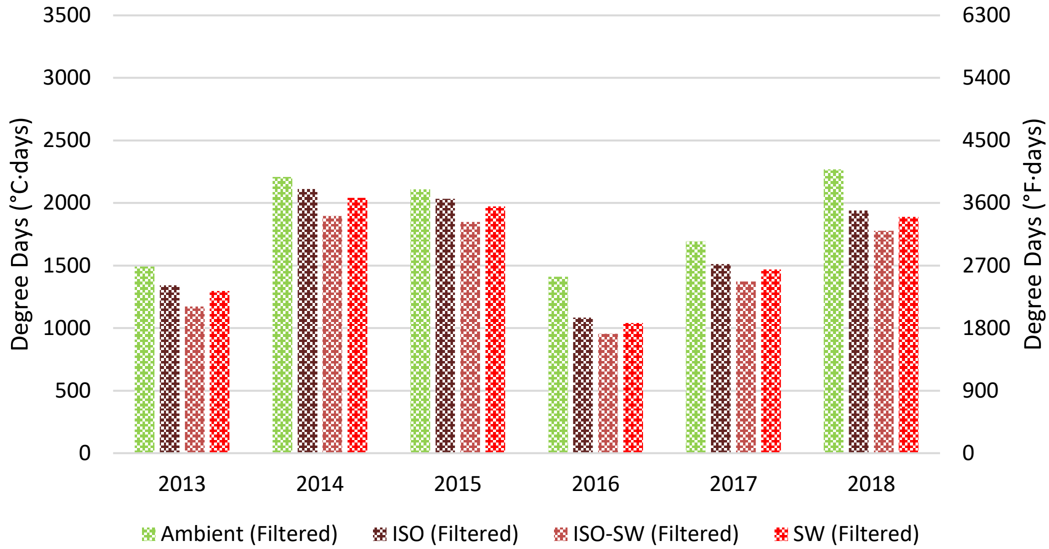

Figure B.4 – Annual HDD calculated using filtered data from 2013 to 2018. Note that the filtering removed data points; consequently, absolute calculated HDDs presented here are appropriate for relative comparison only.

While Figure B.4 allows for relative comparison, it does not allow for assessment of absolute heating degree days, as may be required if using this information as part of whole building energy modelling. To provide information for this potential input, heating degree days based on weather data from Agassiz airport, which has the data integrity of nearly 100%, were used to scale the measured and filtered HDDs and CDDs. The adjusted degree days are provided in Figure 2.4.12, which compare annual HDDs and CDDs based on the ambient temperature and the roof surface temperature of the different insulation arrangements on a yearly basis.

Appendix C

ASTM C518 – Measured Thermal Performance Polyisocyanurate and Stone Wool Insulation Over Time

TABLE C.1 MEASURED AVERAGE R-VALUE PER INCH OF POLYISOCYANURATE (AND STONE WOOL) INSULATION AT PRIOR TO INSTALLATION, AGED 3-YEARS AND AGED 8-YEARS AGED FROM C518 APPARATUS.

Mean Temperature (˚C)	**Apparent R-inch (hr·˚F·ft²/BTUin)**		
	Original	**Aged 3-years**	**Aged 8-years**
-4	5.30 (4.00)	4.75	4.92 (4.12)
4.5	5.82 (3.91)	5.25	5.37 (3.97)
24	6.04 (3.66)	5.51	5.38 (3.77)
43	5.46 (3.50)	5.03	4.94 (3.55)

Appendix D

2015 Interim Report Update – Insulation Dimensional Stability Analysis

The analysis in this section provides a general update to the plots from the previous interim report, which includes additional data for the complete 6-year monitoring period. See Section 2.6 for additional monitoring data analysis.

Figure D.1 illustrates the measured change in gap size between the insulation boards over the course of the six-year monitoring period. The plots are provided for both north-south and east-west sensors in the lower insulation layer in the black roof assemblies. Displacement is provided both in millimetres (mm) and in % change in dimension of the 48" x 48" boards. Negative displacement corresponds with an increase in the gap between the boards. Note that % change is intended for reference only and does not necessary indicate actual change in the physical dimension of the insulation boards.

It is also important to note that the displacement sensors only measure the size of the gap between the boards, and that changes in this gap size could be the result of insulation expansion or contraction, insulation shrinkage (permanent contraction), or could alternatively be caused by movement of the insulation boards relative to each other. Movement of the insulation boards could potentially be driven by thermal expansion and contraction of the SBS roof membrane or by movement of the roof structure such as deflection of the steel roof structure. Furthermore, the sensors are not fixed to the structure which means that the monitoring data does not indicate direction of the movement. Therefore, an insulation board with the sensor moving away from the adjacent insulation would provide the same data as if the adjacent insulation board moving away from the insulation board with the sensor since the gap widens in both cases.

Figure D.1 clearly shows that the amount of displacement in the lower insulation layer for black SBS membrane case has a stronger correlation to insulation arrangement/type than to the orientation of the measurements. This observation is consistent with findings in the three-year report, which noted that the lack of a correlation between the orientation of measurements and the amount of displacement was typical of the displacement data.

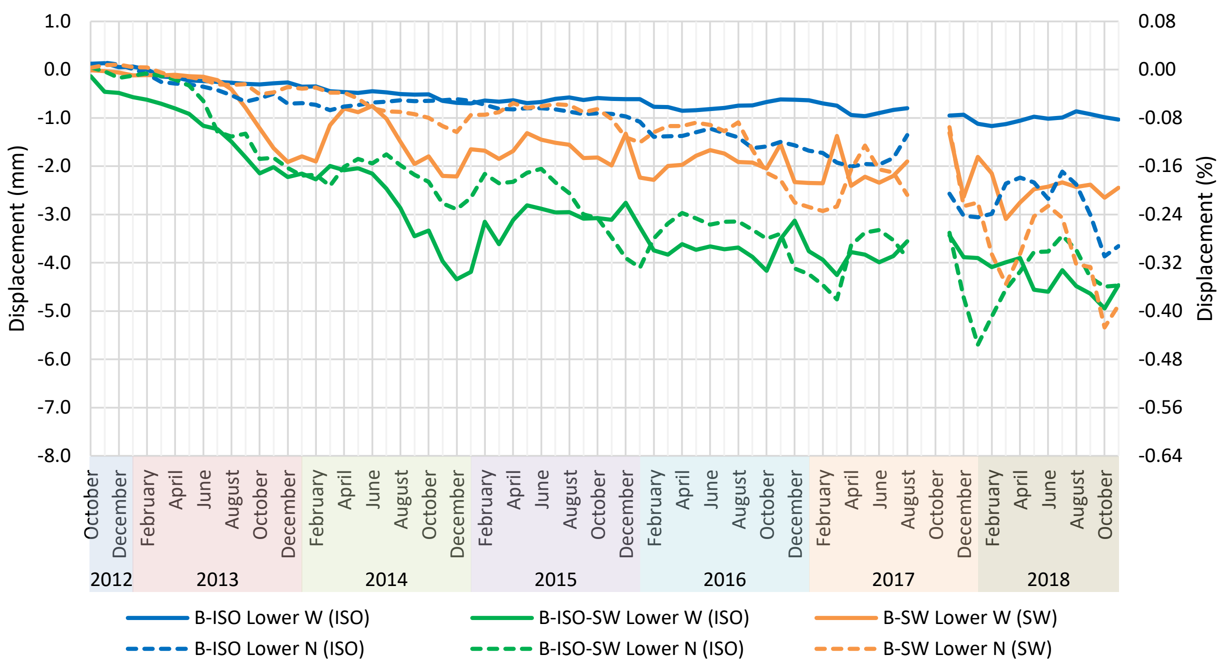

Figure D.1 – Monthly average displacement of lower insulation layer by insulation arrangement and sensor direction (W = West, N = North) for black roofs (parenthesis indicate insulation type of lower layer).

North-south and east-west measurements were averaged for each roof assemblies and insulation layers to provide comparison between white and black cap sheet and plotted in Figure D.2 and Figure D.3 to further investigate the correlation between SBS roof membrane colour and the amount of displacement.

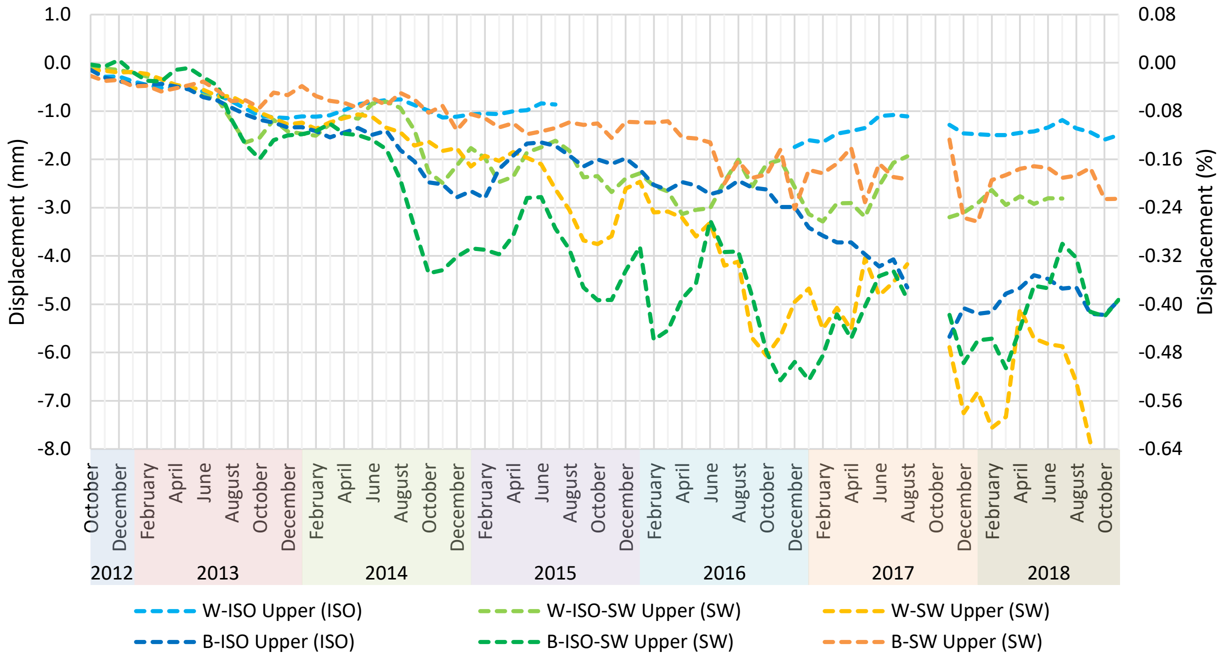

Figure D.2 – Monthly average displacement of upper insulation layers by insulation arrangement and membrane colours averaged for both north-south and east-west direction (parenthesis indicate insulation type).

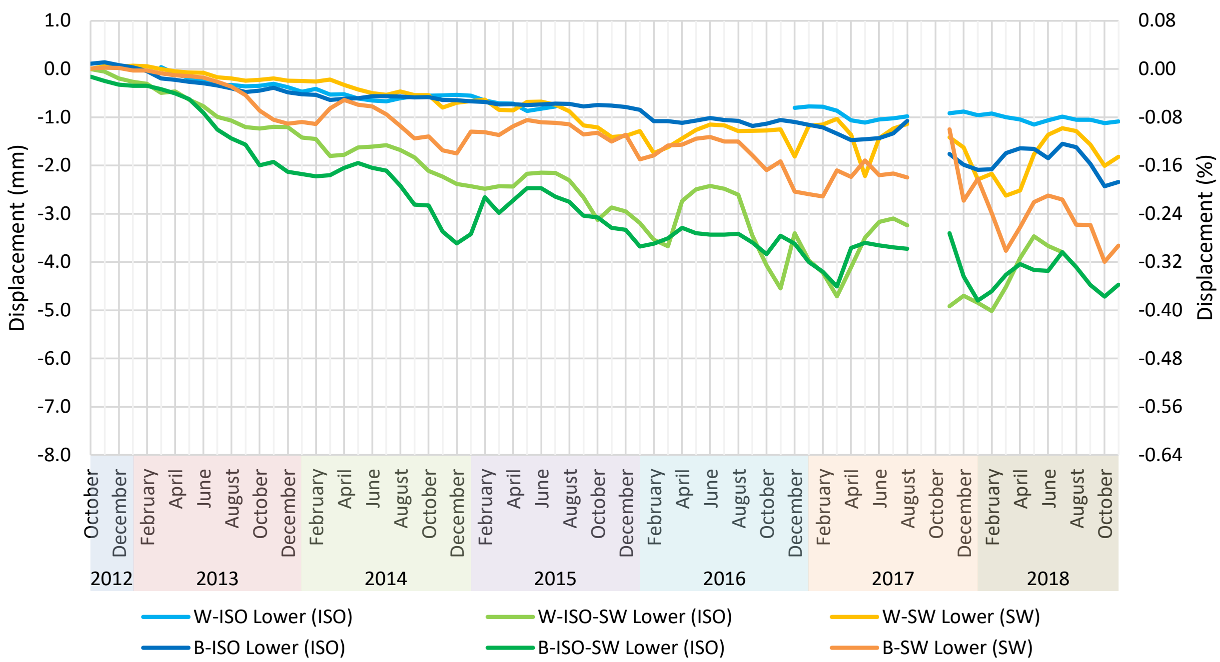

Figure D.3 – Monthly average displacement of lower insulation layers by insulation arrangements and membrane colours averaged for both north-south and east-west direction (parenthesis indicate insulation type).

As noted in the previous report, the amount of scatter shown in Figure D.2 and Figure D.3 (especially, in the upper layer) make drawing a definite conclusion difficult; however, the collection of data over six years further reinforces the previous observation that the relationship between insulation arrangement/type and the amount of insulation movement appears to be stronger (particularly for the lower insulation layers) where they would be less directly impacted by the colour of the roof membrane. Since the colour of the membrane appears to have no significant impact on the amount of insulation movement, displacement data for white and black cap sheet were averaged by insulation arrangements for the upper and lower insulation layers in Figure D.4 and Figure D.5, respectively.

The displacement data averaged by insulation arrangement/type for upper insulation layer (Figure D.4) shows very similar downward trend for all insulation arrangements, especially in the first two years. While stone wool in both the SW-only assembly and hybrid assembly continue to experience very similar movement, polyiso appears to experience slightly less movement.

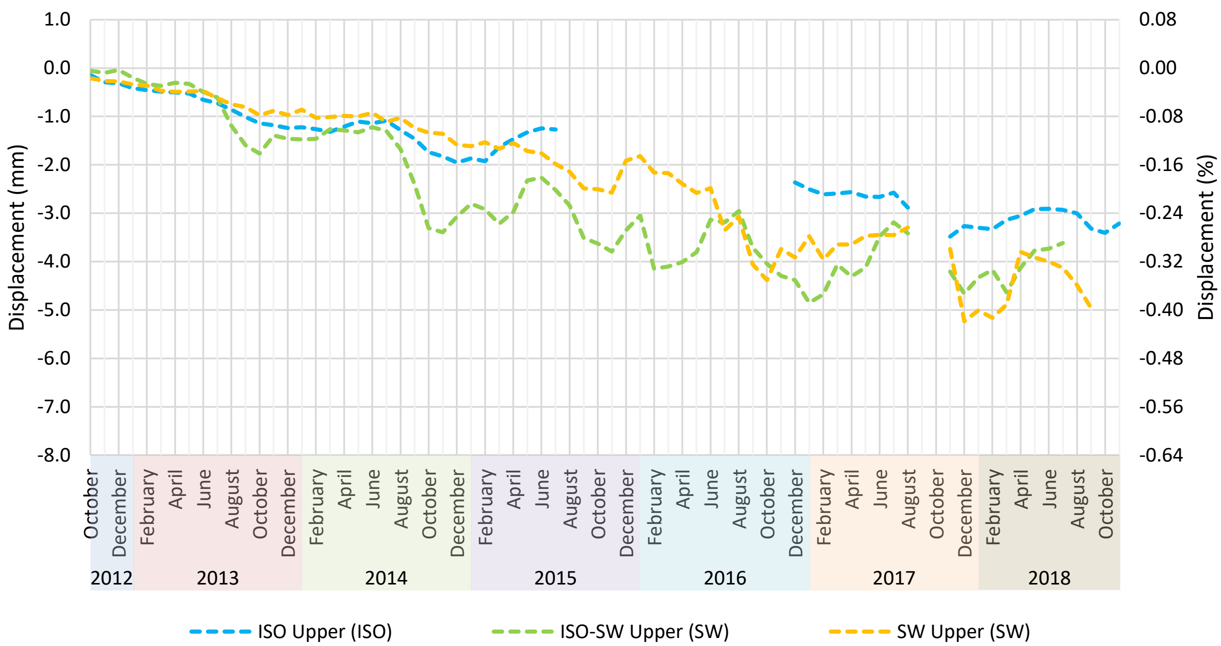

Figure D.4 – Monthly average displacement of the upper insulation layers by insulation arrangements averaged for both sensor directions and both membrane colours (parenthesis indicate insulation type).

The comparison of the averaged data for the lower insulation layers (Figure D.5) shows slightly different rates at which each insulation arrangement/type experienced movement more distinctively likely due to less scatter in the data. Polyiso (or ISO) in the hybrid assembly experienced the most movement, followed by stone wool, and then ISO-only.

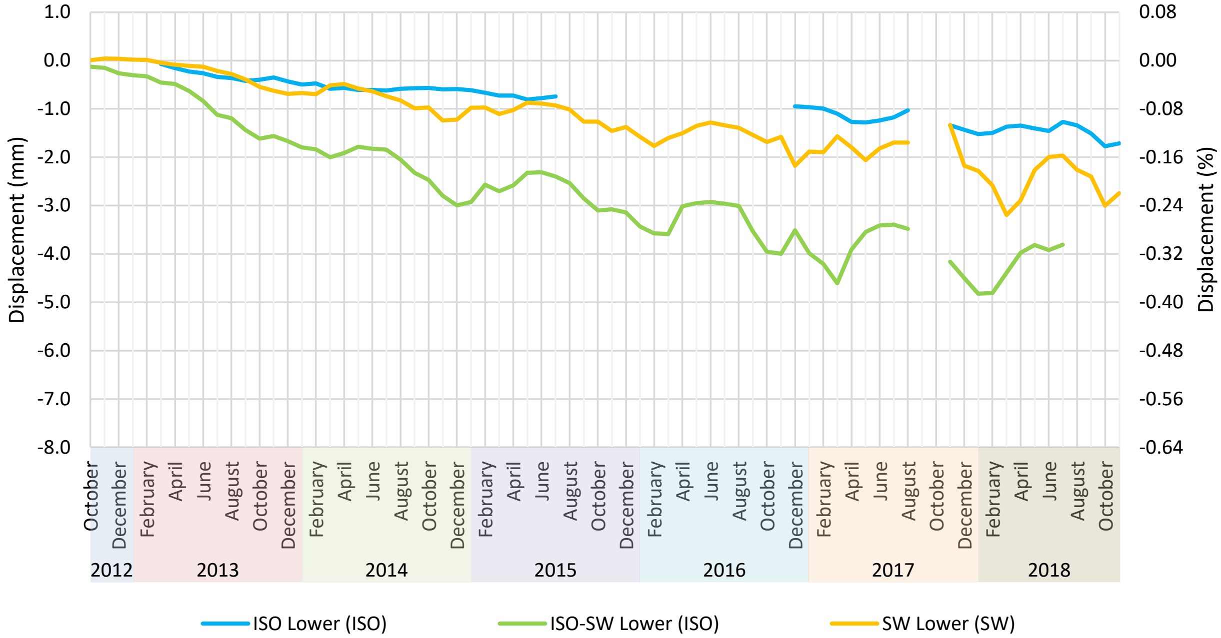

Figure D.5 – Monthly average displacement of lower insulation layers by insulation arrangements averaged for both sensor directions and both membrane colours (parenthesis indicate insulation type).