

Drainage Capabilities and Heat Loss of Different Inverted Roof Assemblies

Matthew Pel, B.Tech., Eng.L.

Derek Budde, B.Sc. EIT

ABSTRACT

Energy use in buildings throughout North America has attracted significant attention over the past decade. In cold marine climates, rainwater management is also a critical aspect of the building enclosure and energy performance. Various drainage practices used for low slope inverted roofing are often designed without quantified data available regarding the cold rain effects on the thermal performance of the systems.

The effect of cold water under the roof insulation and its impact on the effective thermal performance in inverted roofs is well researched. The aim of this project was to develop a better understanding of the impact of cold rain events on the effective thermal performance of inverted roofs in an effort to develop best practice inverted roofs design guidelines.

The project included the construction of a 'calibrated hot box' to mimic the temperature difference between interior and exterior winter conditions. The evaluated roof assemblies consist of typical inverted roofs (membrane, drainage layer, insulation, filter fabric and ballast). Evaluation was conducted with different variables including rain rates, insulation orientation, insulation gaps, different types of drainage mats and the exclusion of drainage mat below the insulation. Later evaluations included a loose-laid moisture shredding layer above the insulation and changing the roof slope.

Evaluations have indicated that although the drainage capacity and leakage rates of different roof assemblies depend on a number of factors, the majority of rain water drains at the membrane level in all test scenarios. Based on the analysis completed, the results show that different drainage scenarios do have an impact on the overall effective thermal performance of inverted roof assemblies. The most significant heat loss and unexpected results was the increased heat loss when the drainage mat was removed and insulation is in direct contact with the roofing membrane.

INTRODUCTION

Energy use in buildings throughout Pacific Northwest and North America has attracted significant attention over the past decade. In British Columbia, rainwater management is also a critical aspect of designing a durable building envelope. Various drainage practices used in low slope inverted roofs (i.e. using grooved insulation, drainage mat, Tyvek, etc.) are often used without much quantified information available as to the thermal performance of the systems when exposed to rainfall. The effect of water under the insulation and its impact on the thermal performance in inverted roofs is well researched over the past several decades.

Matthew Pel, B.Tech., Eng.L. is a Building Science Consultant and Principal at Morrison Hershfield, Vancouver, BC.
Derek Budde B.Sc. EIT is a Building Science Consultant and Principal at Morrison Hershfield, Vancouver, BC

Leakage rates and drainage of water within an inverted roof assembly, on the other hand, has not been extensively evaluated, including draining at insulation levels or at the membrane level and how different drainage options affect the thermal performance of the roof assembly resulting from cold rain water bypassing the insulation.

Inverted roofs assemblies are commonly used within the Pacific Northwest area and generally applied to directly concrete for a variety of reasons:

- Thermal protection of the roofing membrane and minimizing thermal cycling
- Eliminating roofing membrane exposure to ultra violet radiation
- Speed of construction and ability to install roofing membrane shortly after roof structure is completed
- Cost effective roofing assembly

This study included the following tasks:

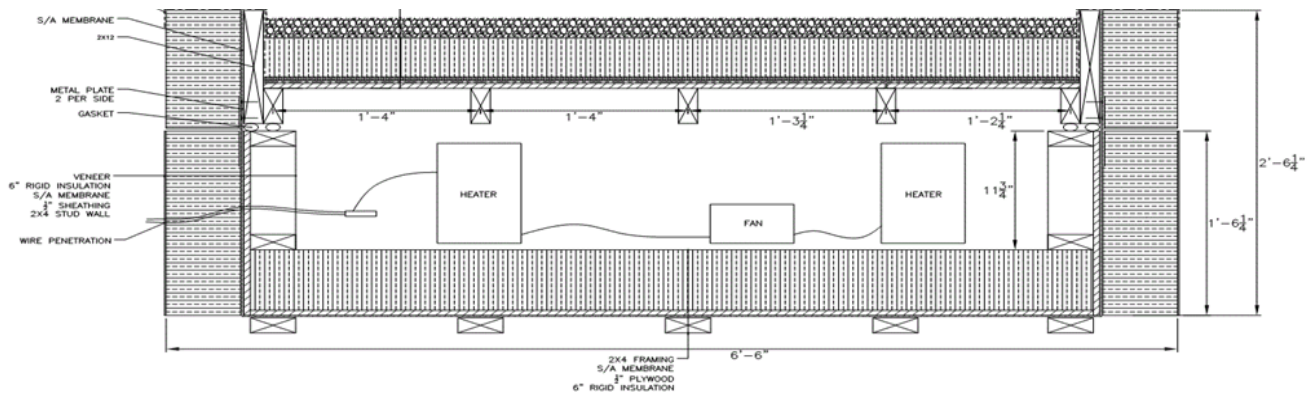
1. Literature review of past research related to heat loss in low slope inverted roof assemblies and drainage rates.
2. Evaluation of impact of different drainage scenarios on the rainfall drainage capability at the membrane level and at the insulation level.
3. Assessing the impact of different drainage scenarios on the thermal performance of the roof during rain periods.

METHODOLOGY AND TESTING EQUIPMENT

Hot Box Construction

In this research project, an insulated hot box was constructed and calibrated to provide a temperature difference across different inverted roof assemblies to mimic an in-situ roof (refer to Figure 1 for hot box section) . The hot box apparatus was constructed in two pieces, the base and lid, and is wood framed. The hot box is designed and constructed to eliminate air leakage within the chamber and minimize thermal bridging at the sides at bottom. Continuous layers of self-adhering membrane were installed over the framed hot box with 6” of adhered rigid extruded polystyrene insulation. To seal the lid to the base a double layer of foam gasket is installed to prevent air leakage and increase the thermal resistance.

Figure 1 – Insulated Hot Box Section



Since the pattern or location of water flow under the insulation is unknown and cannot be confirmed, a continuous aluminum base was installed prior to the roofing membrane installation to help average out and more evenly distribute the localized heat loss paths through the roof assembly.

Drains for the roof assembly (hot lid) were provided at the membrane level and the insulation level, allowing for measurement of drainage and water temperature to allow for measurement of drainage and water temperature.

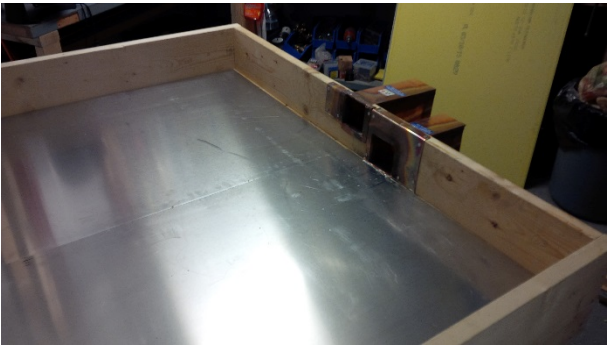


Figure 2 – Hot Box Aluminum Base

Roof Assemblies and Drainage Options

Typical components of an inverted roof assemblies (from bottom to top of the system) include a waterproofing membrane, drainage layer, insulation, filter fabric and ballast. Multiple variations of the above described inverted roof assemblyt can be utilized depending on the design intent and/or consultant/designer preference. Inverted roof assemblies and drainage options commonly used in the Pacific Northwest include:

Table 1 - xxxx

Waterproofing Membrane	• 2-Ply SBS membrane
	• Monolithic hot rubber membrane
	• Monolithic cold applied urethanes
Drainage Layer	• Solid core drainage mat
	• Open drainage mat (percolating)
	• Groove insulation panels
	• No drainage (insulation directly on roofing membrane.

Insulation	<ul style="list-style-type: none"> • 1-layer of extruded polystyrene • 2-layer of extruded polystyrene (with staggered joints)
Ballast	<ul style="list-style-type: none"> • Gravel ballast • Concrete paving slabs • Soil and vegetation

Based on the past research, conventional roof design and building science principals, it is assumed that an inverted roof with a drainage layer between the insulation and roofing membrane provides the most effective drainage but the least efficient thermal performance. This approach allows water drain the rough the insulation and freely flow over the roofing membrane (Insert Reference) lead to rainwater cooling and increased heat loss. Inverted roofs with the insulation in direct contact with the roofing membrane (no drainage layer) provides the least effective drainage but most efficient thermal performance. This approach relies on water draining on the surface of the insulation panels or through small joints or gaps in the insulation. To minimize the numerous inverted roof assembly options, the testing completed considers at the most and least effective drainage scenarios as noted above.

Sensors and Instruments

To collect data during the testing, the hot box was equipped with instruments to record the following:

1. Heat Flux Sensors – W/m^2
2. Temperature Sensors – $^{\circ}C$
 - a. Ambient air temperature inside the hotbox
 - b. Ambient air temperature outside the hotbox
 - c. Surface temperature on the underside of the roof assembly
 - d. Water temperature in (simulated rain water temperature)
 - e. Water temperature – Flow out low (membrane level)
 - f. Water temperature – Flow out high (insulation level)
3. Flow meter – mm/hr (simulated rain fall intensity)
4. Pressure sensor (converted to volume) – Liters (drainage at membrane or insulation level)

A number of measures were in place during this study to ensure the results are repeatable and minimize the potential experimental error, they include:

- Installation of redundant sensors
- Multiple re-tests were completed
- Compared heat loss through roof assembly with water temperature increase (conservation of energy)

Scenarios and variables

As noted in Roof Assemblies and Drainage Options section (above), the most and least effective drainage options and the most and least efficient thermal performance options were considered in testing to determine the upper and the lower bounds of heat loss rates. Within these roof assemblies various scenarios were considered. Test scenarios were developed to isolate individual variables related to roof assembly components and installation. As previously noted, it is commonly thought that the best thermally performing inverted roof assembly is when the insulation is in intimate contact with the roof membrane. It is commonly thought that the best drainage provision for an inverted roof assembly is when drainage mat is provided as a cavity between the roof membrane and the insulation. The primary objective of this study is to compare and evaluate the heat loss through an inverted roof assembly, including or omitting drainage space at the membrane level.

We recognize the variance in installation of individual roof components, such as insulation thickness and changes in environmental conditions, such as temperature differences and rainfall rates, may impact the performance of the roof assembly differently. This study provides a comparison of varying drainage scenarios where holding all other variables and bounded conditions constant.

Construction variances in the installation of rigid extruded polystyrene insulation, such as the orientation of the boards relative to roof slope (long side of insulation panel is parallel or perpendicular direction to slope) and the tightness of insulation board joints (no gaps or gaps) were considered. It is important to recognize that often these variables are encountered unavoidably but are within the standard construction tolerances. For instance, when roofs have centrally located roof drains, half the insulation boards run parallel to the slope and half run perpendicular. Boards may be installed with tight ship-lapped joints in the summer, however in the winter gaps would be present due to shrinkage of the insulation.

The expansion/contraction was calculate using the following:

$$\Delta L = \alpha L_o \Delta T$$

Where: ΔL = *Change in length of specimen (Expansion or Contractoin of Insulation Board)*

α = *Coefficient of Thermal Expansion* (Dow Roofmate: $\alpha = 3.5 \times 10^{-5} / ^\circ\text{F}$)

L_o = *Lineal Length* (Width: 24 in)

ΔT = *Final temperature – Initial Temperature* ($21^\circ\text{C} - 1^\circ\text{C} = 20^\circ\text{C} = 68^\circ\text{F}$)

The gap between board panels was calculated to be 0.0571 inches or approx. 1/16”.

Environmental conditions like temperatures and wind may also affect the performance of the inverted roof assembly. Rainfall rates directly correlate to the amount of water running over the roof, and at different rates it was hypothesized that there may be more flow of water on top of the insulation versus at the roof membrane level.

Considering the information described above, the testing procedures for the project included the following variables: insulation direction (parallel or perpendicular to roof slope), gaps between insulation boards, water flow rate, and inclusion or omission of a drainage mat at the membrane level. To measure the effect of these variables, each test was performed with a single variable change.

Testing Results

The four main roof assemblies with different scenarios were tested as part of this study. Overall, thirty-seven different tests were completed with multiple redundant tests to ensure repeatability and identify the boundary limitations. The following are the tested roof assemblies are the variables that were added to create the different scenarios:

Table 2 - xxxx

Inverted Roof Assembly		Rain Fall Rate	Insulation Orientation	Contact between Adjacent Insulation Boards
1. With Drainage Mat	• 2” gravel ballast	2mm/hr	Parallel	1/16” Insulation Gaps
	• Filter fabric	3mm/hr		
	• 4” of insulation (2-layers of 2”)	4mm/hr	Perpendicular	No Gaps
	• Drainage mat			
	• Roofing Membrane			
2. No Drainage Mat	• 2” gravel ballast	2mm/hr	Parallel	1/16” Insulation Gaps
	• Filter fabric	3mm/hr		
	• 4” of insulation (2-layers of 2”)	4mm/hr	Perpendicular	No Gaps
	• Drainage mat			
	• Roofing Membrane			

3.	Open Drainage Mat			
	• 2" gravel ballast	2mm/hr	Parallel	1/16" Insulation Gaps
	• Filter fabric	3mm/hr		
	• 4" of insulation (2-layers of 2")		Perpendicular	No Gaps
	• Drainage mat	4mm/hr		
	• Roofing Membrane			
4.	No Drainage Mat – Weather Resistant Barrier			
	• 2" gravel ballast	4mm/hr	Perpendicular	1/16" Insulation Gaps
	• Dow - Weathermate			
	• 4" of insulation (2-layers of 2")			
	• Roofing Membrane			

Each test yielded measurements for temperature gain of water entering and exiting the roof assembly, cumulative flow of water above and below insulation (leakage rates), and heat flux through each sensor. The temperature change of the water was graphed to illustrate change over time. Water accumulation from above and below the insulation was graphed to illustrate cumulative flow over time. Data from heat flux sensors were graphed individually as well as averaged to illustrate average heat loss through the roof assembly over time.

Drainage and Leakage Rates

The total drainage amount, or the ‘cumulative flow’, of water was measured at the membrane level (referred to as flow ‘Low’) and at the top of the insulation level (referred to as flow ‘High’) were recorded throughout the tests. Water accumulation was plotted on a volume (Litres, vertical axis) versus time (Hours, horizontal axis) graph. The following graph illustrates typical results.

Figure 3

Leakage rate is the percentage of water draining at the membrane level and is calculated by the following equation:

$$\% \text{ Flow Low} = \frac{\text{Cumulative Flow Low}}{\text{Cumulative Flow Low} + \text{Cumulative Flow High}}$$

Where: % Flow Low=Leakage Rate

Cumulative Flow Low= Total flow at membrane level, Litres

Cumulative Flow High= Total flow above insulation, Litres

Results. Leakage rates were compared for various drainage scenarios and changes in variables. The biggest effect to leakage rates was the presence of gaps in insulation panel joints. In tests where board joints were tight, a smaller percentage of water was able to reach the membrane level. The presence of 1/16" gaps in board joints resulted in more water flowing to the membrane and draining at the membrane level. As illustrated above, introducing gaps in the board joints resulted in an increase of 13% leakage rate (water drainage to the roofing membrane) of water when compared to the same assembly with no gaps in the insulation.

It is important to note that in tests where no gaps were present (low flow and high flow), the majority of water still leaked to the membrane level. This suggests that the majority of water is bypassing the insulation and absorbing heat directly from the roof.

Temperature Readings

Temperatures were measured and the hot box assembly was at steady state prior to test starting, as a baseline. Temperature was plotted on a temperature (°C, vertical axis) versus time (hours, horizontal axis) graph for each sensor. The following temperature measurements were obtained throughout the tests:

- water temperature at 'flow in' or the water supply, (purple curve)
- ambient temperature of the room, (green curve)
- air temperature inside the hot box, (red and blue curve)
- Water temperature at the 'high' outflow (above insulation), (light blue curve)
- Water temperature at the 'low' outflow (waterproofing membrane level), (yellow curve)

Figure 4 - Represents a temperatures during and following a simulated rain water event on one fo the the test assembly:

Referencing Figure 4 above, there is a constant 20°C temperature difference across the roof assembly prior to the start of the rainfall event. This is visible on the left of the zero-time mark. After the rainfall event starts, a short delay occurs as the water accumulates on the gravel ballast, begins to percolate and drain through the system as resistance and surface tension of water is overcome.

As the water $\Delta 20^{\circ}\text{C}$ through the roof assembly and reaches the insulation, a portion is diverted to the roof membrane level through joints between the insulation boards. This water flows below the insulation and contacts the roof membrane (when no drainage mat is present). Heat is transferred from the heated space below through the roof deck resulting in a temperature increase. This is apparent in the spike of the 'water temperature at flow low' trend line in Figure 4 (orange curve). As this water is gaining heat, the interior temperature of the hot box is reduced as visible in the P2 and P5 Ambient trend lines (red and blue lines). These two temperatures, the hot box temperature and the flow-low temperature, are proportionally related and even out to a steady state near the end of the test. The portion of water not drained (remaining on the top of the insulation boards is identified as 'flow-out high' on the graph (light blue line). There is very little change in this water temperature as the rainfall event progresses. Water flowing on top of the insulation is not subject to the same surface temperature difference and therefore does not gain much heat.

It was observed that the more water remains in intimate contact with the roof membrane the greater the temperature increase of the outflow water at the membrane level (flow low) and the greater heat flux through the test assembly.

Figure 4 – Temperature Readings

Heat Flux

Heat flux sensors are arranged in a 3x3 equally spaced grid to provide individual readings of heat flux through the associated roof area. Each sensor measured the flux through a 2ft x 2ft area, and produced data readings every 5 seconds. Heat flux density (W/m², Vertical axis) was graphed versus time (Hours, Horizontal axis) producing a typical group of testing data as follows.

Figure 5 – Typical Heat Flux Readings

High Flow at Drain

Results. Heat flux sensors located near the scupper drain on the roof assembly (low point), receive the most water flow over the sensor as this is the low-spot of the roof. Therefore these roof areas have the highest heat flow. This is illustrated in flux sensor P8 (light blue) above. Sensors located in the mid-roof or mid-slope **Mid Roof** volume of water flow than at the drain. This is illustrated in the group of sensors labelled 'mid roof', above. Sensors located at the high-side of the roof receive little or no water flow over them. As such, the heat flux increase through that roof area is negligible.

All testing completed shows that as rain water percolates through the roof assembly and reaches the membrane level it continually accumulates mass and absorbs energy (increases heat flow) as it flows over the **High Side**

membrane towards the drain. It was observed that the more volume of water that flows over a given roof area (at the membrane level) directly corresponds to an increase in overall heat loss.

Average Heat Flux Increase

Ten heat flux sensors (9 locations, 1 redundant) were averaged to create a single trend line for each test. Variables between tests were then compared to determine the effects.

Insulation Board Orientation

Insulation boards were varied to be oriented either parallel to the roof slope or perpendicular. The following graph illustrates two tests, one with the long side of the insulation boards oriented parallel and the other perpendicular to the roof slope (all other variables remained the same).

Results. The study shows that the direction of the insulation boards affects the thermal performance of the roof assembly. When insulation boards (2-layers of 2" insulation with staggered joints) were oriented perpendicular to the roof slope, the water travelling on top of the insulation boards encountered more joints where it was diverted down to the membrane level. This increased the amount of water flowing over the surface of the membrane which increased the heat flow through the roof assembly. When panel joints were parallel to the roof slope, water was able to run over the insulation board surface for a much longer distance and time before trickling down to the membrane level. For the test illustrated in Figure 6, insulation panels oriented perpendicularly performed approximately 50% less efficiently than panel in parallel orientation.

Often the orientation of insulation boards on a roof compared to the roof slope direction is unavoidable. The majority of flat roofs have centrally located drains, therefore it could be expected that general board orientation would be approximately 50% parallel and 50% perpendicular to the slope.

Insulation Board Joints

The effect of insulation board joint size was measured by running tests with tight board joints or with 1/16" gaps, to mimic construction tolerances and/or shrinkage of panels in cold conditions. A comparison of tight joints versus gapped joints is provided on the following graph:

Figure 6 – Average Heat Flux Readings with Different Insulation Direction

Results. The findings illustrated in this graph show that the increase in heat flux through the roof assembly when insulation is gapped, is small. This follows the previous findings where the majority of water drains at the membrane level regardless of how tight the insulation board joints are, resulting in similar heat loss measurements for these tests.

Drainage Mat vs. No Drainage Mat

It is commonly thought that the best thermally performing inverted roof assembly has the insulation in intimate contact with the roofing membrane. The theory is that the presence of a drainage mat between the insulation

Figure 7 – Average Heat Flux Readings with Different Insulation Joints

and the roof membrane creates an air cavity diminishing the effective insulation value and allows a space for flow of cold rain.

The graph below illustrates typical test results for inclusion or exclusion of drainage mat. A solid-core drainage mat was used, which is comprised of a solid polyethylene dimple board and filter fabric facer.

Results. Contrary to expectations, it was observed that the increase in heat flux through the roof assembly during a rain event was greater if drainage mat was omitted. The red trend line in the graph is the heat flux through the roof assembly including a solid core drainage mat, while the blue trend line is excluding a drainage mat.

For the test illustrated above, it was observed that during the rain event the heat flux through the roof increased by approx. 125% without the presence of a drainage mat. When the drainage mat was included in the roof assembly, with all other testing parameters remaining the same, the heat flux increased by approx. 75%.

It is theorized that the observed performance of included or excluded drainage mat may be associated with the direct contact between the water, flowing under the insulation and on top of the roof membrane. When a solid core drainage mat is provided under the insulation, the water flows on the polyethylene core to the roof drains. This provides one level of separation from direct contact with the roof membrane. In the case when drainage mat is omitted, the water is in intimate contact with the roof membrane resulting in a higher heat transfer.

Open-Core (Percolating) Drainage Mat

To build on the theory of water flow over the solid core drainage mat, rainfall tests were performed with an open-core or percolating drainage mat. The open-core drainage mat is comprised of non-woven polyethylene mesh molded into a dimple profile with a filter fabric facer.

The graph below illustrates typical findings for tests including open-core drainage mat (purple line), solid-core (red line), and no drainage mat (blue line).

Figure 8 – Average Heat Flux Readings With and Without Drainage

Results. It was observed that the thermal performance of the roof assembly with an open-core drainage mat is less efficient than a solid core drainage mat, but more efficient than the system without drainage mat. The test results in Figure 9 show heat loss through the roof assembly increasing by approximately 100% during the rain event with an open core drainage mat installed. As noted above, the same testing scenarios for solid core drainage mat and no drainage mat yielded increases of approx. 75% and 125% respectively.

It is theorized that the solid-core drainage mat provides an additional layer of separation for water to flow over rather than the roofing membrane. Where the open-core drainage allows water to flow directly over the roofing membrane thus increasing heat transfer.

Water Resistant Weather Barrier Overlay

The final testing scenario included the installation of a loose-laid water resistant weather barrier (WRWB) over the insulation, in lieu of filter fabric. The WRWB that was used is a non-woven polyolefin-based sheet and is vapour permeable. The sheet was installed directly over the insulation and taped and sealed to the scupper drains.

Figure 9 – Average Heat Flux Readings with Open Drainage Mat

Gravel ballast was installed over the sheet. Given the expectation that very little water would run past the overlay sheet and reach the membrane level, a drainage mat was omitted under the insulation.

The effect of Dow Weathermate overlay on the thermal performance of the roof assembly is illustrated with the green trend line in Figure 11 below:

Results. As shown above, the increase in heat flux through the roof assembly with the presence of a WRWB sheet over the insulation is approx. 5%. This minimal increase can be attributed to a small leakage of water to the membrane level, likely caused from detailing of the sheet membrane at the scupper drains. By installing a waterproof sheet above the insulation, the vast majority of water is directed to the drains and is prevented from reaching the roof membrane level.

Figure 10 – Average Heat Flux Readings with Water Resistant Barrier Overlay

Equivalent R-Value Reduction

The heat flux density increase through the inverted roof assembly can be transferred into an equivalent reduction in effective R-Value of the assembly through the following equation:

$$R_{eff} = \frac{\Delta T}{\dot{Q}_A} * 5.67$$

Where: R_{eff} = Effective R – Value of roof assembly

$$\Delta T = \text{Final temperature} - \text{Initial Temperature} \quad (21^{\circ}\text{C} - 1^{\circ}\text{C} = 20^{\circ}\text{C})$$

$$\dot{Q}_A = \text{Heat flux per unit area} \left(\frac{\text{W}}{\text{m}^2} \right)$$

5.678= multiplier from RSI (W/m² K) to R-Value (Btu/h ft² F)

Applying this equation to the test data outlined in Section 4.9 – Water Resistant Weather Barrier Overlay, the heat flux density increases were converted into effective R-Value decrease as follows.

The roof assembly began with an effective R-value off approximately R15 at steady-state. It is notable that the effective decrease in R-Values for the following testing scenarios are:

- No drainage mat- Loss of approx. R9.
- Open-core drainage mat- Loss of approx. R8
- Solid-core drainage mat- Loss of approx. R7
- Waterproof sheet overlay- Negligible R-Value loss

SUMMARY

The drainage capacity of different roof assemblies depends on a number of factors, however in all the test scenarios the majority of rainwater runoff drains at the membrane level. The quantity of water that drains at the membrane level and from the top surface of the insulation largely depend on the following factors:

1. Insulation panel direction. The leakage rates are reduced when the insulation panels are installed parallel to the slope
2. Gaps between insulation panels. The thermal contraction of insulation panels during colder months increases the leakage rates.
3. Rain fall rates. As the rain fall rates increases the leakage rate decreases which improves the thermal performance of the roof assembly.

Figure 11 – Average R-Value Reduction

Based on the testing completed, despite the small sample size, the results show that different drainage scenarios do have an impact on the thermal performance of inverted roof assemblies. While insulation panel direction, rain fall rates and insulation panel direction all affected the thermal performance of inverted roof assemblies. The most significant heat loss and unexpected results was the increased heat loss when the drainage mat was removed and the insulation is in direct contact with the roofing membrane. As expected, installing a vapour permeable WRWB layer over the insulation significantly reduces water drainage and improves the thermal performance of the inverted roof.

The findings show the effective thermal performance (from most to least efficient) of inverted roof assemblies is

1. Inverted assembly with no drainage mat under the insulation and a vapour permeable layer over the insulation.
2. Inverted assembly with a solid core drainage mat under the insulation
3. Inverted assembly with insulation in direct contact with the roofing membrane.

ACKNOWLEDGMENTS

This research project was prepared by Morrison Hershfield Ltd. and funded by the Homeowner Protection Office, a branch of BC Housing. Special thanks is extended to Dow Building Solutions for providing technical and construction expertise for the development of solutions outlined in this report. Roofing products for this project were supplied by Soprema Canada and installed by Pacific Waterproofing Ltd.

REFERENCES

- Dr. Steve Johnson, Dow Building Solutions, September 2015. *Making U-value Calculations for Inverted Flat Roofs*.
- Dow Building Solutions, Updated January 2013. *Insulating Inverted Flat Roofs with STYROFOAM Solutions: Basic Principals*.
- British Board of Agrement, January 2011. *Inverted Roof – Drainage and U-Value Corrections*.
- Fraunhofer-Institute of Building Physics (Germany), 1996. *Assessing Precipitation Heat Losses of Protected Membrane Roofs*.
- Holger Merkel, Ph.D. *Inverted Roofs with Reduced Heat Losses Due to a Water-Repellent Separating Layer*.
- BBS Institut, University of Denmark, Fraunhofer, Vienna U. *Requirements of inverted roofs with a drainage layer*.
- Cold Region Research and Engineering Laboratory, April 1977. *Observations and Analysis of Protected Membrane Roofing Systems*.
- Cold Region Research and Engineering Laboratory March 1976. *Protected Membrane Roofs in Cold Regions*.