CONVENTIONAL ROOF ASSEMBLIES:
6-YEAR FIELD MONITORING STUDY UPDATE

by

Jun Tatara, Dipl.T., Christopher Marleau, MASc, Lorne Ricketts, MASc, P.Eng., and Graham Finch, MASc, P.Eng.

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ABSTRACT

A long-term field monitoring study was implemented to measure the impacts of membrane color and insulation strategy on the in-situ performance of conventional roof assemblies. The same roof membrane cap sheet type with three different surface colors (white, grey & black) was installed over three different conventional insulation strategies with approximately the same R-value, creating a total of nine unique roof assemblies on the same building. Sensors were then installed to monitor key performance indicators for the roofs including temperature at key layers of the roofs, relative humidity within the assemblies, and solar reflectance of the roof membranes.

This paper presents the results of this monitoring work after six years of study. In particular, updates and further analysis are presented with respect to moisture movement and accumulation within the assembles, insulation performance, long-term reflectivity and soiling of the roofing membranes. Exploratory openings have been performed to confirm results of the monitoring and collect samples for laboratory testing of the roofing materials post-field exposure, and results will be discussed in a separate paper. The various measurements are analysed and synthesized to allow for discussion of advantages and disadvantages of the different membrane colors and insulation arrangements.

LEARNING OBJECTIVES

- → Appreciate advantages and disadvantages of insulation strategies and roof membrane colors in conventional roof assemblies
- → Understand moisture movement and accumulation within conventional roof assemblies
- → Develop an awareness of the impact of long-term exposure on roof membrane cap sheet reflectance, and impact on thermal performance of the roof
- → Understand insulation performance and selection characteristics beyond a nominal R-value per inch

BACKGROUND

Conventional roof assemblies (low-slope roof assemblies in which the waterproof membrane is located above the insulation) constitute the majority of low-slope roof assemblies in North America. The design of these roof assemblies can have significant impacts of the thermal performance of the roof assembly and consequently on building energy consumption, occupant comfort, membrane durability, and assembly service life. This conventional roof research and field monitoring study analyzes the performance of nine different roof assemblies with different membrane colors (white, grey, and black) and insulation arrangements (polyisocyanurate, stone wool and hybrid) for a large roof with relatively few obstructions located on an industrial building in the Lower Mainland of British Columbia. Various sensors were installed within each of the different roof assemblies to measure indicators of their performance including solar reflectance, material temperatures, relative humidity, and heat flux. This report provides a six-year update and data analysis from the beginning of September 2012 to the end of November 2018, and is an update to previous analysis published by Finch, 2010, Dell & Finch, 2013 and Finch, Dell & Ricketts, 2014.

The three membrane colors are white, grey, and black, and the solar properties of the sheets as specified by the manufacturer are provided in Table 1. The three insulation arrangements are polyisocyanurate (polyiso), stone wool, and hybrid (stone wool on top of polyiso) as shown in Figure 1, Figure 2 and Figure 3, respectively. The combined roof assemblies cover a 40' x 40' area (1600ft^2). Figure 4 shows the arrangement of the roof assemblies on the study building.

Table 1 - Roof membrane cap sheet properties specified by manufacturer.

Cap Sheet Color	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

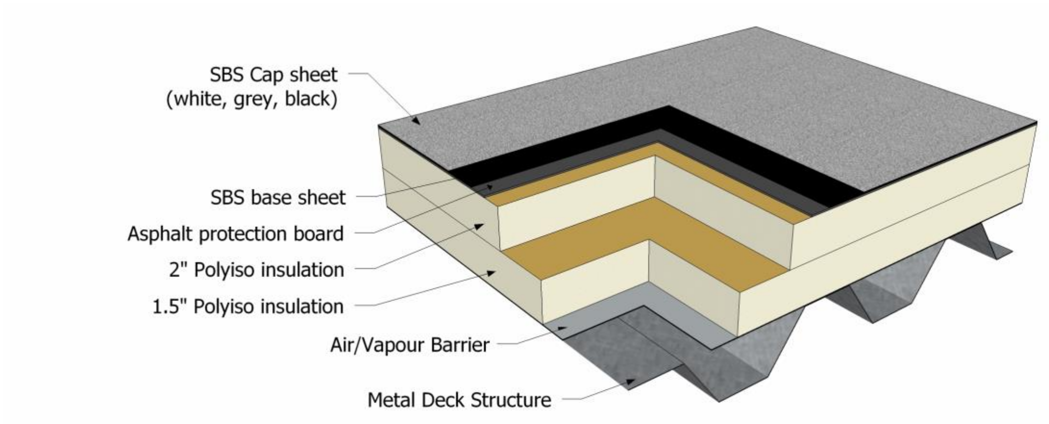

Figure 1 - Polyiso Roof Assembly – two layers of polyiso insulation.
Total nominal R-value (hr·ft²·°F/Btu) = R-21.0 (Top Layer = R-12.0, Bottom Layer = R-9.0)

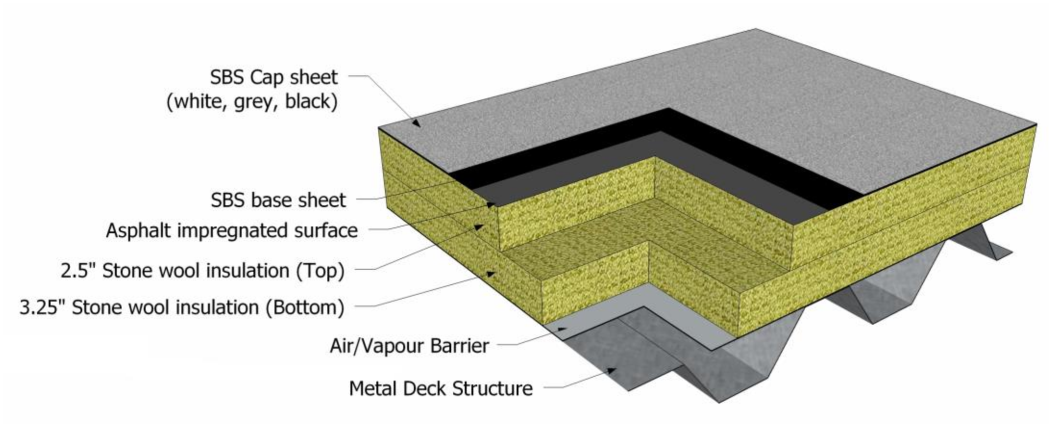

Figure 2 - Stone Wool Roof Assembly – two layers of stone wool insulation.
Total nominal R-value (hr·ft²·°F/Btu) = R-21.9 (Top Layer = R-9.5, Bottom Layer = R-12.4)

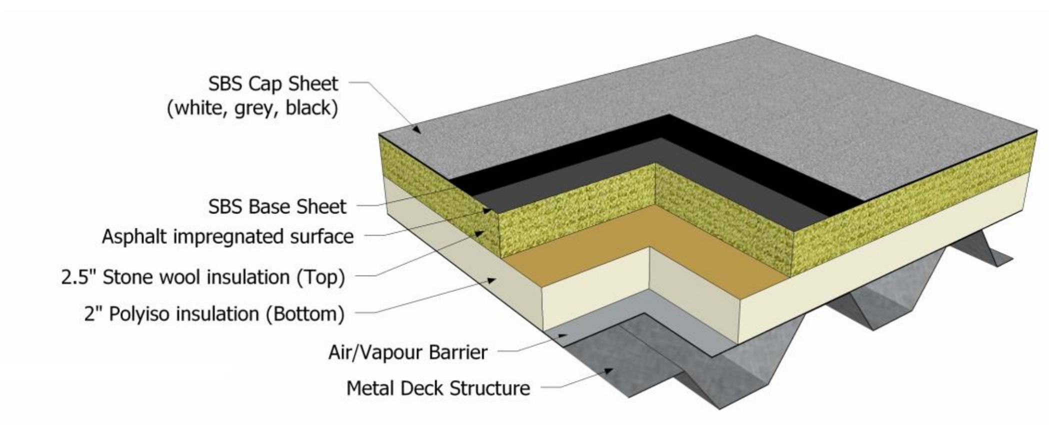

Figure 3 - Hybrid Roof Assembly – base layer of polyiso insulation and top layer of stone wool insulation.
Total nominal R-value (hr·ft²·°F/Btu) = R-21.5 (Top Layer = R-9.5, Bottom Layer = R-12.0)

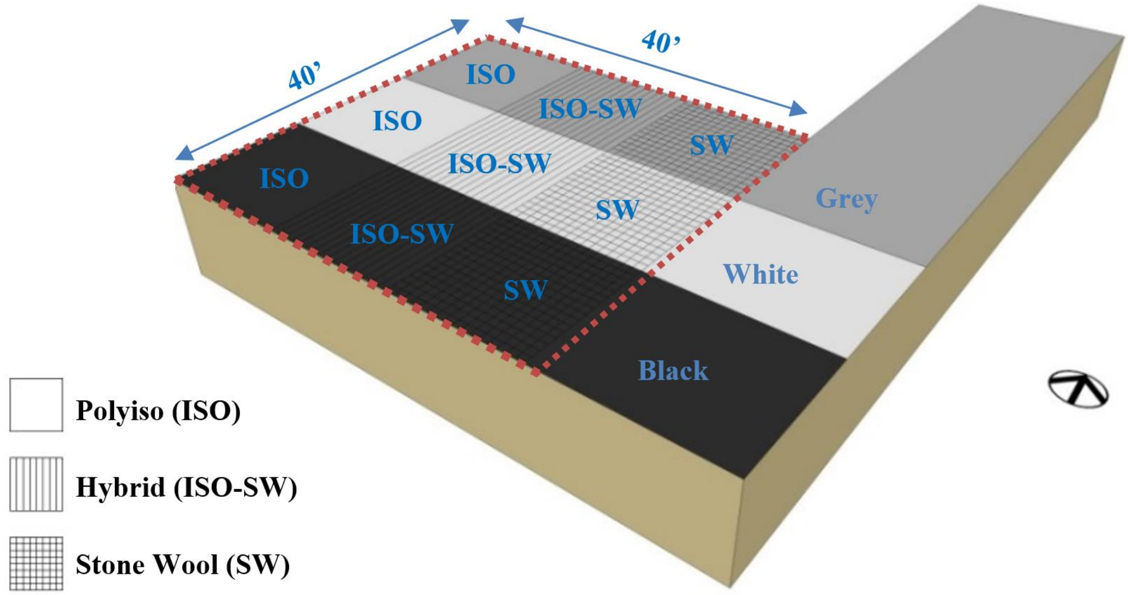

Figure 4 - Layout of the nine test roofs on the study building (test area in red dash).

FIELD MONITORING RESULTS

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

The exterior conditions were obtained from the weather station at Agassiz Airport (Environment Canada, 2018) and the 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 and interior conditions for each month are provided in Figure 5.

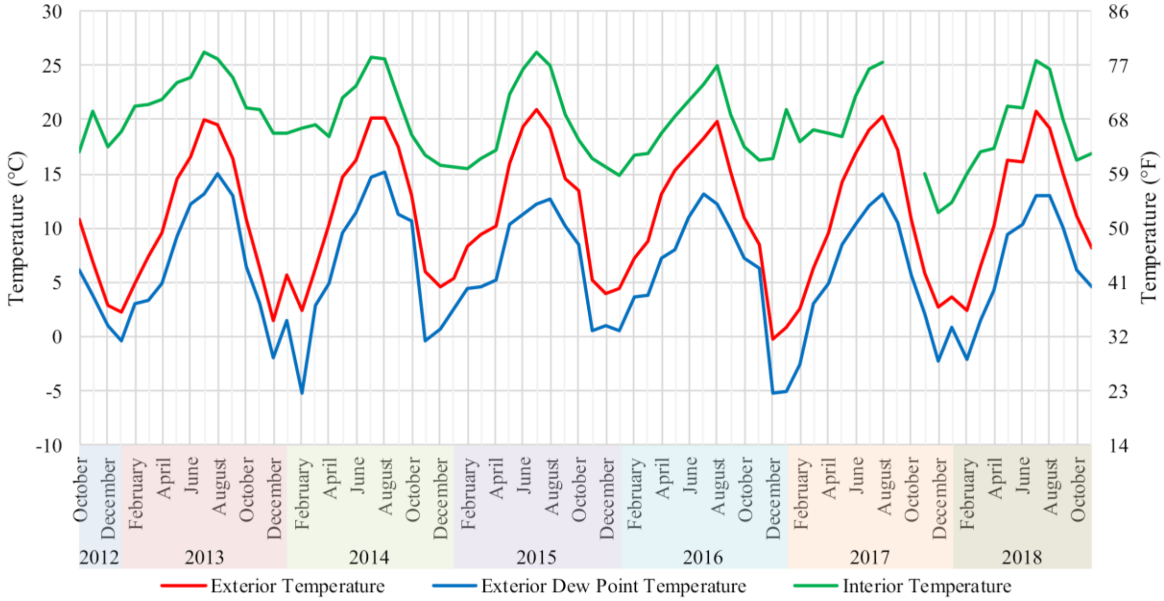

Figure 5 - Graph of monthly average temperature and dew point temperature during the monitoring period from October 2012 to December 2018.

EFFECTS OF MEMBRANE CAP SHEET COLOR

Reflected solar radiation from the roof cap sheets was measured using solar radiation sensors (pyranometers) mounted approximately 1m (3.2ft) above the roof surface and pointed downwards.

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 determine their in-service solar reflectance. This testing was not performed in accordance with ASTM reflectance measurements typically used for rating of roofing membranes. 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.

Figure 6 compares the average wintertime solar reflectance of the roof membranes between December 21st and March 20th from 2013 to 2018 (including manufacturer rating). The comparison was made for wintertime due to data loss that occurred in spring, summer and fall of 2014 and summer of 2017. Note that the measurement of the reflectance of the white membrane at a low point on the roof is less than that of the membrane at a high point which is likely due to the low point being more prone to collecting dirt and becoming soiled faster than the high point.

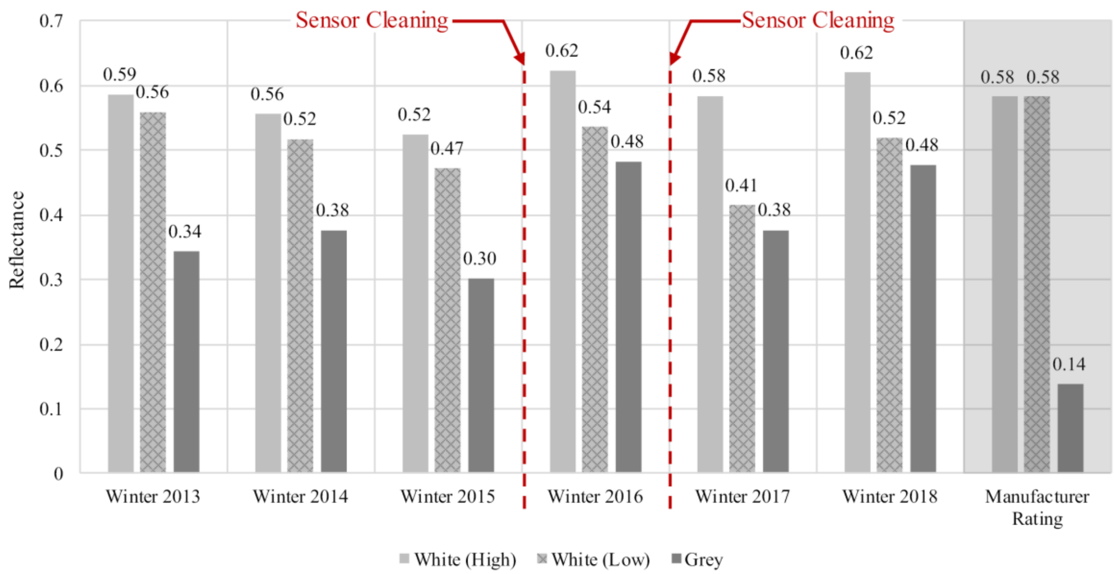

Figure 6 - Average reflectance of membrane between December 21 and March 20 over the six-year monitoring period. Note that the sensors were cleaned (March 2015 and December 2016) indicated with red dashed lines.

The difference between the field measured values and manufacturer's rated value is expected due to the difference in measuring techniques. While the measured reflectance of the white membrane in winter 2013 is similar to the manufacturer's rated reflectance, the measured grey membrane reflectance is significantly higher than the rated value. This is potentially because the sensor on the grey roof is located relatively close to the white roof and may be measuring some reflected radiation from the white roof or other adjacent surfaces. It's also possible that the grey membrane is simply more reflective than its rating indicates.

Results after three years of monitoring implied a declining trend in the white roof membrane reflectance, assumed to be caused by soiling and weathering of the membrane over time. However, an overall spike in winter 2016 shows that reflectance levels increased, in general, slightly above or similar to the initial values measured for winter 2013. This is almost certainly a result of cleaning the monitoring equipment which occurred in March 2015 and December 2016. Therefore, the trend found in the first three years which indicated soiling of the membrane was likely caused by soiling of the sensor rather than soiling and weathering of the membrane. Results from the continued monitoring period indicate that the reflectance of the white membrane at the higher areas has not reduced significantly over the six-year service life.

Despite uncertainty due to cleaning of the sensors, it is apparent that the white membrane in the lower portion of the roof does become more soiled than at the higher area, and this results in a measurable difference in reflectance. Portable instruments are available that can be taken to the roof to get accurate measurements (Smith, Liu & Paroli, 1998); however, a sample of each membrane was instead removed from the roof to compare with the same type and color of membrane kept from 2012 and stored in a controlled laboratory setting.

It is visually evident in Figure 7 below that the aged membranes have darkened over time, with the exception of the black membrane. Further laboratory testing of aged membranes is scheduled, and results will be discussed is a separate paper. Interestingly, while changes in reflectance for the white membrane are often attributed to soiling, visual observation seems to indicate that the most significant contributor to surface reflectance of the membranes is degranulation.

Figure 7 - Roof membrane samples comparing original 2012 vs. aged 2019 for black, grey and white membrane color.

Periods of snow accumulation were also found to slightly affect the measured results; however, the average yearly accumulation on the ground between 2013 and 2019 was only 18.5cm (7.3”). During periods when the roof was covered in snow, the overall reflectance was found to increase for all cases. In addition, the insulative properties of the snow were shown to maintain the cap sheet temperature at approximately 0°C (32°F).

A total of nine sensors were installed to measure the roof membrane cap sheet temperature, one for each of the different roof assemblies. The daily maximum and minimum roof membrane cap sheet temperatures were determined using hourly data obtained from the sensors. The plot provided in Figure 8 shows monthly average membrane temperature by membrane color, and the dots indicate the maximum and the minimum temperature that the membrane experienced each month. The values provided for each membrane color are the average of the values for all of the different insulation arrangements (i.e., "white" is the average of polyiso only, stone wool only and hybrid insulation with white roof membrane cap sheet).

Figure 8 reinforces the large impact that the roof membrane color has on roof membrane temperatures over the monitoring period. This impact is most significant during the summer months when roof membrane temperatures reach their annual maximums. For example, in July 2014, the maximum surface temperature of the black membrane was observed to be 51.2°C (92.2°F) above the maximum ambient temperature while the maximum temperature of the grey and white roof was 42.3°C and 27.7°C (76.1°F and 49.9°F) higher than ambient temperate, respectively. During colder ambient temperatures with less incident solar radiation, the difference in temperature between roof membrane is less significant. In December 2014, for example, the minimum surface temperature for the black, grey and white membrane was 5.5°C, 5.1°C and 5.2°C (~9°F) colder than the minimum ambient air temperature, respectively.

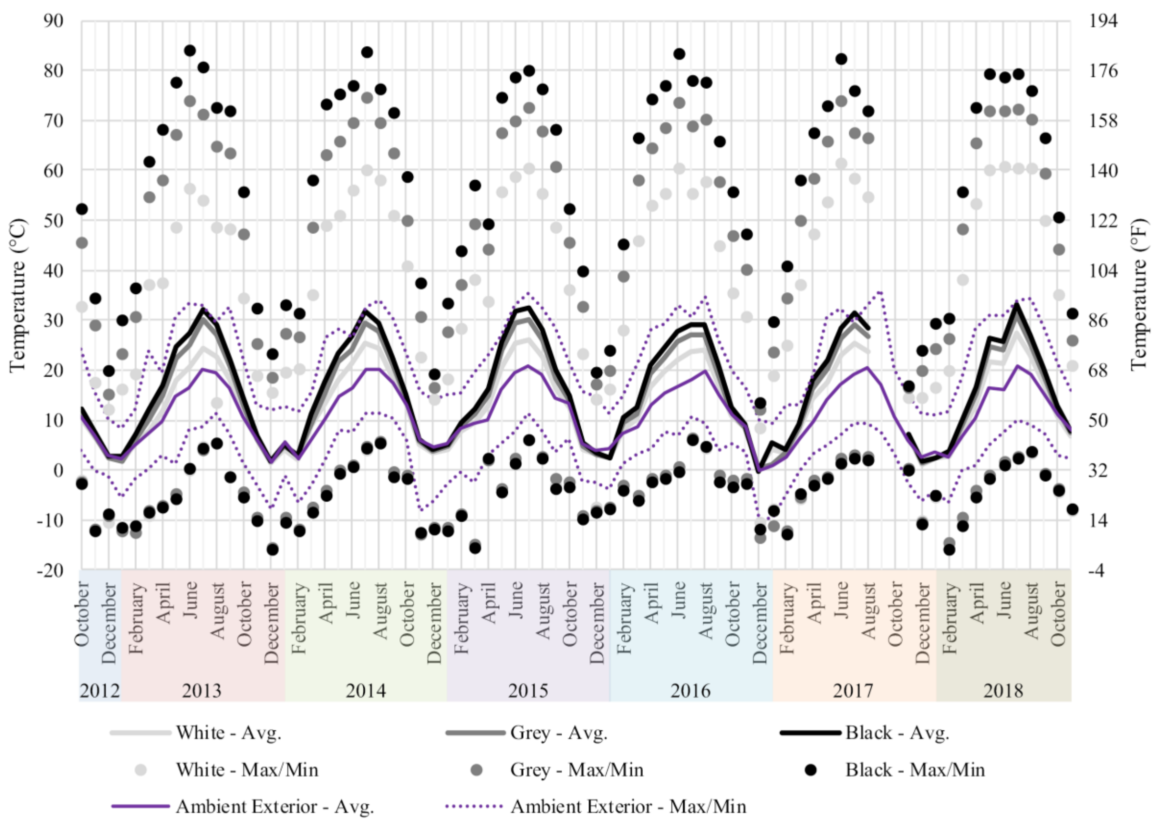

Figure 8 - Graph of monthly average membrane temperatures and maximum/minimum membrane temperature for each month by membrane color.

Measurement data also shows that membrane color has a more significant impact during the day, and that nighttime temperatures are relatively similar for each of the three membrane colors. This finding is consistent with the relatively significant difference in the solar reflectance but similar emittance for the three membrane colors (see Table 1).

Figure 9 shows the inward and outward heat flux (flow) through the roofs for each of the different roof membrane colors. This figure shows a slight trend of increasing inward heat flow for all membrane colors 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, it is theorized that this trend is likely primarily due to changes in the thermal performance of the polyiso insulation as it ages. This chart also indicates that typically there is more heat flow inward through the black roofs than through the other assemblies due to the more extreme temperatures experienced on the surface of these roofs.

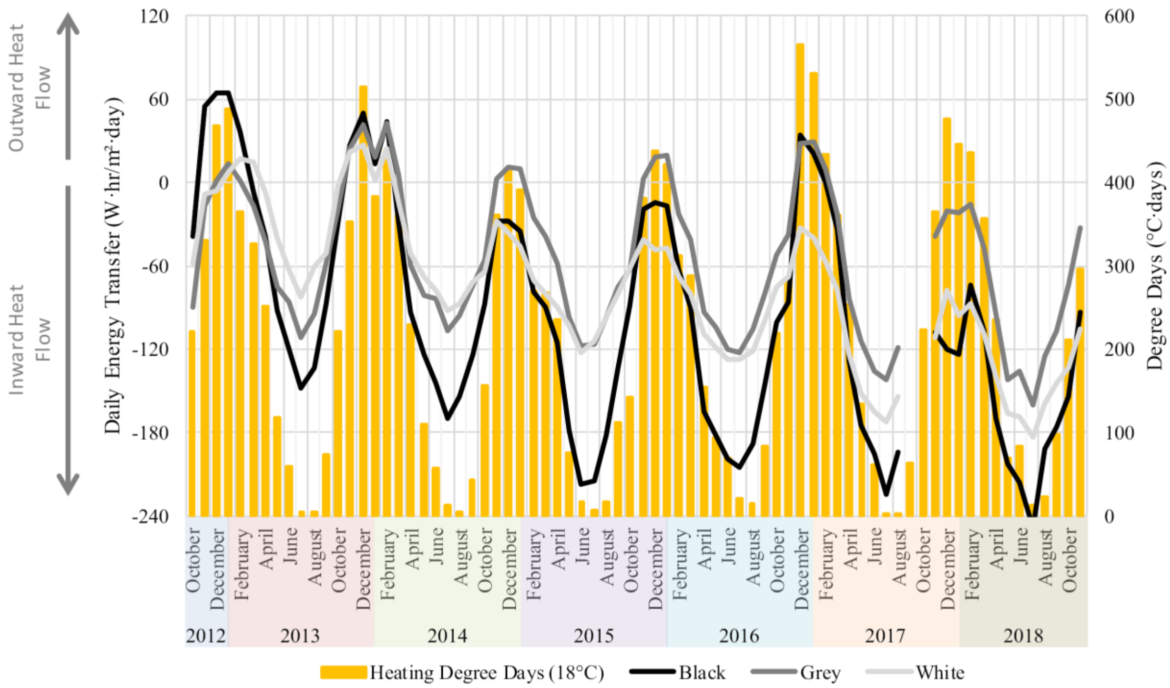

Figure 9 - Graph of monthly average daily energy transfer by roof membrane color.

Another method for assessing the potential energy implications of different roof membrane colors is to use roof surface temperatures to calculate cooling degree days (CDD) and heating degree days (HDD), similar to the values calculated using ambient exterior air temperatures. HDD and CDD provided in this report are calculated with a base temperature of 18°C and 10°C (64°F and 50°F), respectively. The comparisons were made between degree days calculated using ambient temperature and roof surface temperature. The roof surface temperature used to determine degree days for each membrane color are averaged for the different insulation arrangements with the same roof membrane colors. HDD and CDD calculated using the roof surface (sol-air) temperature instead of ambient (exterior air) temperature allows for a more accurate indication of heat flows through the assemblies. Note that CDD are presented as negative values in this report.

Figure 10 shows reduced HDD for the black roof membrane due to increased solar heat gain when compared to the grey or the white roof membrane. Similarly, the lower reflectance of the black roof membrane results in a significantly increased CDD (heat flow into roof assembly) as shown in Figure 11. This finding clearly illustrates that energy modelling of buildings based on ambient air temperatures with a lack of accounting for solar absorption on surfaces such as roofs can create significant inaccuracy in the result. In particular, the balance between heating and cooling demand for a building can be significantly altered by roof color.

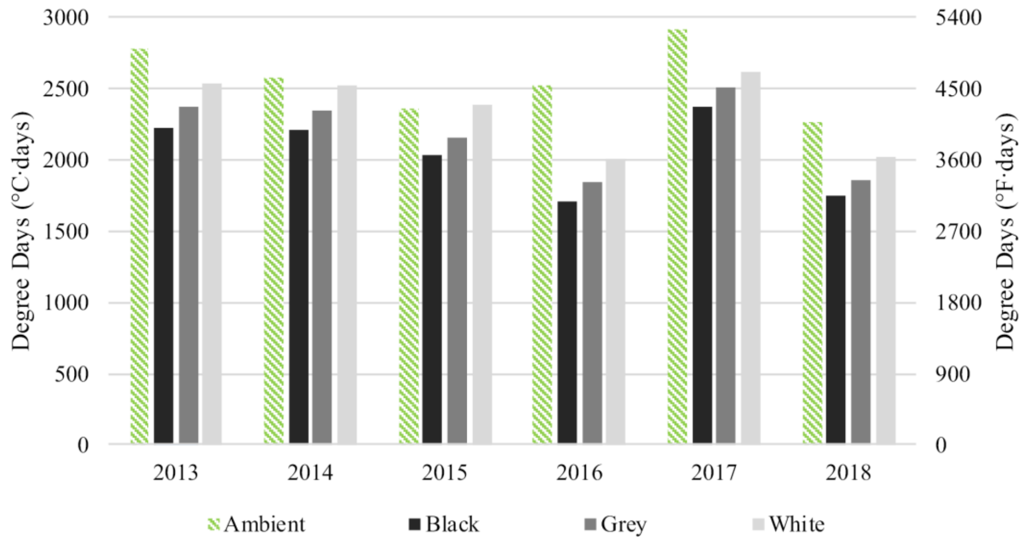

Figure 10 - Annual HDD from 2013 to 2018 based on membrane cap sheet color.

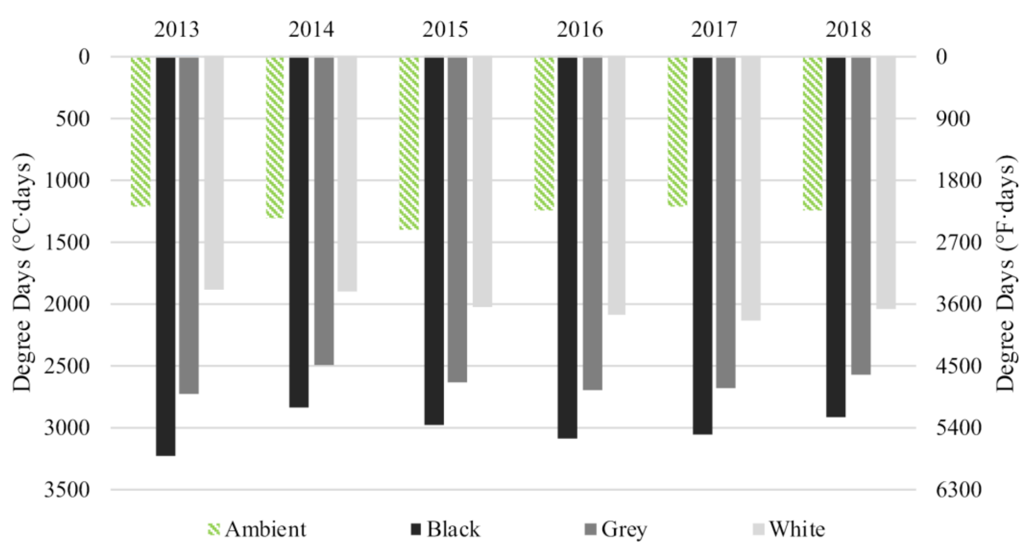

Figure 11 - Annual CDD from 2013 to 2018 based on membrane cap sheet color.

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.

The thermal performance of the three insulation arrangements varies with temperature. Polyiso insulation in particular exhibits strongly temperature dependent conductivity, generally leading to reduce thermal resistance at lower temperatures (Dell & Finch, 2013). Additionally, ageing of polyiso has also been shown to reduce its thermal resistance as blowing-agents are off-gassed from the cells of the foam plastic insulation (Finch, 2010; Dell & Finch, 2013; BSC, 2013). It should be noted that the polyiso insulation used in these roofs was manufactured before more recent advancements in the blowing agents used to manufacture these products, and thus more modern polyiso products are likely to exhibit a different response.

The plot provided in Figure 12 shows monthly average membrane temperature by insulation arrangements, and the dots indicate the maximum and the minimum temperature that the membrane experienced each month. The values provided for each insulation arrangement are the average of the different roof membrane colors for the similar insulation arrangements. (i.e. “ISO” is the average of polyiso only roof assemblies with black, grey, and white roof membrane cap sheet).

While the impact of insulation arrangement on the roof membrane temperature is less significant than the membrane color, insulation arrangement does influence the roof membrane temperature and the most significant impact is observed in the maximum monthly temperatures. Generally, the hybrid insulation arrangement had the lowest maximum temperatures throughout the year followed by stone wool. The polyiso insulated roofs have the highest maximum membrane temperatures. The minimum membrane temperatures are similar for the different roof types, but typically the polyiso insulated roofs also experience the coldest temperatures.

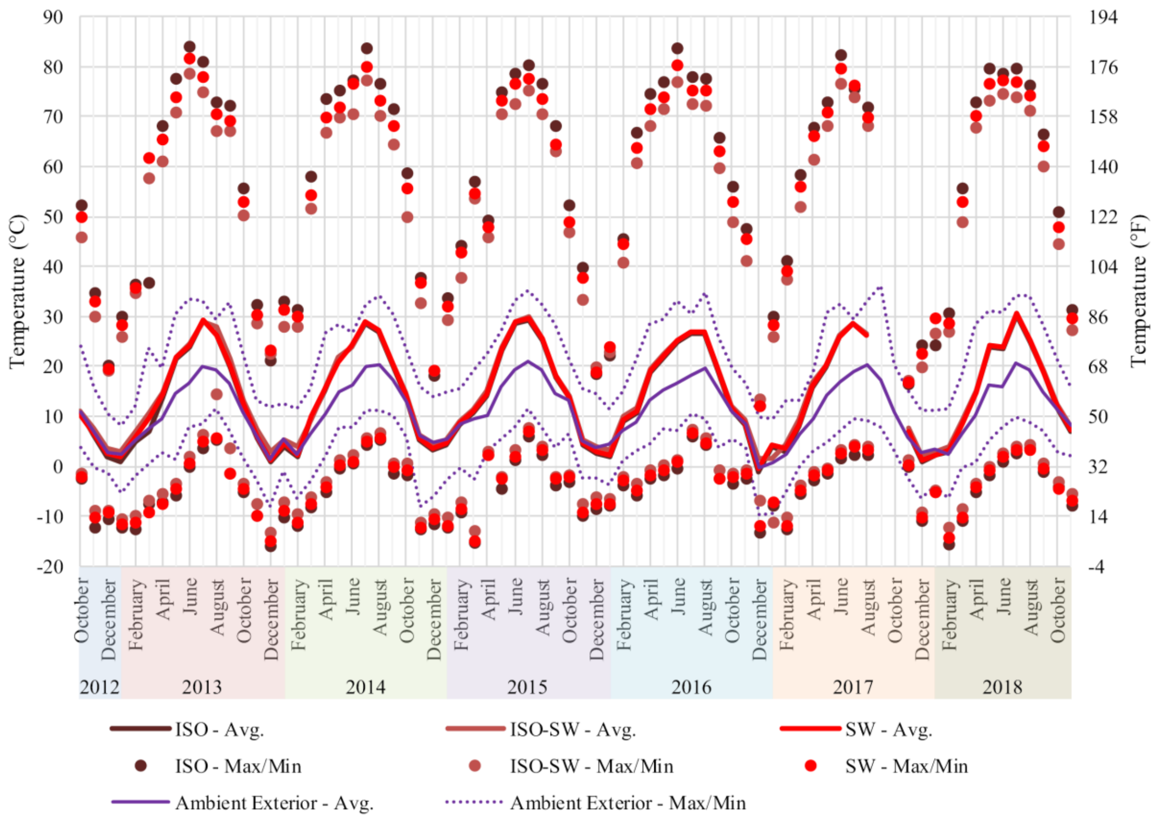

Figure 12 - Graph of monthly average membrane temperatures and maximum/minimum membrane temperature for each month by insulation arrangement. Note that the ISO average line is positioned directly behind the red ISO-SW average.

Daily roof membrane temperatures also 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 as compared to the hybrid roof and the stone wool roofs likely due to the combination of a difference in thermal mass (heat capacity) of the insulation types, latent energy transfer within the insulation, and the influence of temperature dependent R-values of the insulation. These reduced maximum and minimum temperatures in the hybrid and the stone wool roofs are consistent with previous findings (Finch, Dell & Ricketts, 2014) and will likely have a positive impact on the durability and service life of the roof membrane and insulation itself (the rate of deterioration of asphalts is temperature dependant – lowering the surface temperature of the membrane will extend its performance life).

To further assess the impact of insulation arrangement on the heat flow through the assemblies, Figure 13 plots the inward and outward heat flow through the different insulation arrangements, averaged for each month during the monitoring period. 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; while the stone wool arrangement also indicates some increase, 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 is consistent with previous findings (Finch, 2010; Dell & Finch, 2013; BSC, 2013).

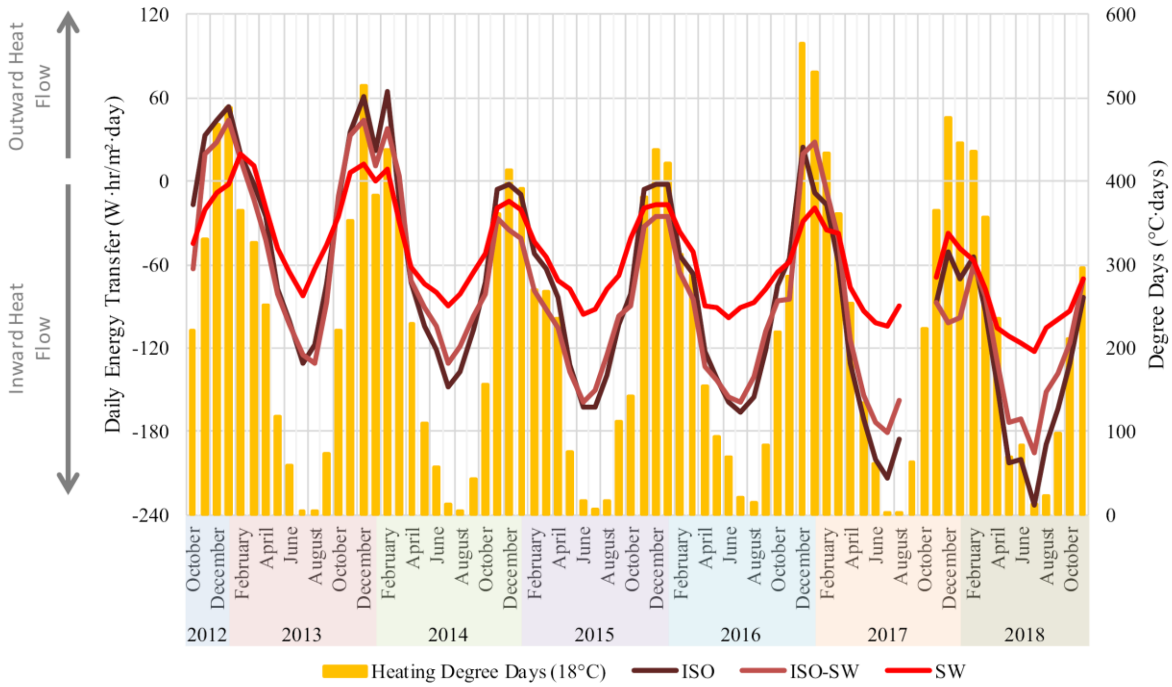

Figure 13 - Graph of monthly average daily energy transfer by insulation arrangement.

Similar to the analysis of energy implication due to membrane color, the impact of insulation arrangements was assessed by calculating degree days. HDD and CDD were calculated using roof surface temperatures with the same values calculated using ambient exterior air temperatures, as is standard practice. The roof surface temperature used to determine degree days for each membrane color are averaged for the same insulation arrangements with the different roof membrane colors. HDD and CDD calculated using the roof surface temperature instead of ambient exterior air temperature allows for a more accurate indication of heat flows through the assemblies. Again, note that CDD are presented as negative values in this report.

Figure 14 shows reduced HDD for the hybrid insulation roof when compared to the polyiso and stone wool roof assemblies. Naturally, HDD calculated using roof membrane temperature has a strong correlation to daily minimum roof membrane temperature experienced by each insulation arrangements. Roof membrane with polyiso insulation experienced the coldest minimums while those with hybrid insulation experienced the warmest minimums, and these are reflected on the annual HDD with coldest roof having the most HDD. The same but opposite correlation between CDD and daily maximum roof membrane does not seem to apply to annual CDD provided in Figure 15. The figure shows slightly increased CDD for the hybrid and stone wool-only roofs while the polyiso-only roof, which experienced the highest of the daily maximum temperatures, had the least

CDD. These differences in annual HDD and CDD between the insulation arrangement is likely due to combination of thermal mass and latent heat transfer. Additionally, while there is no significant difference in the cooling degree days by insulation arrangements, this finding clearly illustrates that energy modelling of buildings based on ambient air temperatures with a lack of accounting for solar absorption on surfaces such as roofs can create significant inaccuracy in the result.

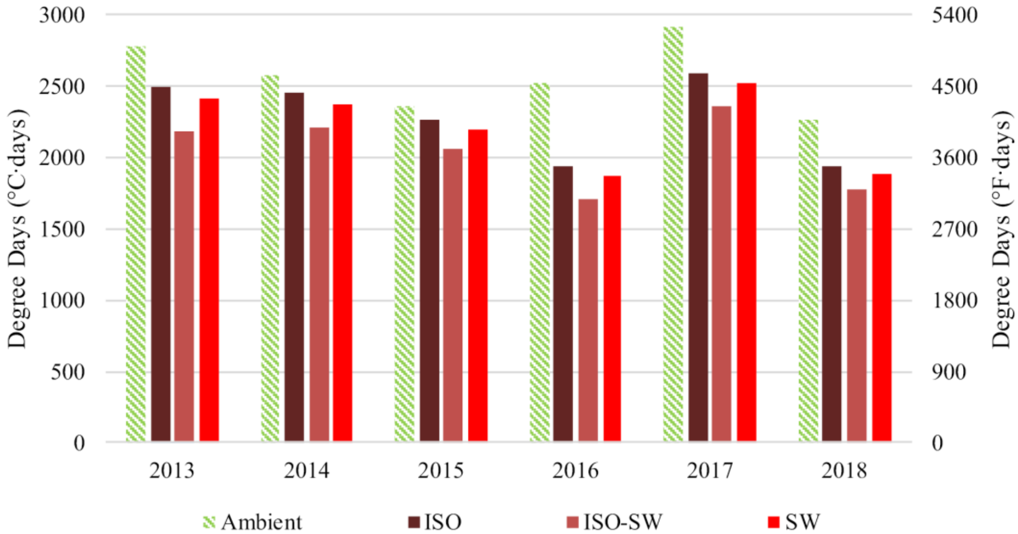

Figure 14 - Annual HDD from 2013 to 2018 based on insulation arrangement.

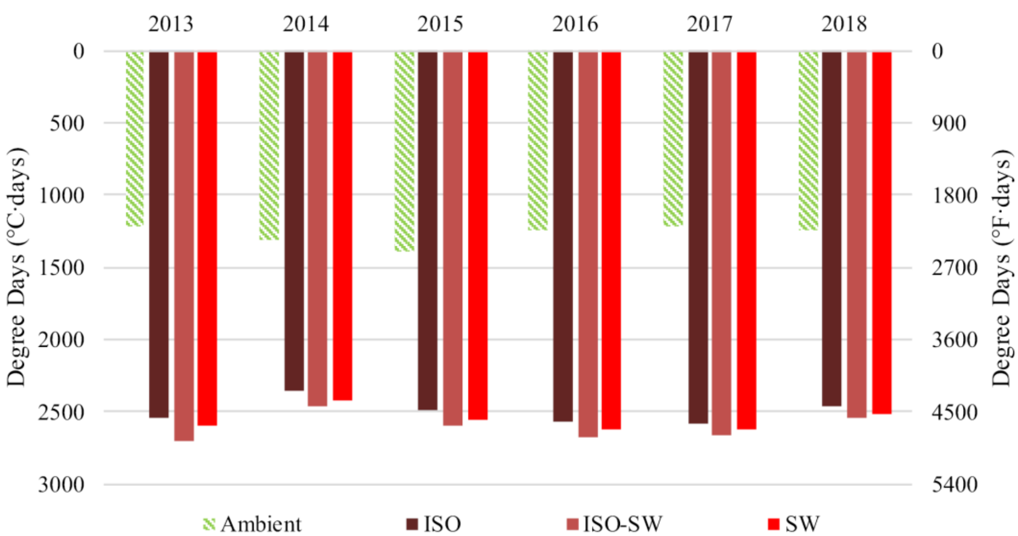

Figure 15 - Annual CDD from 2013 to 2018 based on insulation arrangement.

MOISTURE MOVEMENT IN ROOF ASSEMBLIES

Moisture movement within a roof assembly impacts the heat transfer by carrying latent energy with it as it moves within the insulation layers. The relative humidity levels below the insulation (i.e., on top of the air/vapor barrier) over the course of the six-year monitoring period are provided in Figure 16 by insulation arrangement. The values provided for each insulation arrangement are averaged across different roof membrane colors for the similar insulation arrangements.

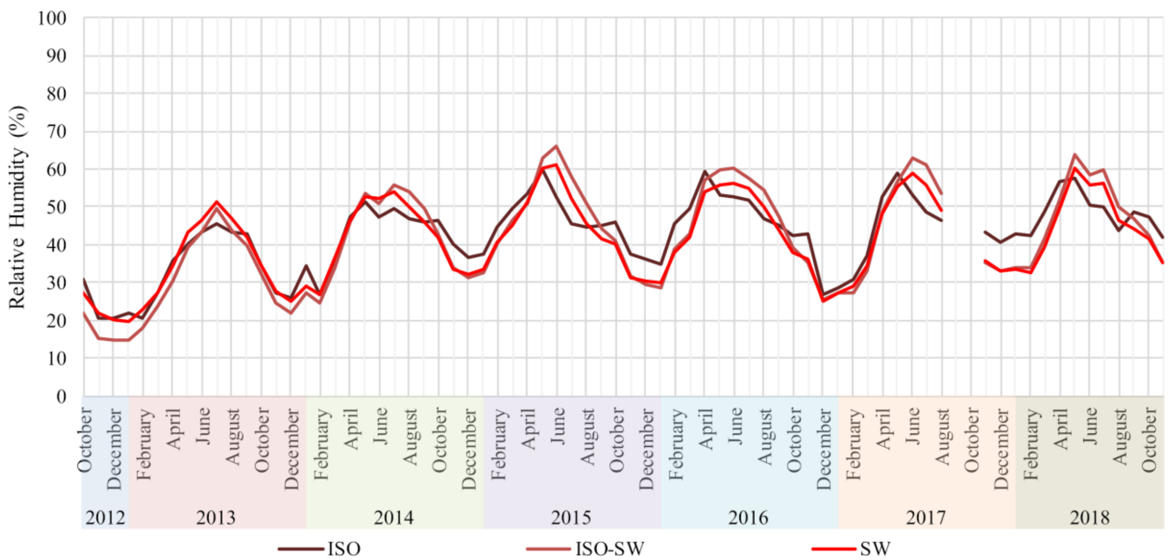

Figure 16 - Monthly average relative humidity levels below the insulation for each insulation arrangement.

Figure 16 shows monthly average relative humidity levels at the bottom of the assembly below insulation (i.e., on top of the air/vapor barrier) for each insulation arrangement. The figure indicates that there is a seasonal trend in the moisture levels within the assembly at these locations. The seasonal trend is a result of change in the predominant direction of the seasonal vapor drive. During the summer, the top of the insulation is being heated, driving vapor towards the bottom of the insulation where relative humidity sensors are located. The vapor drive is reversed during the winter.

The trend in average relative humidity throughout the monitoring period 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, then appears to stabilize from 2015 onward. This finding likely indicates that it took the roof assemblies approximately three years to reach equilibrium conditions based on the climate to which they are exposed and the initial conditions of the materials of which they were constructed (care was taken to ensure no precipitation entered the roof assemblies during construction).

Figure 17 and Figure 18 plot the relative humidity levels below the insulation layers for different insulation arrangements during sample periods of 48-hours in summer and winter.

The daily movement of vapor is more apparent with the stone wool insulation arrangement because stone wool is more vapor permeable, whereas polyiso is relatively impermeable and consequently restricts the movement of moisture within the insulation. Vapor is driven from the warmer side of the insulation towards the cooler side and the direction of vapor movement reverses from day to night. The vapor drive is most significant during sunny and hot days in the summer.

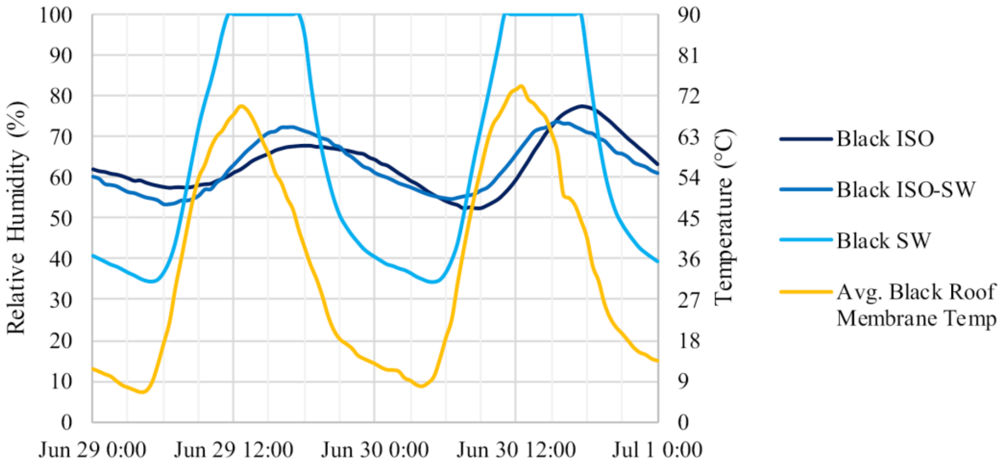

Figure 17 - Sample daily relative humidity levels for different insulation arrangements in Summer 2017.

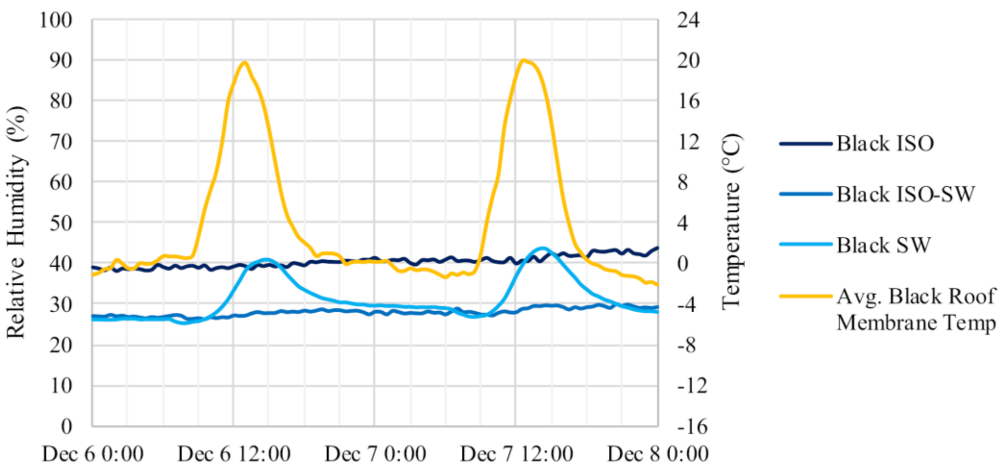

Figure 18 - Sample daily relative humidity levels for different insulation arrangements in Winter 2017.

Exploratory openings and moisture content field measurements in the fall of 2019 showed that the roof insulation for all assemblies was generally dry and no liquid water was observed. The results of field exploratory openings will be further discussed in subsequent papers.

DISCUSSION AND CONCLUSIONS

Long term monitoring studies offer unique opportunities to expand our understanding of the performance of building enclosure materials and assemblies. The field monitoring data acquired over the last six years provides insight into the different performance of conventional roof assemblies depending on insulation arrangement and roof membrane color.

The in-service reflectance of roofs was measured for grey and white (high and low point) roof membranes in two locations. Measurements over the six-year period generally did not confirm preliminary findings from the first three years of monitoring. It was initially assumed that the decreased 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 initial installation levels from 2012. Because the sensors were prone to soiling in the field, samples of the installed roof membrane have been removed and are scheduled to be tested for their reflectance in a controlled lab setting to accurately measure degradation intensity after a six-year period. Results from the lab testing will be included in a separate paper. However, a preliminary visual comparison of grey and white roof membranes from 2012 and 2019 show that the aged membranes have darkened over time, largely due to degranulation.

The difference in performance between the roof membrane colors was examined using the field monitoring data acquired over the period. Consistent with previously reported results (Finch, Dell & Ricketts, 2014), roofs with higher solar reflectance were generally found to experience less extreme temperatures and slower changes in temperature. The impact of membrane color is greatest during sunny and warm periods, and consequently, the impact of the membrane color on cooling degree days was found to be much greater than on heating degree days (as expected), and 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 color membrane. However, this result is not applicable if the interior space is not air conditioned, as is the case for the building on which the monitoring was performed.

The relative performance of insulation arrangements was also evaluated. The monitored measurements reinforced previously reported findings with regards to factors affecting peak temperatures and temperature lag effects (Finch et al., 2014). The data showed a trend of increasing inward heat flow for all insulation arrangements over the course of the monitoring period and it is most significant with polyiso roof. 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 (Finch, 2010; Dell & Finch, 2013 and BSC, 2013).

For all three insulation arrangements, a slight overall annual increase in the relatively 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 greater than 100% are measured within the assemblies in some cases, potentially indicating the presence of liquid water. Exploratory openings and moisture content field measurements in the fall of 2019 showed that the roof insulation for all assemblies was generally dry and no liquid water was observed.

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