Balancing Waterproofing and Thermal Performance for Vegetative Roof Assemblies

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Abstract

In contrast with traditional roofing practice, many building deck waterproofing systems, including those used in vegetative roof assemblies, place insulation above the waterproofing membrane, in part to improve the system's waterproofing performance. This assembly often is referred to as an inverted roof assembly. With this construction, water flows down through the insulation and at the membrane level compromises the insulation layer's thermal resistance. This often is recognized as an acceptable compromise to improved waterproofing performance. The magnitude of the loss in thermal resistance is not well understood and difficult to quantify and, therefore, typically is not compared scientifically to waterproofing performance.

This paper discusses the effects when insulation is placed above the membrane on the roof assembly's waterproofing performance, and presents a thermal model incorporated into a computer energy model to evaluate the effects of water flow through a drainage layer beneath the insulation. We analyze the heat transfer effects of inverted roof

assemblies for vegetative systems on building energy use by performing building energy simulations, using weather data for various locations in the U.S. The popularity of vegetative roofing and the perception of these roof systems as sustainable, energy-efficient, and high-performing make research of this topic timely.

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Introduction

Vegetative roof systems continue to gain popularity and often are perceived as durable, sustainable, energy-efficient and high-performing systems. Vegetative roof systems include layered assemblies that combine landscaping, thermal insulation, waterproofing components, and other elements to provide a functioning system. Insulation often is placed above the waterproofing membrane to improve the assembly's waterproofing performance, particularly isolating the membrane from thermal changes and placing the membrane directly on the roof deck, the most stable substrate typically available. However, water flow at the waterproofing membrane level compromises the insulation's performance. This paper discusses the waterproofing and thermal performance of the described layered assembly, and summarizes the authors' analysis of the heat loss to understand the energy implications of the inverted roof assembly. The purpose of the analysis is to estimate an "upper bound" for energy use and heat loss effects for vegetative roof systems based on specific assumptions and building upon studies previously published by others.

Inverted roof assemblies

Design principles for building deck waterproofing assemblies, including plaza systems, locate the waterproofing membrane on the roof deck with the protection and drainage layer(s), insulation and additional landscaping components above the waterproofing membrane (Ruggiero 1990, Henshell 2000, Figure 1). This layered system is referred to as an inverted roof membrane assembly (IRMA) because the insulation is located above the membrane, whereas in conventional roof assemblies, the roof membrane typically is above the insulation.

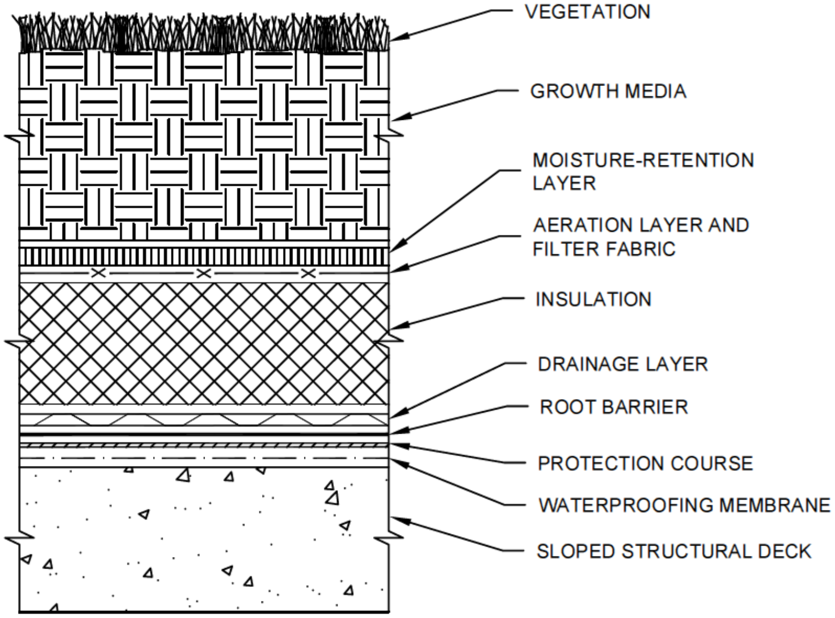

Figure 1 – Vegetative roof system with inverted assembly (Note: Position of the root barrier varies by design)

Building deck waterproofing design principles apply to vegetative roof systems, and inverted roof assemblies provide advantages to the performance of the waterproofing system as follows (NRCA 2009):

- Fully adhered and compartmentalized [loose-laid] waterproofing membranes can be used to limit the horizontal migration of water, which assists in the investigation of leaks and subsequent repairs. Water that leaks through the membrane of conventional roof systems can travel variable distances over the roof deck and produce leaks to the building's interior remote from the breach in the membrane.

- Conventional roof systems typically include polyisocyanurate insulation, which can deteriorate when exposed to moisture, further increasing the cost and extent of repairs to restore a failed roof system.
- Insulation above the waterproofing membrane reduces temperature cycling of the membrane, which improves the membrane's long-term durability.
- Insulation above the waterproofing membrane provides protection from construction activities, components above the membrane and live loads.
- The roof deck provides a rigid substrate to support the membrane; conventional roof systems install the membrane over insulation or coverboard, which is installed to improve the substrate's rigidity. Compression of insulation resulting from load can deflect the insulation and cause the membrane to be unsupported. An unsupported membrane has a decreased puncture resistance and is prone to seam failure.
- The waterproofing membrane can act as an air barrier and vapor retarder for the roof assembly and is located on the warm side of the insulation, which generally is consistent with design practices to address moisture migration. Conventional roof assemblies that lack an air barrier or dedicated vapor retarder are more likely to develop condensation at the underside of the membrane because of air leakage and moisture migration from the building's interior. This moisture can cause roof system components to deteriorate, wetting of construction and finish materials that are susceptible to mold growth, and

perceived “leaks” to the building’s interior. These problems are exacerbated in high-humidity buildings (for example, museums and natatoriums).

For inverted assemblies, insulation that is located above the waterproofing membrane should have low moisture absorption and high compressive strength, and be resistant to freeze-thaw damage (unless in a climate where this is not a concern). Extruded polystyrene (XPS) insulation is the most appropriate material for this application. XPS boards in buried applications show a loss of 5 to 10 percent in thermal resistance within three to five years that can be attributed to moisture absorption (Dechow, 1978).

Conventional roof assemblies

Though generally in conflict with the preferred waterproofing approach [*The NRCA Vegetative Roof Systems Manual, Second Edition* (Manual), 2009], insulation can, as a substantial compromise, be located below the waterproofing membrane in vegetative roof assemblies, particularly in retrofit and other applications where inverted assemblies may not be appropriate or desired. This approach is similar to a conventional roof assembly with the remaining waterproofing and landscaping components placed above the membrane (Figure 2).

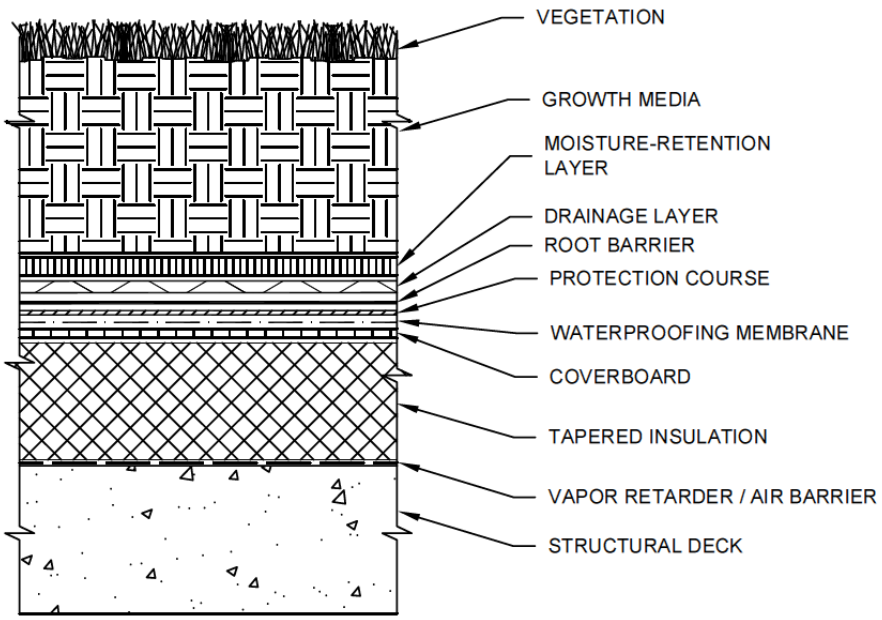

Figure 2 - Conventional roof assembly adapted to a vegetative roof system

Designers might choose this system because its base system is consistent with the design of a typical roof assembly and to avoid reductions in thermal performance that are anticipated when installing the membrane and a drainage layer beneath the insulation. The advantages of such systems for vegetative roof assemblies are as follows:

- Improved thermal performance of insulation compared to an inverted roof membrane assembly. Drainage below insulation in an inverted assembly can contribute to a reduction in the insulation’s thermal performance because of moisture absorption by the insulation, and water and air flow below the insulation.
- The insulation provides a layer that separates the membrane from surface irregularities and movement of the roof deck.

- Insulation below the membrane can decrease the thickness of the roof assembly and allow the use of polyisocyanurate insulation. Polyisocyanurate roof insulation's typical thermal resistance (R-value) is R-6 per inch, according to most manufacturers, compared with the typical R-5 per inch of XPS. Similar to XPS, polyisocyanurate shows a loss in thermal resistance, with an estimated in-service R-value of R-5.6. This is attributed to, in part, loss of insulating gases from foam cells (NRCA/MRCA 1987).

Note, however, that the low compressive strength of polyisocyanurate insulation requires coverboard and soil and live loads still may compress insulation and damage roof membranes.

Drainage layer location in inverted assemblies

Insulation manufacturers generally recommend a single drainage layer be included that is located above the insulation to improve the performance of the insulating system (Dow Chemical Company, 2010). This approach conflicts with building deck waterproofing design principles for the location of the drainage layer for inverted assemblies (Ruggiero 1990). Insulation manufacturers' recommendation to locate the drainage layer above the insulation apparently is to reduce the potential decrease in thermal performance because of the following:

- Cold water that flows below the insulation absorbs heat from the roof membrane and drains through the storm water system, increasing heat loss through the building envelope.

- Air flow through a drainage layer below insulation increases convective heat loss, increasing heat loss through the building envelope.
- Water that drains through insulation increases moisture absorption by the insulation, which can decrease insulation's thermal performance over time. If water drains above the insulation, less moisture is absorbed by the insulation.

The authors' experience is that drainage layers located above the insulation alone are not entirely effective at limiting water at the membrane level and at limiting water absorption in the insulation. Drainage layers typically consist of plastic composite sheets butted to provide continuity, with permeable geotextile fabric adhered to the top. Water migrates through the geotextile fabric and can pass through the plastic sheet at joints, holes and other discontinuities; bypass taped seams in insulation boards; and pond on the waterproofing membrane. Water that ponds on the waterproofing membrane increases the membrane's moisture absorption, which can decrease the membrane's service life. At any defects in the membrane (for example, holes, weak and unsealed seams), the hydrostatic pressure of the ponded water can increase leakage to the building's interior. Ineffective drainage commonly contributes to leakage through the waterproofing membrane on horizontal surfaces; waterproofing membranes are more effective and durable when membrane level drainage is provided to facilitate horizontal movement of the water to the drains. Water ponding on the membrane also can be absorbed by the insulation, countering the expected benefit of placing the sole drainage layer above the insulation.

To improve thermal and waterproofing performance, two drainage layers can be provided; one drainage layer is located below the insulation, and a second drainage layer is provided above the insulation (Figure 3). The drainage layer above the insulation allows for drainage of water migrating through the soil and the moisture retention system; the membrane level drainage layer allows for horizontal travel of water that penetrates the top drainage layer.

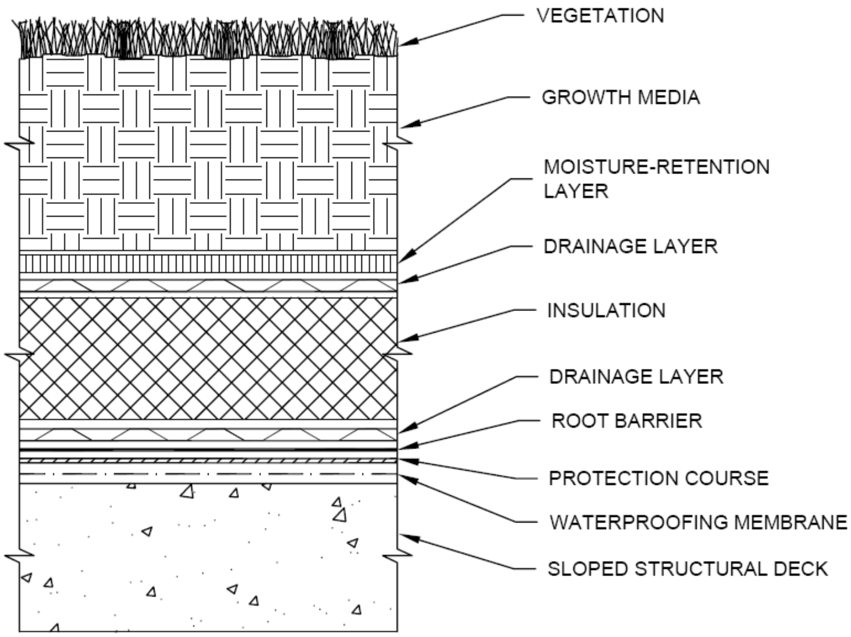

Figure 3 –Vegetative roof system with inverted assembly and drainage layers above and below the insulation.

Airflow below insulation

Air flows as a result of differences in pressures and is resisted by friction. A drainage layer at the waterproofing membrane level in vegetative roof applications is buried and not directly exposed to flowing air (wind) and will provide significantly more resistance to airflow than in an exposed system, such as plaza deck applications with open joint pavers; we are not yet able to quantify this difference. Drainage layer edges, however, may be exposed at drains, providing a potential path for airflow if pressure differences exist across the vegetative roof assembly. The magnitude and effect of convective air currents within the drainage layer remain unknown and can affect a roof assembly's energy performance in opposite ways: increased heat loss because of airflow or decreased heat loss because of the insulating value of a still air layer. The analysis described in the next section does not evaluate the difference in the convective airflow effect of an assembly with drainage layer above and below insulation to that of an assembly with drainage only above insulation.

Thermal and energy analysis

Methodology and assumptions

A mathematical model of heat flow at the membrane/deck level was developed by the authors to evaluate the effects of water drainage below insulation on thermal performance. The flow of water in the drainage layer is laminar. Therefore, the average heat transfer coefficient for laminar flow over a flat plate was used for the convection coefficient of the flow of water at the membrane/deck level (Incropera 394). A 30-foot spacing between drains was assumed, resulting in an average distance from a drain of 11.9 feet, which was used as the characteristic length in fluid flow and heat transfer calculations.

The total heat transfer between the drainage flow and roof deck was calculated based on the analytical solution of a flat surface in contact with fluid flow (Incropera 256-259). Because of the transient analysis, the heat transfer calculation includes an infinite series. For the purposes of this analysis, the series was truncated to four terms. The difference between the calculated result using the first three terms of the series and the calculated result using the first four terms of the series is less than 0.01 percent; therefore, the four- term approximation is reasonable for this analysis.

The permeability of the vegetative roof soil was calculated using a correlation to the effective grain size of the soil (D_{10}), which is valid for D_{10} sizes between 0.1 and 3.0 mm and with less than 5 percent of the soil passing the No. 200 sieve (Holtz 1981: 211). Several commercially available vegetative roof systems include soil meeting these criteria with D_{10} sizes of about 0.1 mm. Using Darcy's Law (Holtz 1981: 203) with an assumed constant hydraulic gradient through the soil, the flow rate through this soil is calculated as 10^{-6} m/s. To provide a conservative estimate of the drainage flow at the membrane/deck level, the flow rate through the soil was assumed to be the lesser of 10^{-6} m/s and the actual rainfall rate.

The thermal model was incorporated into a building energy analysis in EnergyPlus[i] Version 6.0 (DOE 2010) using the Energy Management System feature of the software program to evaluate the drainage layer heat transfer effects on annual building energy use.

The Department of Energy (DOE) "Medium Office" Commercial Reference Building models (Deru et al. 2010) were used to perform comparative whole building energy analyses for Miami, Florida; Baltimore, Maryland; and Chicago, Illinois. These locations were selected to represent a range of climates typical of the contiguous U.S. The Medium Office Reference Building was developed by DOE, National Renewable Energy Laboratory, Pacific Northwest National Laboratory and Lawrence Berkeley National Laboratory (LBNL) to be representative of a typical mid-rise (three-story) commercial office building. The total floor area of the building is 53,628 square feet.

The Medium Office building systems meet the minimum prescriptive requirements of ASHRAE 90.1-2004 (ASHRAE 2004), “Energy Standard for Buildings Except Low-rise Residential Buildings.” The building is served by a variable air volume HVAC system with electric cooling and natural gas heating. The exterior walls are steel-framed with insulation between the steel studs and, in some cases, continuous insulation outboard of the back-up wall. The roof system contains continuous insulation installed entirely above the roof deck. The roof insulation values were adjusted from those in the DOE file to reflect the minimum prescriptive requirements of the applicable building energy code for the location of each of the simulations and included 6-inch soil above the insulation in the models. The effects of thermal resistance reduction of XPS and polyisocyanurate insulation were not estimated or included in our analysis. Table 1 contains the roof insulation R-value for each location analyzed, obtained from the 2009 International Energy Conservation Code (IECC; ICC 2009) and ASHRAE 90.1-2007 (ASHRAE 2007), “Energy Standard for Buildings Except Low-rise Residential Buildings.”

Table 1 – Roof Insulation by Location

Location	Roof insulation R-value
Miami	R-15
Baltimore	R-20
Chicago	R-20

For each location, a typical meteorological year (TMY2) weather file was used to perform annual simulations. Precipitation schedules (the amount of precipitation at each time step in the analyses) were based on the TMY2 weather file for the location and "were developed using EnergyPlus' weather file (EPW) observations and the average monthly precipitation for the closest weather site provided by" the National Oceanic and Atmospheric Administration (LBNL 2010: 63). The total annual precipitation and number of days with precipitation in the simulations are summarized in Table 2 for each location.

Table 2 – Total Annual Precipitation by Location

Location	**Total annual precipitation (inches)**	**Days with precipitation**
Miami	63.9	124
Baltimore	44.6	129
Chicago	38.2	159

The analysis was simplified to consider three cases: one case with no dedicated drainage layer between the above-deck roof insulation and waterproofing membrane (the "Baseline" case that will be discussed); one case with a low magnitude of flow at a dedicated membrane level drainage layer ("Low"); and one case with a high magnitude of drainage at a dedicated membrane level drainage layer ("High"). The "Low" and "High" cases were defined based on measurements of leakage rate through the insulation layer in inverted roof assemblies at the Technical University of Berlin (Leimer 2005). In that study, the majority of the water reaching the system is stopped at the upper layer with a layer of filter fabric. The "Low" case assumes 1 percent of water reaches the membrane level, and the "High" case assumes 5 percent of water reaches the membrane level. In both cases, water reaching the membrane level was assumed to be at the greater of the exterior air temperature or 32 F. To provide an “upper bound” on the heat transfer rate, the effects of the moisture retention system used in vegetative roof assemblies, which further would decrease the amount of water reaching the drainage layer at the membrane level, was ignored.

Analysis results

Table 3 contains the annual on-site energy use for each case described, the Energy Use Index (EUI; a measure of energy use per square foot of floor area per year), and the percentage increase in annual energy use compared to the Baseline case. Because of the conservative assumptions regarding drainage water temperature and moisture flow past the water retention layer, the energy increases represent an upper bound for the assumptions outlined previously for the Low and High cases.

Table 3 – Total Annual On-Site Energy Use

Location	**Total annual site energy use (10^6 Btu)**			**Site energy use per square foot (kBtu/sf)**			**Percent increase**	
	Baseline	**Low**	**High**	**Baseline**	**Low**	**High**	**Low**	**High**
Miami	2711	2711	2711	50.6	50.6	50.6	0%	0%
Baltimore	2671	2686	2706	49.8	50.1	50.5	0.5%	1.3%
Chicago	2755	2771	2792	51.4	51.7	52.1	0.6%	1.4%

In cooler climates, the effect of a drainage layer below the insulation can be significant, particularly in the case of higher water flow volume through the insulation layer. This is because of the increase in heating energy use associated with the flow of cold water beneath the insulation, as shown in Table 4.

Table 4 – Annual Heating Energy Use

Location	**Annual heating energy use (10^6 Btu)**			**Heating energy use per square foot (kBtu/sf-yr)**			**Percent increase**	
	Baseline	**Low**	**High**	**Baseline**	**Low**	**High**	**Low**	**High**
Miami	12.4	12.7	13.2	0.23	0.24	0.25	2.6%	6.7%
Baltimore	431.6	446.6	466.8	8.05	8.33	8.70	3.5%	8.1%
Chicago	621.7	638.1	660.2	11.6	11.9	12.3	2.6%	6.2%

The effects of a drainage layer below insulation on thermal performance can be significant. The calculated total heating energy use and increased energy use for Baltimore is lower than it is for Chicago, but the percentage increase is greater for Baltimore. This likely results from the higher total annual precipitation and higher average rate of precipitation in Baltimore.

Although the relative increase in heating requirements is higher in Baltimore than in Chicago, the relative increase in total energy as shown in Table 1 is slightly higher in Chicago than in Baltimore. This is caused by the larger contribution of heating energy use to total energy use in Chicago.

The effects of the membrane level drainage layer on cooling energy use also were evaluated. The results of these simulations are shown in Table 5.

Table 5 – Annual Cooling Energy Use

Location	**Annual cooling energy use (10^6 Btu)**			**Cooling energy use per square foot (kBtu/sf-yr)**			**Percent increase**	
	Baseline	**Low**	**High**	**Baseline**	**Low**	**High**	**Low**	**High**
Miami	791.8	791.3	790.8	14.8	14.8	14.7	-0.1%	-0.1%
Baltimore	339.4	338.9	338.5	6.33	6.32	6.31	-0.2%	-0.3%
Chicago	232.4	231.8	231.2	4.33	4.32	4.31	-0.3%	-0.5%

The analysis predicted modest decreases in cooling energy use, with the relative effect increasing in cooler climates. Cooling energy loads generally are caused by internal loads and solar heat gain through glazing, with thermal transmission through the opaque building enclosure being less significant than it is for heating loads. Because of these effects, cooling generally is required even during periods when exterior temperatures are below interior temperatures. When this occurs, heat loss through the building enclosure decreases cooling requirements. Therefore, an increase in heat loss through the roof system when cooling is required and the exterior temperature is below the interior temperature will reduce cooling loads on the top floor. In colder climates, internal loads contribute a higher percentage to total cooling loads than solar heat gain through glazing. As such, the trends observed in the results of this analysis are consistent with expectations.

The effects of additional roof insulation were analyzed to determine if increased insulation R-value would mitigate the effects of drainage beneath the insulation. This analysis was performed with R-25 and R-30 roof insulation for Chicago, which exhibited the largest increase in total annual energy use and heating energy use when insulation meeting the minimum prescriptive requirements for R-value was used. Tables 6 and 7 summarize the results of this analysis. The percentage increase values are relative to the R-20 Baseline case.

Table 6 – Total Annual On-Site Energy Use in Chicago

Insulation R-value	**Annual heating energy use (10^6 Btu)**			**Heating energy use per square foot (kBtu/sf-yr)**			**Percent increase**	
	Baseline	**Low**	**High**	**Baseline**	**Low**	**High**	**Low**	**High**
R-20	2755	2771	2792	51.4	51.7	52.1	0.6%	1.4%

R-25	N/A	2760	2782	N/A	51.5	51.9	0.2%	1.0%
R-30	N/A	2753	2775	N/A	51.3	51.7	-0.1%	0.7%

Table 7 – Annual Heating Energy Use in Chicago

Insulation R-value	Annual heating energy use (10^6 Btu)			Heating energy use per square foot (kBtu/sf-yr)			Percent increase	
	Baseline	Low	High	Baseline	Low	High	Low	High
R-20	621.7	638.1	660.2	11.6	11.9	12.3	2.6%	6.2%
R-25	N/A	628.0	650.2	N/A	11.7	12.1	1.0%	4.6%
R-30	N/A	620.5	643.0	N/A	11.6	12.0	-0.2%	3.4 percent

Increasing the roof insulation mitigates the effects of the drainage layer below the insulation in the total energy use and heating energy use calculations. However, unless the water flow through the insulation layer is low and the insulation thickness is increased by 50 percent, the analysis predicts that heating energy requirements remain higher than in the Baseline case. Therefore, modest increases in insulation thickness may be insufficient to offset the effect of sub-insulation drainage on annual energy use.

Conclusions

The popularity of vegetative roof systems and the common perception that vegetative roof systems are durable, sustainable, energy-efficient and high-performing makes analysis of the waterproofing and thermal performance of these systems of particular interest to the industry. Building deck waterproofing design principles established by the industry for inverted roof assemblies apply to vegetative roof systems, and potential reductions in thermal performance often are recognized as an acceptable compromise to improve waterproofing performance.

The results of the thermal and energy analysis described in this paper, using certain assumptions, provide an “upper bound” for potential energy losses and indicate that the heat loss and energy use because of drainage below insulation in inverted systems can be significant (for example, 6 to 10 percent additional heating energy used). Effective drainage above the insulation decreases heat loss and energy use. However, drainage above insulation alone should not replace a membrane level drainage layer because omission of the latter could compromise waterproofing performance and membrane durability. Increasing insulation for inverted assemblies can mitigate the effects of drainage below insulation but may not eliminate the aggregate effect during the course of a year. The results of the analysis outlined in this paper are for the specific range of water reaching the membrane over the roof deck (1-5 percent). Other IRMA systems (for example, without soil and plantings) may result in significantly more moisture reaching the membrane and, therefore, more significantly reduce the insulation’s effectiveness.

The actual effect on thermal performance of drainage below insulation may be less significant than predicted by the analysis discussed in this paper. The analysis can be further refined through laboratory and field measurements of the parameters contributing to heat transfer between the drainage layer and roof deck. The analysis described herein is for a specific building model and may vary considerably for other buildings. For example, the effect of sub-insulation drainage on building energy use will be more significant for a building with fewer stories than the three story “Medium Office” model and the effect will be less significant for a high-rise building. Further analysis and project-specific evaluations may provide additional information to more accurately predict heat transfer through the vegetative roof system and adjust designs to mitigate the associated increase in building energy use.

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[i] EnergyPlus is building simulation software developed by the United States Department of Energy (DOE). It is capable of performing more complex heating and cooling analyses than many of the simulation programs commonly used in the industry, and it includes inputs for many building characteristics that affect energy use, including mechanical equipment, envelope construction, internal thermal mass, interior electrical loads, occupancy schedules, thermostat settings and external shading devices. EnergyPlus has been validated in accordance with ANSI/ASHRAE Standard 140-2007 (ASHRAE 2008; Henninger and Witte 2009-1; Henninger and Witte 2009-2; Henninger and Witte 2009-3; Henninger and Witte 2009-4) and ASHRAE Research Project 1052 (Henninger and Witte 2009-5). HVAC Component Comparative Tests (Henninger and Witte 2009-6), Global Energy Balance Tests (Henninger and Witte 2009-7) and IEA BESTEST In-Depth Ground Coupled Heat Transfer Tests (Henninger and Witte 2009-8) have also been performed for EnergyPlus.

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