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Conventional Roofing Assemblies: Measuring the Thermal Benefits of Light to Dark Roof Membranes and Alternate Insulation Strategies

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Abstract

This is the latest publication concerning a large, multiyear conventional roofing study being performed by the authors. This paper builds off of the 2013 RCI Building Envelope Technology Symposium (Minneapolis 2013) publication, "Monitored Field Performance of Conventional Roofing Assemblies – Measuring the Benefits of Insulation Strategy" and applies the newer findings from this study to the wider North American audience. The 2013 publication focused on the differences in insulation performance, whereas this 2014 publication looks at both insulation and roof membrane color and utilizes calibrated energy modeling to look at the impact in different climate zones.

Speaker

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GRAHAM FINCH is a principal and research engineer with RDH Building Engineering Ltd. in Vancouver, BC. He has a passion for technology and for making better buildings. He leads RDH's building science research group and is actively involved in a wide range of projects from building research studies to forensic investigations, building monitoring, hygrothermal modeling, and new construction. Finch has helped develop numerous industry guideline documents related to durable building enclosures and roofing and energy use in buildings. In addition, he is a part-time instructor at the British Columbia Institute of Technology, where he teaches building science courses at the undergraduate and masters' levels.

Conventional Roofing Assemblies: Measuring the Thermal Benefits of Light to Dark Roof Membranes and Alternate Insulation Strategies

ABSTRACT

A field monitoring study was implemented to measure the impacts and benefits of membrane color (white, gray, and black) and insulation strategy on the performance of conventional roofing assemblies. The same roof membrane cap sheet type with three different surface granule colors was placed over three different conventional insulation strategies, creating a total of nine unique roofing assemblies (each 16 squares, 1,600 sq. ft. [150 m^2] in size) on the same building. The thicknesses of the different insulation products were varied to achieve approximately the same R-value for each of the nine roof assemblies. Sensors were installed to measure temperature, relative humidity, moisture content, and heat flux at various points within each of the roof assemblies. Displacement sensors were also installed within the insulation boards to measure the dimensional stability of the different insulation products, and solar radiation sensors were installed above the cap sheet to document the long-term reflectivity and soiling of the roofing membranes. In conjunction with the sensors, webcam photos were captured to study the impact of night sky cooling, wetting/frost, and other differences among the assemblies. To complement the field study, supplemental laboratory testing of the insulation products was performed to measure the installed insulation R-values, and whole-building energy simulations were performed to apply the calibrated results from the study to other building types and climate zones across North America.

Presented in this paper are findings from the study that highlight the impact of both roof membrane color and insulation strategy on the thermal behavior and energy gains/losses through conventional roofing assemblies. Whole-building energy modeling is used to synthesize the study findings and demonstrate how whole-building heating and cooling energy consumption is affected by different roof membrane colors and insulation types/strategies within North American climate zones.

BACKGROUND

Exposed membrane roofs (i.e., roofs with exposed roofing membrane on top of the roof insulation and structure—also called conventional roofs) make up the majority of low-slope roofing assemblies in North America. Membrane colors from dark to light are chosen based on product availability, aesthetics, building type/use, energy efficiency, and standard practices, which vary from southern to northern latitudes. Lighter, more-reflective membrane colors or finishes (high solar reflectivity index [SRI]) are common in the southern U.S. where required by energy code (ASHRAE 90.1); though with Leadership in Energy and Environmental Design® (LEED®) projects and some other energy-rating programs, light- or white-colored roofs are often used regardless of geography. In northern climates, the benefit of using white membrane roofs to achieve cooling savings is often small and can be offset by higher wintertime heating loads (DOE Cool Roof Calculator, 2013; Roof Savings Calculator, 2013; Smith, 2001).

The thermal insulation used within new conventional roofing assemblies typically consists of rigid polyisocyanurate (varying from <R-5 to R-6/inch), expanded polystyrene (EPS, R-4 to R-4.5/inch), or rigid stone wool[1] (R-3.7 to R-4.3/inch). (The R-value of insulation products varies depending on age, density, moisture content, etc.; and some variation can even exist among batches of the same product.) Wood fiberboard, rigid fiberglass, extruded polystyrene (XPS), and spray polyurethane foam insulations are also used in some applications, but these additional insulation types are less common in new conventional roofs. It is also common to use a combination of insulation layers within conventional roofs, thus blending the positive attributes of each insulation type in "hybrid systems."

An example of a hybrid system would be using polyisocyanurate over tapered EPS or the use of rigid stone wool over polyisocyanurate as investigated in this research. In this hybrid system, the stone wool is used on top of the polyisocyanurate, as it is generally more dimensionally stable than polyisocyanurate (diurnal movement and long-term shrinkage), which reduces exposed membrane stresses and keeps the lower polyisocyanurate insulation layer within a tighter temperature range, closer to the interior temperature (depending on the ratio of outboard insulation to polyisocyanurate insulation). This also results in conditions that optimize the apparent R-value of the polyisocyanurate insulation as covered later within this paper.

The research study investigates the thermal differences and net heat flux through conventional roof assemblies utilizing light- to dark-colored (low to high solar absorptivity) roof membranes in conjunction with different insulation material combinations, including polyisocyanurate and stone wool. It then extends these findings using whole-building energy modeling to demonstrate how building energy consumption is affected by these roof characteristics.

FIELD MONITORING PROGRAM AND STUDY BUILDING

A large-scale field monitoring study was implemented in the Lower Mainland of British Columbia with the intent of measuring the impacts and benefits of roof membrane color and insulation strategy on the long-term thermal and hygrothermal behavior and performance of conventional roofing assemblies.

The roofing variables consist of three different 2-ply SBS membrane cap sheet colors placed over three different conventional insulation strategies (polyisocyanurate, stone wool, and a hybrid combination of both), creating a total of nine unique roofing assemblies (each 16 squares, 1,600 sq. ft. [150 m^2] in size) on the same building. The thicknesses of the insulation combinations were varied to achieve approximately the same total effective R-value in each assembly.

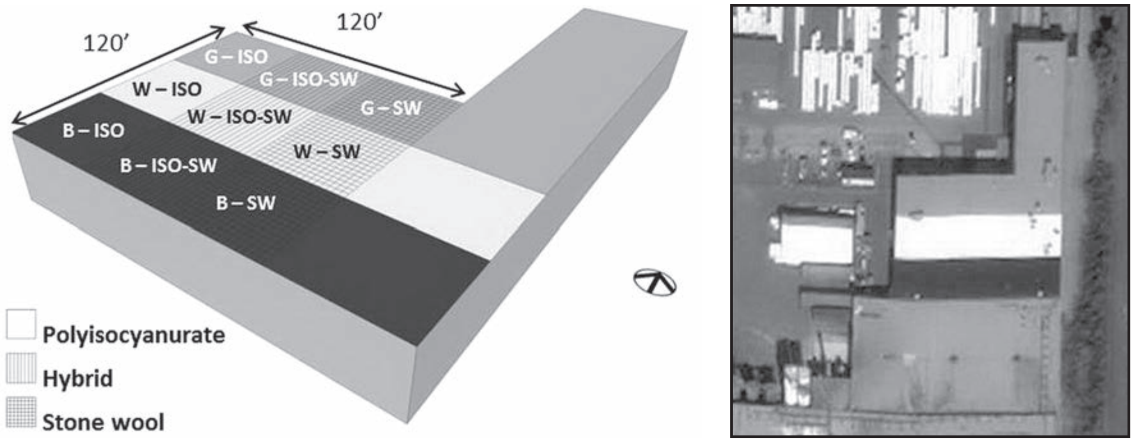


Figure 1 – Study building and layout of roof membrane cap sheet color and insulation strategy.

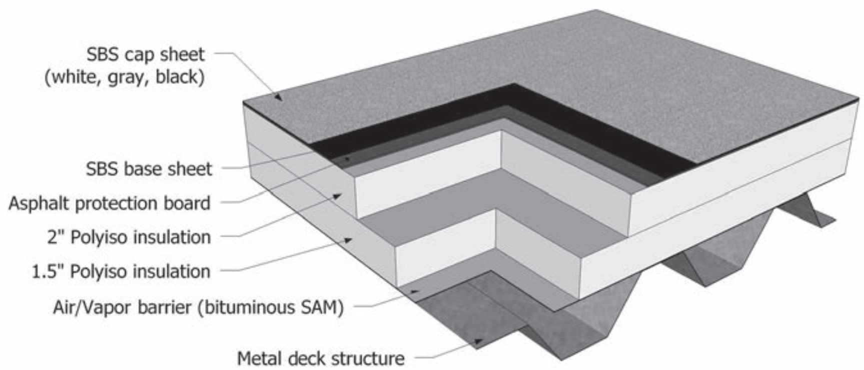


Figure 2 – Polyisocyanurate roof assembly (3.5 in., R-21.5); weight: 4.6 kg/m², heat capacity: 6.75 kJ/K/m².

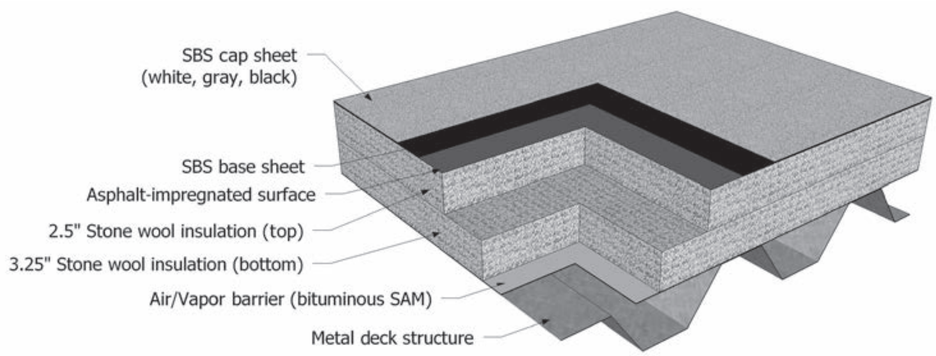


Figure 3 – Stone wool roof assembly (5.75 in. stone wool, R-21.4); weight: 26.7 kg/m², heat capacity: 22.7 kJ/K/m².

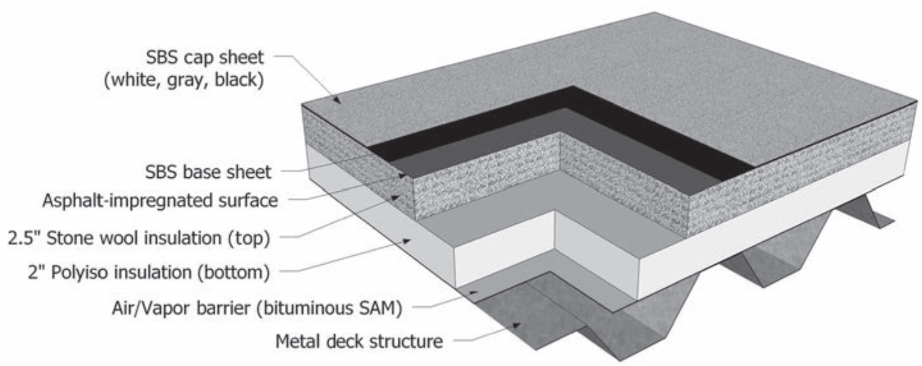


Figure 4 – Hybrid roof assembly (2.5 in. stone wool over 2-in. polyisocyanurate, R-21.3); weight: 14.3 kg/m², heat capacity: 13.7 kJ/K/m².

Sensors were installed within each of the nine roof assemblies to measure material temperatures, relative humidity, moisture content, heat flux, and dimensional stability of the insulation. Reflected solar radiation from the roof cap sheets was measured using solar radiation sensors (pyranometers) pointed downwards toward the roof surface, and direct solar radiation was measured with a solar radiation sensor as part of the weather station used to measure exterior conditions. In addition, a camera was set up to automatically capture photos of the roof surfaces to study the impact of night sky cooling, wetting/frost, and soiling of the white membrane. Finally, the apparent R-values of the insulation products were measured in a laboratory to allow for comparison with the in-situ values calculated using the embedded heat flux and temperature sensors. Further information about the monitoring equipment and sensors can be found within a previous paper by Dell and Finch, presented at the 2013 RCI Building Envelope Technology Symposium and within the full report (RDH 2013).

The study structure is an industrial building located in Chilliwack within the Lower Mainland of British Columbia, Canada. The climate of Chilliwack is similar to the larger metropolis of Vancouver; though, as it is farther inland, it gets hotter in the summer and colder in the winter. The average annual temperature at the Chilliwack airport, located approximately 1 km (0.6 miles) from the site, is 10.5°C (50.9°F), with the average July temperature of 18.5°C (65.3°F) and January temperature of 2.2°C (36.0°F) (Environment Canada 2013).

The building was selected because it provided a single, large, uninterrupted test area for the roof monitoring; the construction schedule coincided with the research study; and the building owners were willing to have a number of different roof assemblies installed on their building. Prior monitoring of an adjacent building housing similar industrial equipment ascertained that the interior conditions in the new building would be on average between 20°C (68°F) and 25°C (77°F) year-round. A sketch

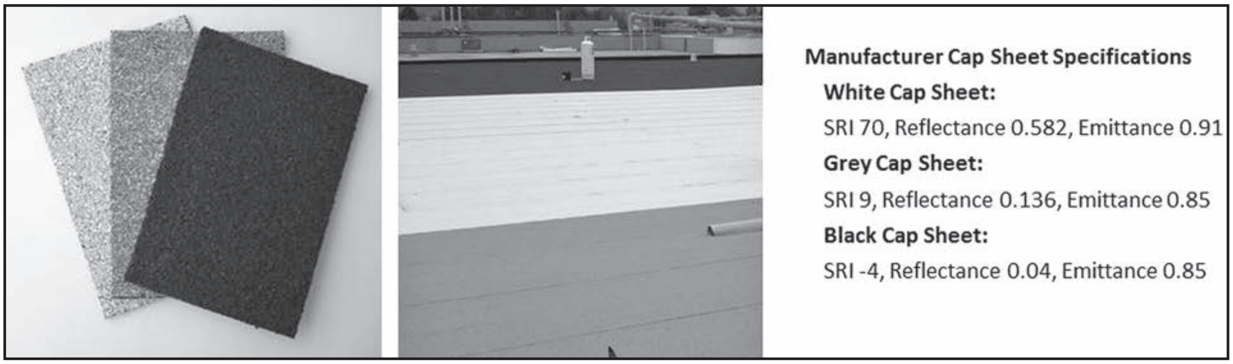


Figure 5 – Membrane cap sheet colors (white, gray, and black) shown on left in lab (unsoiled and new) and shown on right in field shortly after installation.

of the building showing the three different membrane colors and three insulation combinations, as discussed in the following section, is presented in *Figure 1*.

As shown, a total of nine unique roof assemblies, each 40 x 40 ft. in area (16 squares, 1,600 sq. ft. [150 m^2]) were constructed and monitored at the west part of the building. The adjacent section of the roof along the east side is insulated with stone wool but is not monitored or included within the study.

ROOF ASSEMBLIES AND INSULATION R-VALUES

Each roof assembly consists of a 2-ply, torch-on SBS cap (white, gray, or black) and base sheet over asphalt protection board (only over polyisocyanurate), insulation layers (as indicated), reinforced air/vapor barrier membrane, and metal Q-deck over open-web steel joists. The air/vapor barrier membrane spans between the metal deck flutes and has been designed and tested by the manufacturer to do so without sagging in this application. The use of a continuous rigid gypsum board over the deck flutes with standard self-adhered membrane is generally more common in this application.

The asphalt protection board (where used) and insulation layers are structurally adhered together and to the air/vapor barrier membrane using a low-rise, two-part urethane adhesive, negating the need for mechanical fasteners in the assembly and associated perforations in the air barrier membrane. The top surface of the stone wool insulation contains an integral asphalt-impregnated surface and does not require an additional overlay protection board.

The three SBS cap sheet colors include standard black, gray, and white (LEED®-compliant SRI cap). The thickness of each insulation combination was varied to achieve approximately the same design R-value of R-21.5 (at standard test conditions of 23.9°C [75°F]). Samples of insulation were taken from the site for laboratory testing (covered later in this paper). These three insulation combinations are shown in *Figures 2* through *4*, along with the apparent R-value of the insulation, insulation weight, and total insulation heat capacity. *Figure 5* shows the membrane cap sheet colors. The solar reflective index (SRI), reflectance, and emittance as specified by the manufacturer are also listed for each cap sheet type. The insulation thickness transitions (3.5 in., 5.75 in., and 4.5 in.) between the three different insulation strategies were made using a few feet of tapered insulation, well away from sensors and monitoring equipment.

In conjunction with the field-monitoring program, ASTM C518 laboratory material testing of the thermal resistance of polyisocyanurate and stone wool insulation was undertaken on representative batch samples of the products installed within the test roofs and some additional polyisocyanurate products that were aged for four years. These data are used to support the field monitoring data and demonstrate that while the total effective R-value for each assembly is between R-21.3 and R-21.5, the apparent[2] R-value for each case will vary depending on the in-service conditions.

As previously published from this study (Dell and Finch, 2013), *Figure 6* presents the apparent R-value per inch as determined by ASTM C518 testing from six polyisocyanurate and three rigid stone wool samples used in this study. These samples were removed from the site and were two months old at time of testing. The results for the minimum, maximum, and average of the six polyisocyanurate samples are provided to indicate the range of performance. In addition, results from a four-year-old sample of the same brand of polyisocyanurate are shown for comparison. The results agree well with published data for stone wool and polyisocyanurate data from the National Roofing Contractors Association (Graham 2010, NRCA 2011) and Building Science Corporation (BSC 2013a), which have also found a strong relationship between polyisocyanurate insulation temperature, age, and its apparent R-value.

These laboratory measurements of the apparent R-value/inch for each insulation

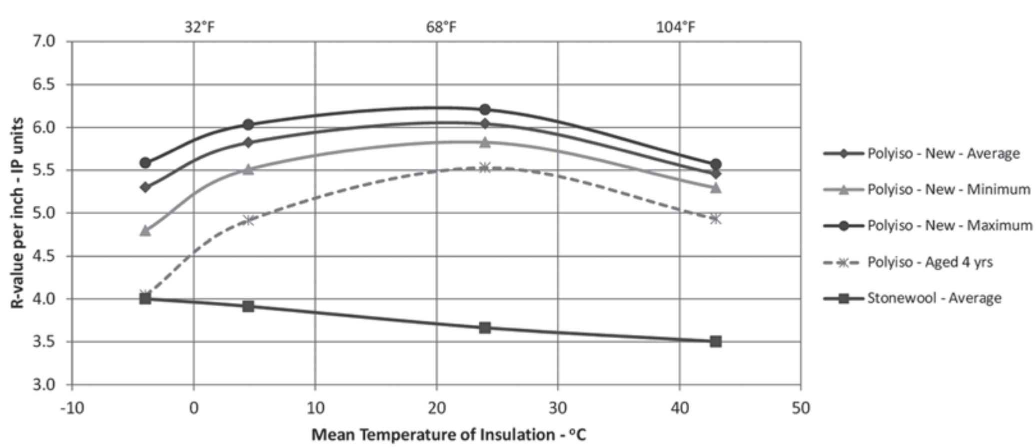


Figure 6 – Apparent R-value per inch vs. mean temperature for polyisocyanurate and stone wool insulation (Dell and Finch, 2013)

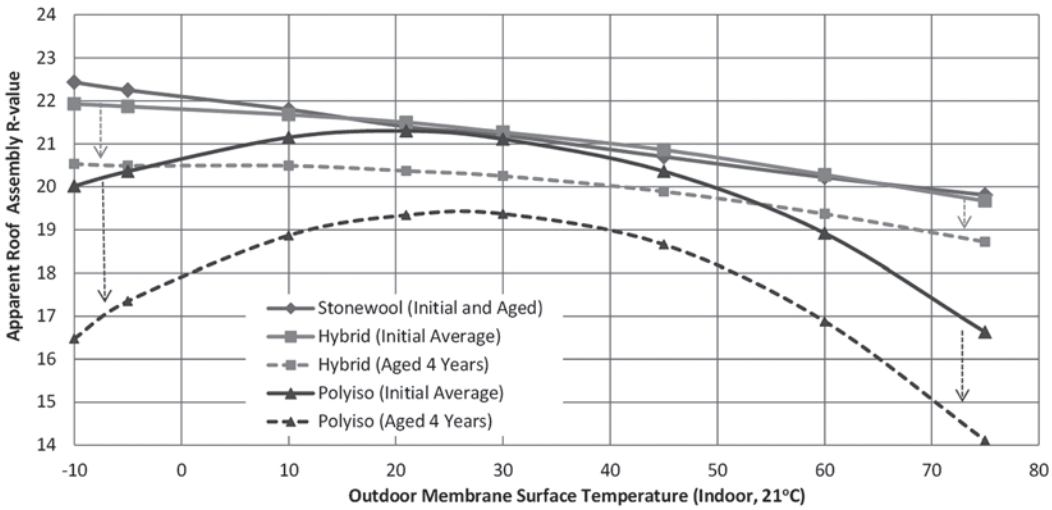


Figure 7 – Apparent R-values of study building roof assemblies based on roof membrane surface temperature over a range of -10°C to 75°C (14°F to 167°F) (Dell and Finch, 2013).

product were then applied to the three roofing assemblies from this study to determine the apparent R-value of the roof assemblies:

- Stone wool (5.75 in. [146 mm] stone wool, R-21.4)
- Hybrid (2.5 in. (64 mm) stone wool over 2 in. [51 mm] polyisocyanurate, R-21.5)
- Polyisocyanurate (3.5 in. [89 mm] polyisocyanurate, R-21.3)

Figure 7 provides apparent R-values for each assembly based only on the roof membrane surface temperature and a typical indoor condition of 21°C (70°F) as originally published by Dell and Finch (2013). The impact of long-term polyisocyanurate aging is predicted with the matching color dashed lines for both the hybrid and polyisocyanurate assemblies. This plot demonstrates the sensitivity of the apparent R-value of the different roof assemblies when exposed to either extreme cold or hot outdoor temperatures.

The roof assembly constructed polyisocyanurate may have a calculated effective R-value of R-21.3, but when exposed to cold (-10°C [14°F]) would drop to R-20 or potentially as low as R-16.5, depending on aging effects; and when exposed to hot temperatures (75°C [167°F] membrane surface temperature) would drop to R-16.5 or potentially as low as R-14.0, depending on aging effects. In the hybrid assembly, the use of a layer of stone wool insulation (in this case, equivalent to approximately 45% of the assembly R-value) over top of the polyisocyanurate significantly improves the effective R-value of the polyisocyanurate as it keeps it near optimum temperatures (which are similar to typical interior temperatures) and, therefore, results in a better assembly R-value in cold and hot conditions. The roof assembly insulated with entirely stone wool insulation will have a more stable R-value (increasing at colder temperatures but decreasing at hot temperatures from calculated R-value) but is not susceptible to a loss of R-value with age.

FIELD-MONITORING RESULTS OF HEAT FLOW AND THERMAL BEHAVIOR

This paper presents selected results for the first year of the field-monitoring program with a focus on the differences in thermal behavior among the different insulation strategies and membrane colors. To compare the insulation assemblies, the measured heat flux data, along with cap surface temperature and interior surface temperatures, are compared for each assembly. Of interest are key behavioral differences between the polyisocyanurate and stone wool due to varying apparent R-value and different heat capacities in conjunction with roof membrane color.

Measured heat flux data compare the hourly transfer of heat energy across each assembly from interior to exterior. A positive value indicates that heat flow is upwards (i.e., when the interior is warmer than the exterior membrane surface temperature), and a negative value indicates that heat flow is inwards (i.e., membrane heated above interior temperature by solar radiation).

Based on the monitoring to date, we have found large differences in heat flux and the interior and exterior surface temperatures due to light to dark membrane color, as would be expected. Significant differences in the heat flux and interior and exterior surface temperatures were found, depending on the insulation strategy. This finding is unique to this study. An apparent thermal lag is observed within the stone wool insulation and hybrid insulation assemblies compared to the polyisocyanurate insulation. This finding presents as dampened heat flux measurements, reduced cap sheet surface temperatures, and lower interior surface temperatures, primarily when the roof is heated by the sun. At night, the differences among the assemblies are very small. This lag in temperatures can be beneficial from a thermal comfort and energy-efficiency standpoint, because it moderates peak temperatures well as energy losses and gains. The reduction in peak membrane temperature and in rate of membrane temperature change also likely reduces the rate of deterioration of the membrane. It is theorized that this thermal lag effect is primarily due to the difference in heat capacity between the two types of insulation (6.75 kJ/K/m^2 for polyisocyanurate, 13.7 kJ/K/m^2 for hybrid, and 22.7 kJ/K/m^2 for stone wool) and thus the difference in heat capacity of the three insulation arrangements. The temperature dependence of the polyisocyanurate thermal resistance (R-value) and latent energy transfer from moisture movement through the stone wool insulation may also be relevant factors.

Figures 8 and *9*[3] present the hourly heat flux measurements for four representative two-day seasonal periods during winter (average winter design condition), spring (cool), spring (warm), and summer (peak summer design condition). Average outdoor temperature and solar radiation for each period are provided in *Figure 10*. As expected, there is a large difference in the heat flux between the black and white cap membranes at peak conditions, but there are also significant differences between the polyisocyanurate and stone wool insulation arrangements. The heat flow through the stone wool compared to the polyisocyanurate in these cases is typically less and is offset by a few hours. (For reference, *Figure 10* presents the average outdoor temperature and solar intensity during each of the periods presented in *Figure 8* and *Figure 9*.)

Figure 10 presents the average daily energy transfer for the same four selected two-day periods from late winter, early spring, late spring, and summer. These periods were selected as data was complete and representative of typical conditions for this climate. Average exterior temperature and solar radiation intensity during those periods are summarized within the figure. This figure clearly illustrates the different performance of the roof assemblies. Differences are more dramatic during the warmer months when exposed to more solar radiation and indicate less heat flow through the stone wool assemblies than through the polyisocyanurate assemblies.

In summary, the lowest amount of inward heat flux occurs with the stone wool assemblies followed by the polyisocyanurate and then the hybrid insulation assemblies. The assemblies with a white cap sheet also typically had less inward heat flux than the black and gray roofs.

Roof membrane surface temperatures and interior metal deck surface temperatures are presented for selected days for the winter (Feb. 22), spring (May 9),

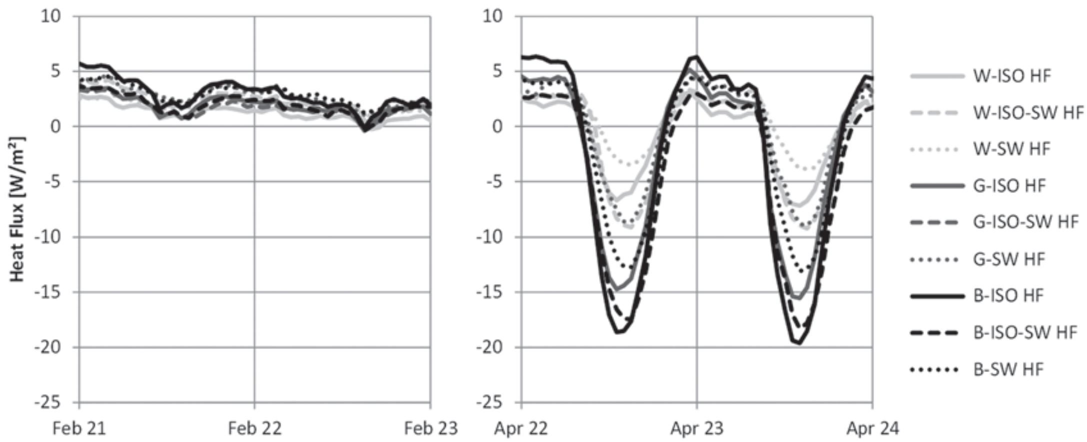


Figure 8 – Heat flux measurements through each roof assembly – February 21-23, 2013 (winter) and April 22-24, 2013 (spring cool). Note: G-ISO-SW data unavailable during April 22-24 period.

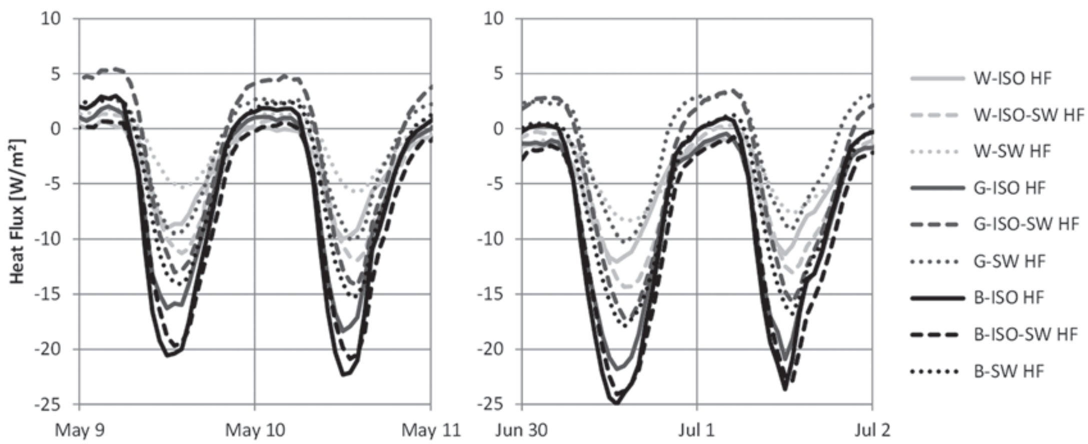
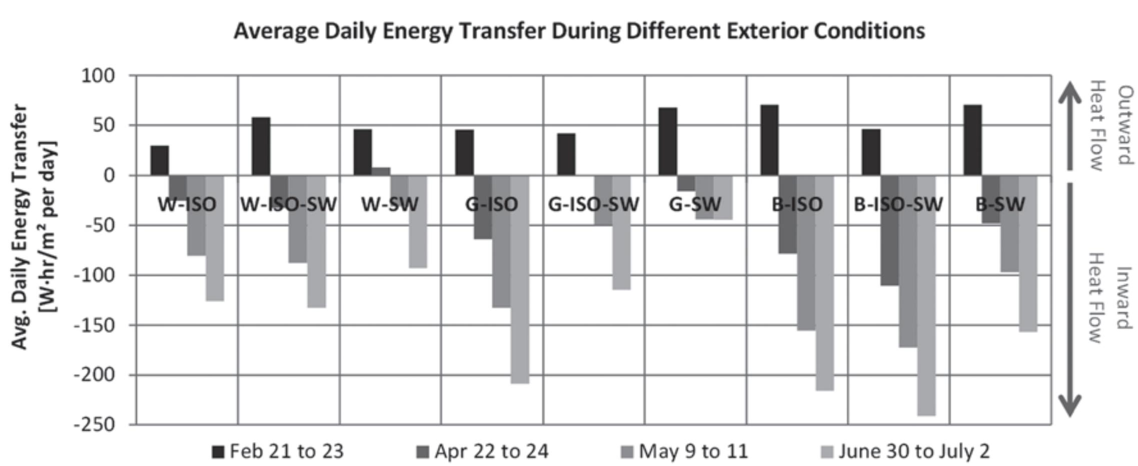


Figure 9 – Heat flux measurements through each roof assembly – May 9-11, 2013 (spring warm) and June 30 – July 2, 2013 (summer peak design). Note: Potential error offset with G-ISO-SW and G-SW heat flux data during time period.



	Average Outdoor Temperature	Average Solar Intensity (on horizontal roof all hours of day)
Feb 21-23	4.4°C (39.9°F)	27 W/m^2
Apr 22-24	11.3°C (52.3°F)	273 W/m^2
May 9-11	18.3°C (64.9°F)	289 W/m^2
June 30 – July 2	25.8°C (78.4°F)	331 W/m^2

Figure 10 – Heat flux measurements through each roof assembly – May 9-11, 2013 (spring warm) and June 30 – July 2, 2013 (summer peak design). Note: Data missing for G-ISO-SW for April 22-24 period and potentially inaccurate G-ISO and G-ISO-SW data for May 9-11 and June 30-July 2. White and black data for all three insulation materials are, however, accurate and representative of monitored conditions.

and summer (June 30) within *Figures 11* through *16*, respectively. These plots show the seasonal differences in membrane and interior surface temperatures from dark to light roofing and demonstrate the thermal lag among the stone wool, hybrid, and polyisocyanurate insulation strategies. These findings support the differences in measured heat flux as shown above. Note that variations in the deck temperature are partially influenced by the interior temperature; however, the deck temperature is also not the same as the indoor ambient temperature.

As shown by the summertime data, the use of stone wool insulation compared to polyisocyanurate reduces peak membrane surface temperatures, reduces the peak interior surface temperature, and shifts the peak temperatures by one to two hours later. This can be a potential benefit for both thermal comfort and cooling energy consumption. Data for spring conditions are similar to the summer but not as pronounced.

As demonstrated by the first set of wintertime data, the exterior surface of the polyisocyanurate insulation roof typically has the coldest temperatures (all colors), followed by the stone wool insulation and hybrid insulation assemblies. This indicates less heat loss through and higher apparent R-value of the polyisocyanurate insulation compared to the hybrid or stone wool under these conditions. The cause of this effect appears inconsistent with the determined apparent R-values, and it will be further investigated as additional monitoring data become available, as the polyisocyanurate ages, and as the roof membranes become soiled.

SELECTION OF ROOFING MEMBRANE COLOR AND INSULATION STRATEGY FOR OPTIMUM ENERGY EFFICIENCY

Whole-building energy modeling was performed to investigate the optimum roof membrane color (solar absorptivity) and insulation strategy for a conventional roof. Simulation runs were used to compare the same white, gray, and black roof membranes, and the polyisocyanurate, stone wool, and hybrid insulation strategies as used in the monitoring study. Energy modeling of these variables was performed using the U.S. Department of Energy (DOE) Building Energy Codes Program commercial

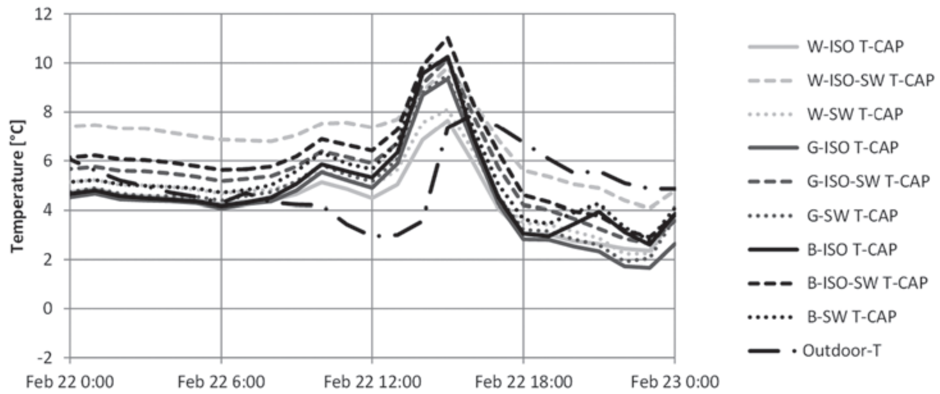


Figure 11 – Roof membrane cap sheet temperature for nine monitored roof assemblies – Feb. 22, 2013 (winter).

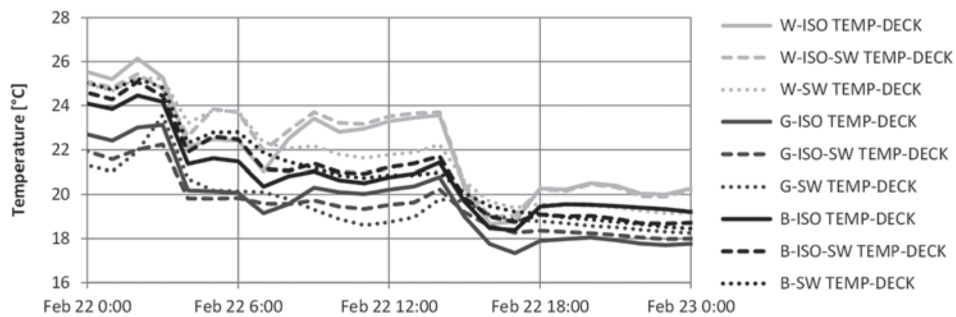


Figure 12 – Interior metal roof deck surface temperature for nine monitored roof assemblies – Feb. 22, 2013 (winter).

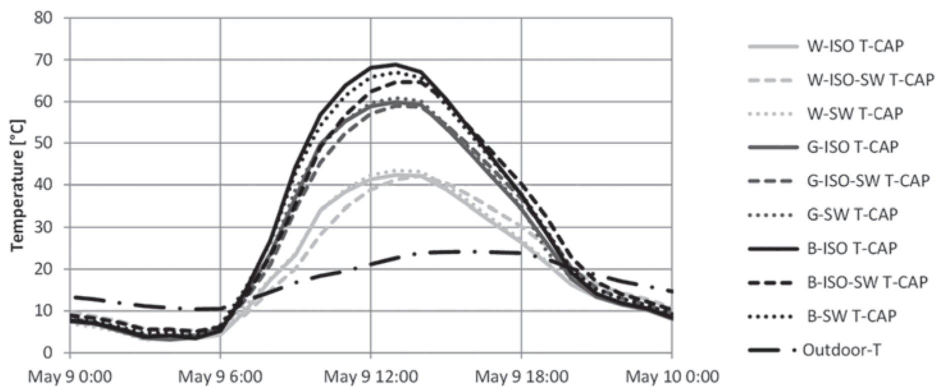


Figure 13 – Roof membrane cap sheet temperature for nine monitored roof assemblies – May 9, 2013 (spring).

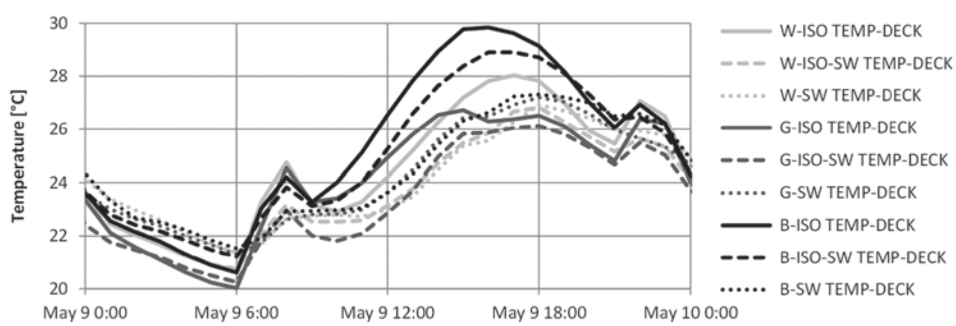


Figure 14 – Interior metal roof deck surface temperature for nine monitored roof assemblies – May 9, 2013 (spring).

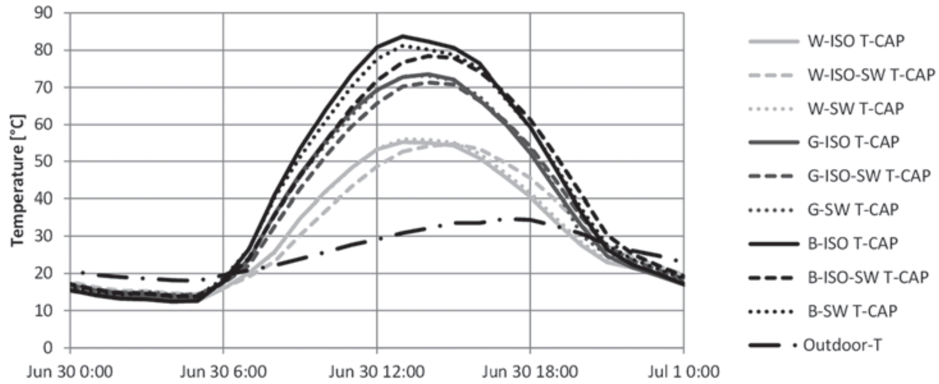


Figure 15 – Roof membrane cap sheet temperature for nine monitored roof assemblies – June 30, 2013 (summer).

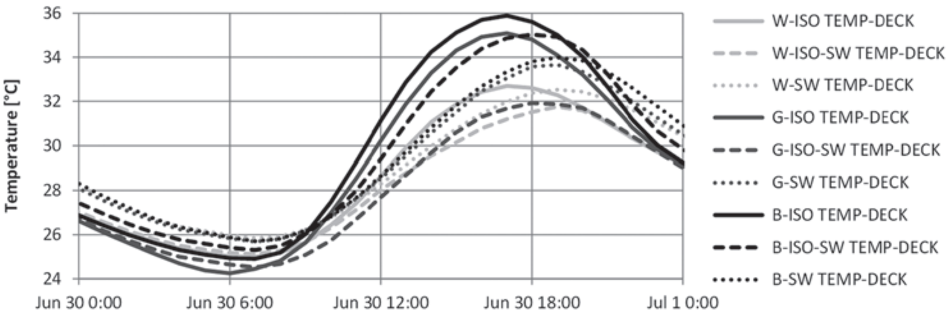


Figure 16 – Interior metal roof deck surface temperature for nine monitored roof assemblies – June 30, 2013 (summer).

building prototype model for a stand-alone retail building designed to meet ASHRAE 90.1-2010. These files are available online and use the hourly energy modeling program EnergyPlus (DOE, 2012). Models were run for one representative city in each of the eight ASHRAE North American climate zones.

One goal of the energy modeling was to investigate the impact of temperature-dependent insulation R-values on whole-building energy consumption. While the material testing discussed earlier in the paper identified that thermal conductivity variations with temperature are different for polyisocyanurate and stone wool insulation, this effect is typically not modeled in most whole-building simulation programs but can be modeled in EnergyPlus.

Figure 17 shows the energy simulation results with constant insulation conductivity and with temperature-dependent insulation conductivity per the values reported earlier within this paper. Though the overall difference in heating energy consumption between the two cases is low (generally within 1 kWh/m^2 [320 Btu/ft^2] per year), the results show that polyisocyanurate has the lowest heating energy consumption when constant conductivities are used, but stone wool has the lowest heating energy when the more accurate temperature-dependent conductivities are included. The differences in the first case can be attributed to the differences in heat capacity of the three insulation strategies, where polyisocyanurate has a lower heat capacity and responds faster than the stone wool (also seen from the monitoring results). This is an important finding for energy modelers and needs to be addressed by the default insulation material properties within energy modeling programs.

Energy modeling was also completed to investigate the impact of using aged temperature-dependent conductivity values for polyisocyanurate insulation, since the conductivity has been shown to degrade over time. In all cases, the four-year aged conductivity of the polyisocyanurate insulation was used and was varied in relation to temperature based on the relationships presented previously in this paper. *Figure*

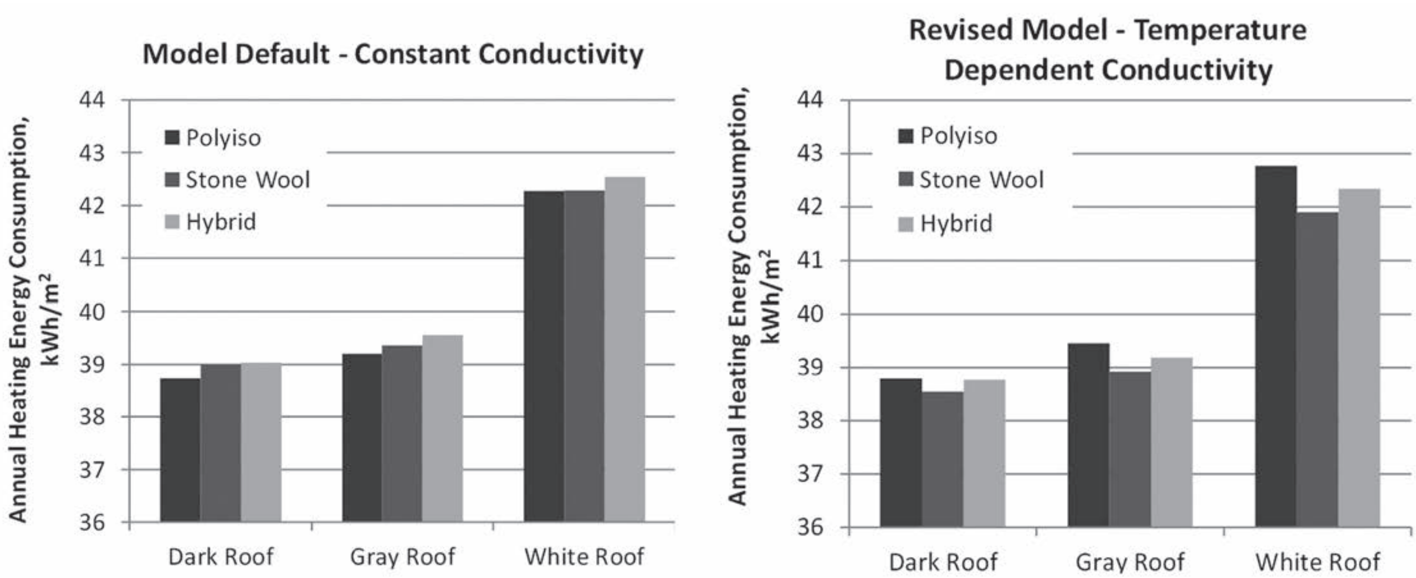


Figure 17 – Impact of modeling constant roof insulation conductivity (left) and temperature-dependent conductivity (right) for retail building in Vancouver.

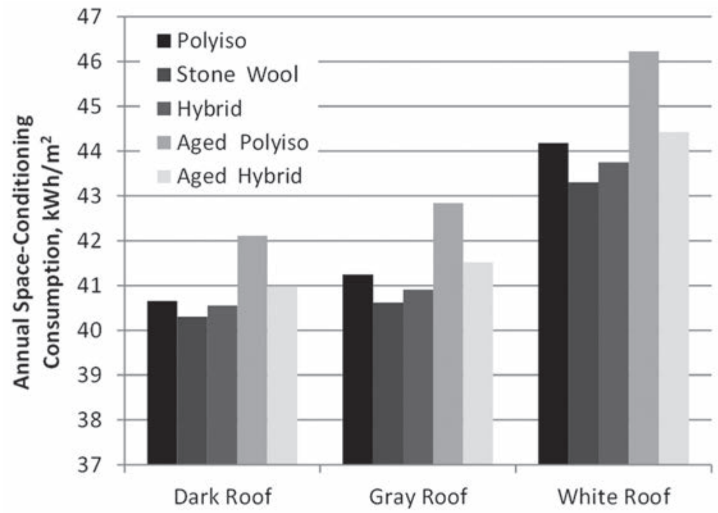


Figure 18 – Impact of modeling aged conductivity of polyisocyanurate insulation on total building energy consumption in Vancouver.

18 shows the total energy consumption (heating and cooling) simulation results for Vancouver, including new and aged polyisocyanurate insulation. The results show a clear increase in energy consumption for aged polyisocyanurate as expected from the lower R-value, making it the highest energy consumption case.

Whole-building energy simulations were run for one representative city in each of the eight ASHRAE/DOE climate zones. *Figures 19* through *21* show the annual heating, cooling, and total heating and cooling energy, respectively, for the eight ASHRAE climate zones with the same black and white roof membranes (SRI -4 and +70 respectively) as used in the study, and aged polyisocyanurate, stone wool, or hybrid insulation. Note that this modeling

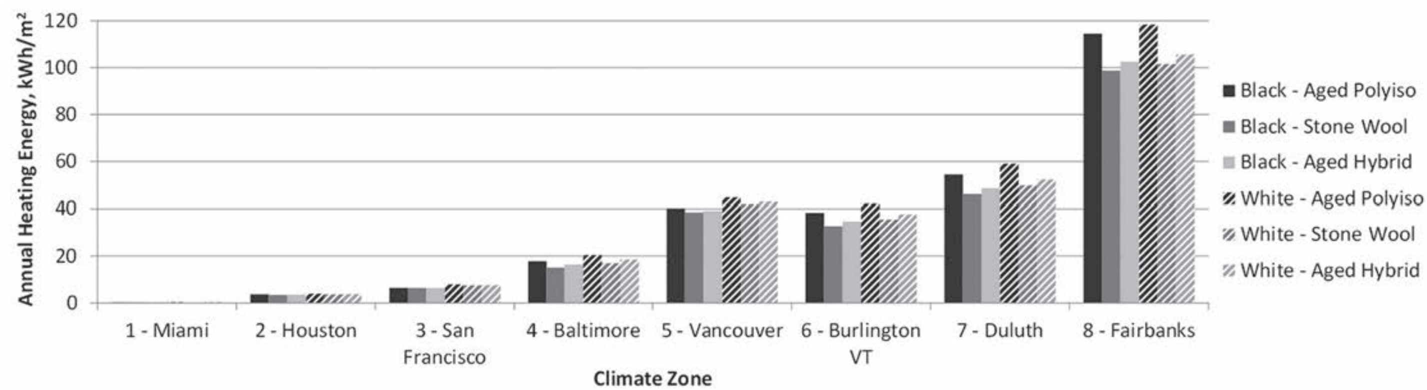


Figure 19 – Commercial retail building annual heating energy use intensity in eight climate zones.

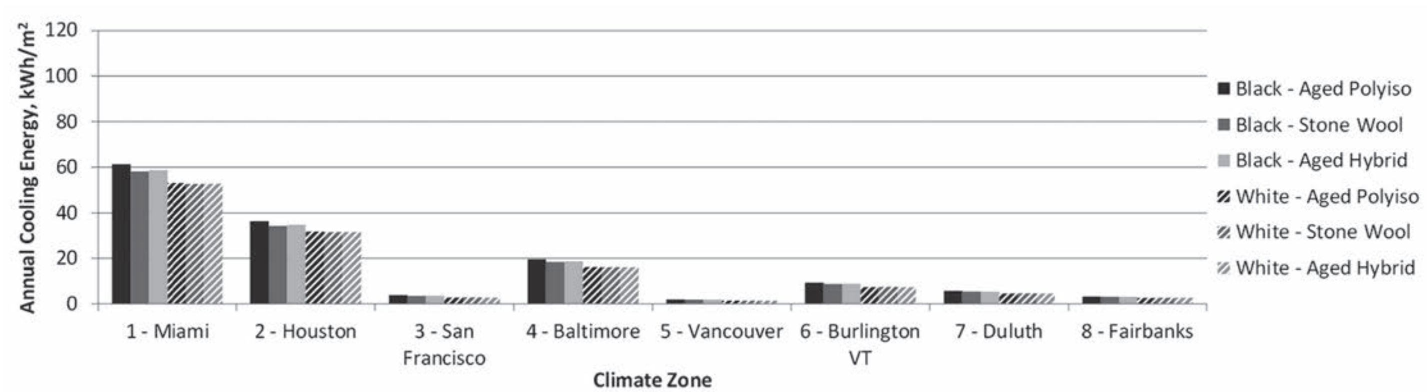


Figure 20 – Commercial retail building annual cooling energy use intensity in eight climate zones.

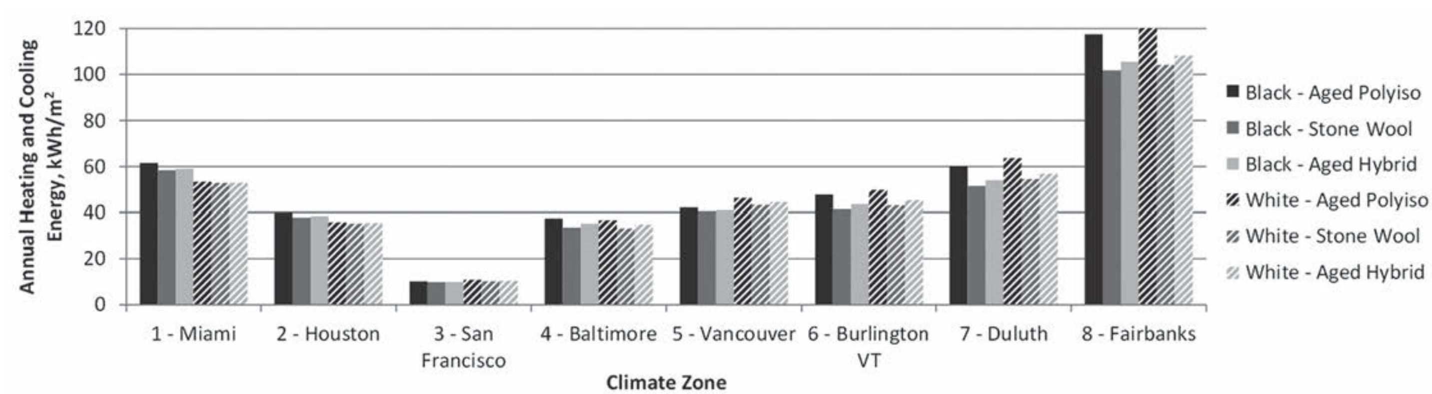


Figure 21 – Commercial retail building annual combined heating and cooling energy use intensity in eight climate zones.

does not account for the effect of snow on the reflectivity of the roofs.

Comparing roof membrane color across each climate zone, the black membrane uses less heating energy but more cooling energy, while the white roof uses less cooling energy but more heating energy. The overall space conditioning consumption depends on the balance of heating and cooling energy within that climate zone.

The total heating and cooling plot (*Figure 21*) shows that overall energy use is lower for white roofs in cooling-dominated climate zones (zones 1 and 2), and lower for black roofs in heating-dominated climate zones (zones 5 through 8). In mixed heating and cooling climate zones (zone 3 and 4), the differences are very small between light- and dark-colored roof membranes. The use of a more reflective white roof membrane (higher than SRI 70 modeled here) would exacerbate these results. With membrane aging and dirt soiling, the cooling savings of white membranes will be reduced as the SRI decreases. Other factors such as comfort and urban heat island effects are not considered here.

Across all climate zones, stone wool insulation results in the lowest heating and cooling energy consumption, while the four-year aged polyisocyanurate insulation has the highest energy consumption due to the loss of its initial R-value. The hybrid approach of stone wool over polyisocyanurate results in a good compromise of performance and maintains the higher R-value of the polyisocyanurate insulation by reducing temperature fluctuations.

CONCLUSIONS AND RECOMMENDATIONS

This large-scale field monitoring study was implemented with the intent of measuring the impacts and benefits of roof membrane color and insulation strategy on the long-term thermal and hygrothermal behavior and performance of conventional roofing assemblies. At the study building in the Lower Mainland of British Columbia, Canada, three different 2-ply SBS membrane cap sheet colors (white, gray, and black) were placed over three different conventional insulation strategies (polyisocyanurate, stone wool, and hybrid combination of both), creating a total of nine unique conventional roofing assemblies. Sensors were installed within each of the roof assemblies to measure material and surface temperatures, relative humidity, moisture content, heat flux, and dimensional stability of the insulation.

As part of the study, thermal resistance testing of the polyisocyanurate and stone wool insulation was performed using ASTM C518 procedures. The insulation products were tested at a range of in-service temperatures, and a relationship between R-value and temperature was developed. The results were then applied to the three insulated assemblies monitored within this study to determine in-service apparent R-values based on exterior membrane temperature. The findings show that the stone wool and hybrid roofs will maintain R-values close to calculated values, whereas the R-value in the roof with polyisocyanurate will drop a fair amount when exposed to either extreme of cold or hot outdoor (and solar radiation-induced) temperatures. This is an important consideration when designing roof assemblies.

The heat flow and temperature measurements show a difference in behavior between the polyisocyanurate, stone wool, and hybrid insulation strategies. Stone wool has a heat capacity approximately 3.4 times higher than polyisocyanurate for the same design R-value, which likely reduces peak temperatures of the membrane and interior and offsets the peak load (thermal lag effects). This reduction in peak roof membrane temperatures, as well as in the rate of temperature change, positively affects the longevity of the membrane as larger magnitude and faster dimensional changes of viscoelastic materials (such as modified-bitumen roof membranes) negatively affect their durability (Dell, 1990). Reduced peak interior temperatures also typically improve occupant comfort. In addition, stone wool has a more stable R-value than polyisocyanurate for the same installed R-value (note that installed R-value is different than thickness); so it insulates better when exposed to larger temperature differences, as can frequently be experienced on roofs.

Energy modeling was used as a tool to better understand the impact of temperature-dependent insulation R-values on annual space heating and cooling consumption and to demonstrate the importance of accounting for a varying R-value in energy models. In addition to accounting for a dynamic R-value, including the long-term aging effects of polyisocyanurate is particularly important in predicting long-term energy use within a building.

Whole-building energy modeling was performed to investigate the optimum roof membrane color (solar absorptivity) and insulation strategy for a conventional roof. Simulation runs were used to compare the same white, gray, and black roof membranes and the polyisocyanurate, stone wool, and hybrid insulation strategies as used in the monitoring study. Energy modeling of these variables was performed using the DOE Building Energy Codes Program commercial building prototype model for a stand-alone retail building designed to meet ASHRAE 90.1-2010. Models were run for one representative city in each of the eight ASHRAE North American climate zones.

Comparing roof membrane color across each climate zone, the black membrane uses less heating energy but more cooling energy, while the white roof uses more cooling energy but less heating energy. Overall energy use is lower for white roofs in cooling-dominated climate zones (zones 1 and 2), and lower for black roofs in heating-dominated climate zones (zones 5 through 8). In mixed heating and cooling climate zones (zone 3 and 4), the differences are very small between light- and dark-colored roof membranes. With membrane aging and dirt soiling, the cooling savings of white membranes will be reduced as the surface reflectivity decreases. The impact of membrane soiling and aging is being monitored as part of this study but is not presented within this paper.

Across all climate zones, stone wool insulation results in the lowest heating and cooling energy consumption, while aged polyisocyanurate insulation has the highest energy consumption due to the loss of its initial R-value. The hybrid approach of stone wool over polyisocyanurate results in a good compromise of performance and maintains the higher R-value of the polyisocyanurate insulation.

This study provides insight into the behavior of polyisocyanurate-and-stone-wool-insulated conventional roof assemblies with light- to dark-roofing membranes. The study is ongoing and will continue for the next few years.

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FOOTNOTES

1. Stone wool is within the class of mineral wool/fiber insulation products. Within this paper, it is used to describe a stone fiber insulation material with a higher fiber density (typically above 10 pcf) and is intended for roofing rather than wall applications.
2. Apparent R-value is the actual thermal resistance of the insulation at a given point in time. It varies with temperature and due to other factors such as age.
3. In all of the subsequent plots within the legend code, "W" refers to the white roof membrane, "G" for gray, and "B" for black. ISO refers to the polyiso insulation, ISO-SW refers to the hybrid (stone wool over polyiso), and SW refers to the stone wool. The nine different test areas are defined in short form using a combination of these letters. Within the heat flux plots, negative values indicate gain of energy through the roof insulation (e.g., due to solar loading), and positive values indicate a loss of energy (e.g., due to colder outdoor conditions).