

# ENGINEERING PERFORMANCE OF *Rooftop Gardens* THROUGH FIELD EVALUATION

By Karen Liu, Ph.D.

## ABSTRACT

Rooftop gardens or green roofs have the potential to reduce urban heat island and stormwater runoff. They can also increase membrane durability, provide green space in urban areas, and improve property value. Although green roofs represent an inexpensive adaptation strategy for urban areas, technical information on the benefits and durability, in a Canadian context, is not available. To address these issues, the National Research Council of Canada (NRC), in collaboration with members of the North American roofing industry, initiated a research project in 2000 to provide such information. The main objective of this study was to evaluate the engineering performance of green roofs through field study.

NRC constructed an experimental facility, the Field Roof Facility (FRF), on its Ottawa campus in 2000. This provided an experimental roof area of about 72 m<sup>2</sup> (800 ft<sup>2</sup>). The roof is divided in two equal areas by a 1-m (3-ft) median divider. On one side, a generic green roof was installed and on the other, a conventional roofing assembly with modified bituminous membrane was installed as a reference roof. Both roof sections were instrumented to monitor temperature profile, heat flow, solar reflectance, relative humidity, soil moisture content, and stormwater runoff. This setup allows direct comparison of the performance and benefits of the green roof and the reference roof.

Observations from the FRF showed that a generic extensive green roof with 150 mm (6 in.) of growing medium could reduce the temperature and the daily temperature fluctuation experienced by the roof membrane significantly in the warmer months. While the exposed roof membrane on the reference roof was recorded to reach over 70°C (158°F) in the summer, the membrane underneath the green roof reached about 30°C (86°F). In spring and summer, the median daily temperature fluctuation of the membrane was reduced from 42 - 47°C (76 - 85°F) on the reference roof to 5 - 7°C (9 - 11°F) under the green roof. The green roof

also significantly moderated the heat flow through the roofing system and reduced the average daily energy demand for air conditioning due to the heat flow through the roof in the summer by more than 75%. The green roof was shown to delay stormwater runoff and reduce peak runoff rate and volume. It retained 245 mm (9.64 in.) out of the 450 mm (17.72 in.) of rain that fell from April to September 2002 - a reduction in runoff of 54%.

## Introduction

Green roofs or rooftop gardens are roofs planted with vegetation. Green roofs are not a new concept and can be traced back to the hanging gardens of Babylon.<sup>1</sup> With advances in roofing materials, innovative research, and technical development of roofing components, green roof systems can now be installed successfully under most climatic conditions. Given the limited space available for parks and green space in many North American metropolitan cities, placing the vegetation on otherwise unused building rooftops becomes an attractive building design option.

Green roofs not only add aesthetic appeal to the unused roof space that is available in most urban areas, they also provide many benefits. Green roofs can protect the membrane from exposure to ultraviolet radiation and hail damage. They can reduce energy demand on space conditioning, and hence greenhouse gas emissions, through direct shading of the roof, evapotranspiration, and improved insulation values<sup>2,3,4,5,6,7</sup>. If widely adopted, green roofs could reduce the urban heat island<sup>8,9</sup> (an elevation of temperature relative to the surrounding rural or natural areas due to the high concentration of heat-absorbing dark surfaces such as rooftops and pavements) that would further lower energy consumption in the urban area.

They can also be used as part of the stormwater management strategy in the urban area. Part of the rain is temporarily stored in the growing medium, to be taken up by the plants and returned to the atmosphere through evapotranspiration.<sup>2,7,10,11</sup> Green roofs delay runoff into the sewage system, thus helping to

reduce the frequency of combined sewage overflow (CSO) events, which is a significant problem for many major cities in North America<sup>7</sup>. The plants and growing medium can also remove airborne pollutants picked up by the rain, thus improving the quality of the runoff. In addition, green roofs can improve air quality, provide additional green space in urban areas, and increase property values.<sup>12</sup>

Green roofs are found throughout many European countries, such as France, Germany, and Switzerland. Green roofs have become a multi-million dollar industry in Germany,<sup>12</sup> where a significant amount of technical research was carried out on root repelling agents, waterproof membranes, drainage, lightweight growing media, and plants. Green roofs are rapidly gaining popularity across different parts of the world as well. In North America, Portland, Oregon, has pioneered an incentive program (Clean Air Incentive and Discount Program) to encourage the installation of green roofs on commercial, industrial, institutional, and residential properties, with the aim of reducing the stormwater runoff problem and relieving the load on the sewage infrastructure.<sup>13</sup> In Asia, Tokyo, Japan, has initiated a new ordinance to install green roofs on new buildings with floor space more than 1000 m<sup>2</sup> (10,800 ft<sup>2</sup>) to mitigate the urban heat island effects.<sup>14</sup>

A green roof system requires additional components (Figure 1). These components consist of a specialized roof waterproofing membrane, a drainage layer, a filter membrane, a growing medium, and vegetation.

1. **Waterproofing Membrane:** The most important component of any roofing system is the waterproofing membrane that prevents water penetration into the building. To prevent root damage to the roofing membrane, some manufacturers incorporate a root repellent agent in the formulation of the product, while others offer a physical root barrier, which can be a layer of PVC, TPO, or high-density polypropylene.
2. **Drainage Layer:** The drainage layer is installed over the waterproofing membrane to remove excess water from the growing medium. This comes in different forms – from a simple layer of gravel to specialized polymer foam panels or highly porous polymeric mat. In some cases, the drainage

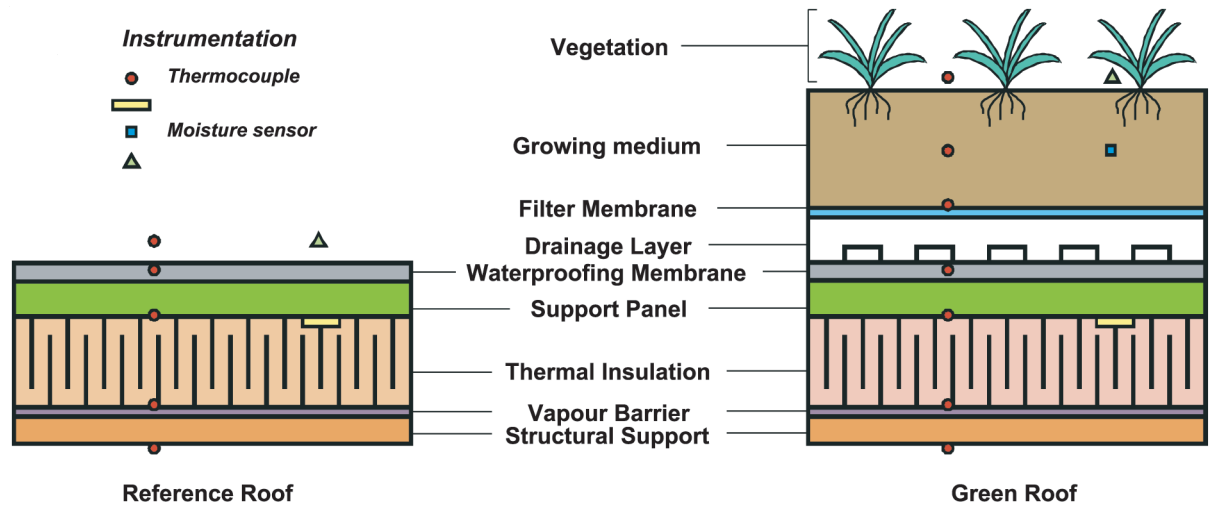


Figure 1 - Major components and instrumentation location of the green roof and the reference roof.

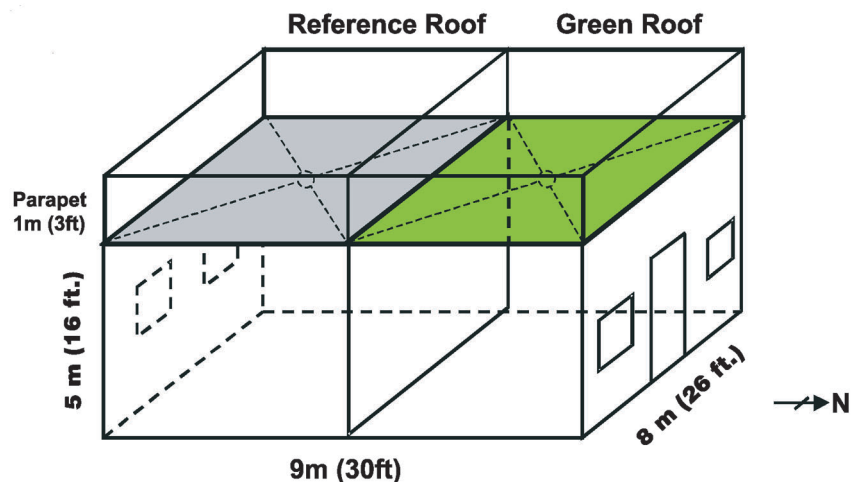


Figure 2 - Schematics of the Field Roofing Facility (FRF) at the NRC campus in Ottawa. Each roof section is sloped at 2% to a central drain where the runoff is collected and monitored in the building.

- layer can also be designed to retain some water and serve as a reservoir for irrigating the plants between rainfalls.
3. **Filter Membrane:** The filter membrane is a geotextile filter fabric that is installed on top of the drainage layer. It prevents fine particles in the growing medium from clogging the drainage layer.
4. **Growing Medium:** The growing medium supports plant growth. Its composition and depth depend on the vegetation selected. Water-saturated soil can be heavy, and the roof structure should be designed to bear the load. Artificial lightweight growing medium can be used to replace regular soil to reduce the weight.
5. **Vegetation:** The plants should be selected for their adaptability to the local climate. Considerations should be given to the more extreme conditions experienced on rooftops, such as exposure to a wide range of temperatures and soil moisture levels, higher winds (erosion of plants and soil), and solar exposure. An irrigation system might be needed, depending on the plants and weather conditions.



Figure 3 – A wildflower meadow (left) was established on the Field Roofing Facility (FRF) on the NRC campus in Ottawa (2001).

The National Research Council of Canada (NRC), in collaboration with members of the North American roofing industry, is leading a research project to study the thermal performance and environmental benefits of green roof technology. The objectives of this project are to identify sensitivities to climate variability and to quantify the benefits of the technology under Canadian climatic conditions. This paper summarizes the results and findings from the first two years of this study.

### Experimental Study

NRC has constructed the Field Roofing Facility at its Ottawa campus in Canada (Figure 2). It provides an experimental roof area of about 72 m<sup>2</sup> (800 ft<sup>2</sup>) and can represent a low-slope industrial roof with a high roof-to-wall ratio. The roof is divided into two equal areas separated by a median divider. A generic extensive green roof was installed on one side, and a modified bituminous roofing assembly was installed as a reference on the other. The reference roof represents a conventional system commonly installed in Canada. It consists of a structural deck, a vapor barrier, thermal insulation, support panel, and a 2-ply modified bituminous waterproofing membrane. The cap sheet is covered with light, gray-colored granules, which are intended to avoid the extreme colors of a reflective white membrane or a dark, built-up roof surface. While the green roof has the same basic components up to the mem-



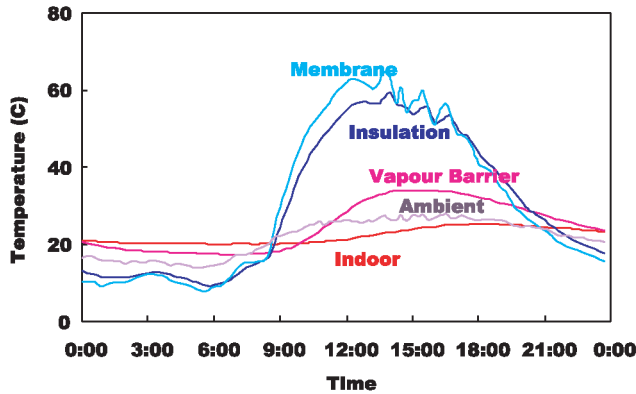
Below: Figure 4 – The sod two weeks after installation (2002). Note that the median divider separates the green roof (right) and the reference roof (left). The weather station is located at the median divider.

brane level, it incorporates additional elements (such as roof repellent) in the membrane, a drainage layer, a filter membrane, and a lightweight growing medium (150 mm or 6 in.) to support plant growth.

Figure 1 shows the components and configurations of the two roofing systems. In the first year of the study (2001), a wildflower meadow was established in the garden, and, in the second year (2002), the garden was planted with sod (Kentucky blue grass). The facility as it appeared in the summer of 2001 and 2002 is shown in Figures 3 and 4.

Both the green roof and the reference roof are instrumented to measure the temperature profile within the roofing system, heat flow across the system, solar reflectance of the roof surface, soil

## Reference Roof



## Green Roof

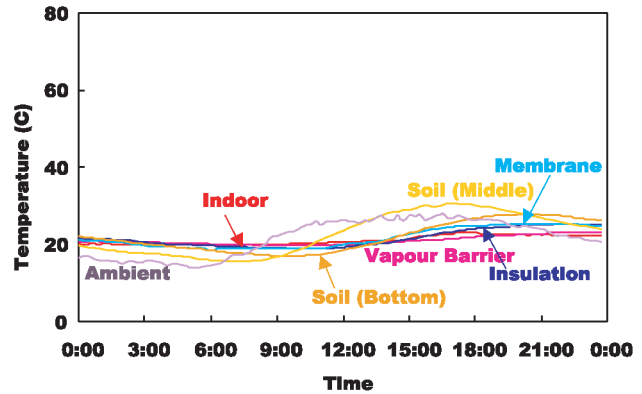


Figure 5 - Temperature profile within the roofing systems on a summer day (July 16, 2001) indicating that the green roof reduces the temperature fluctuations within the system.

moisture content, microclimate created by the plants, and stormwater runoff (Figure 1). The local meteorological data, such as temperature, relative humidity, rainfall, and solar radiation, are monitored continuously by a weather station located at the median divider on the rooftop and an additional weather station situated approximately 50 m (160 ft) from the site. All sensors are connected to a data acquisition system for monitoring.

## RESULTS AND FINDINGS

The Field Roofing Facility has been in operation since November 2000. The data collected from the first two years of operation (November 2000 to September 2002) have been analyzed and are summarized below.

### Temperature Profile

An exposed roof membrane absorbs solar radiation during the day and its temperature rises. The extent of the temperature increase depends on the color of the membrane. Light color membranes are cooler because they reflect solar radiation, but dark color membranes are hotter because they absorb much of the solar radiation. Results from the FRF show that the roof membrane on the reference roof experienced much higher temperatures than that on the green roof. Figure 5 shows the temperature profile within the roofing systems on a summer day. The membrane on the reference roof absorbed the solar radiation and reached close to 70°C (158°F) in the afternoon. However, the membrane on the green roof remained around 25°C (77°F).

Table 1 compares the number of days out of the observation period (a total of 660 days) when the maximum roof membrane temperature exceeded various levels. For example, there are 219 days out of the 660 days (i.e., 33%) observed during which the membrane on the reference roof reached a temperature above 50°C

Temperature Greater Than:	Reference Roof		Green Roof		Ambient	
	No. of Days	% of Days	No. of Days	% of Days	No. of Days	% of Days
30°C (86°F)	342	52	18	3	63	10
40°C (104°F)	291	44	0	0	0	0
50°C (122°F)	219	33	0	0	0	0
60°C (140°F)	89	13	0	0	0	0
70°C (158°F)	2	0.3	0	0	0	0

Table 1: Statistics on the daily maximum temperature of the roof membranes on FRF during the observation period (660 days in total).

(122°F). However, the roof membrane exceeded 60°C (140°F) only on 89 of the 219 days – 13% of the days observed during this period (i.e., 89 days out of 660). While the ambient temperature exceeded 30°C (86°F) for 10% of the days during the 22-month observation period, the membrane temperature of the reference roof went above 30°C (86°F) over half of the time, compared to only 3% for the green roof. In fact, the reference roof membrane reached over 50°C (122°F) about one third of the days during the observation period and over 70°C (158°F) in the extreme conditions. Note that the color of the membrane was light gray; the temperature of a dark color membrane would be expected to be even higher.

Heat exposure can accelerate aging in bituminous material, thus reducing its durability. In the roofing industry, heat aging at 70°C (158°F) is commonly used as an accelerated aging test for these materials (e.g., ASTM D 5869, “Standard Practice for Dark Oven Heat Exposure of Bituminous Materials”). Ultraviolet radiation can change the chemical composition and degrade the mechanical properties of the bituminous materials. Although long-term durability data are not yet available from the study, the growing medium and the vegetation of the green roof can prevent the UV radiation from attacking the roofing membrane and minimize aging of the membrane from heat exposure, which might extend the life of the membrane.

## Membrane Temperature Daily Fluctuation (Nov 22, 2000 - Sep 30, 2002)

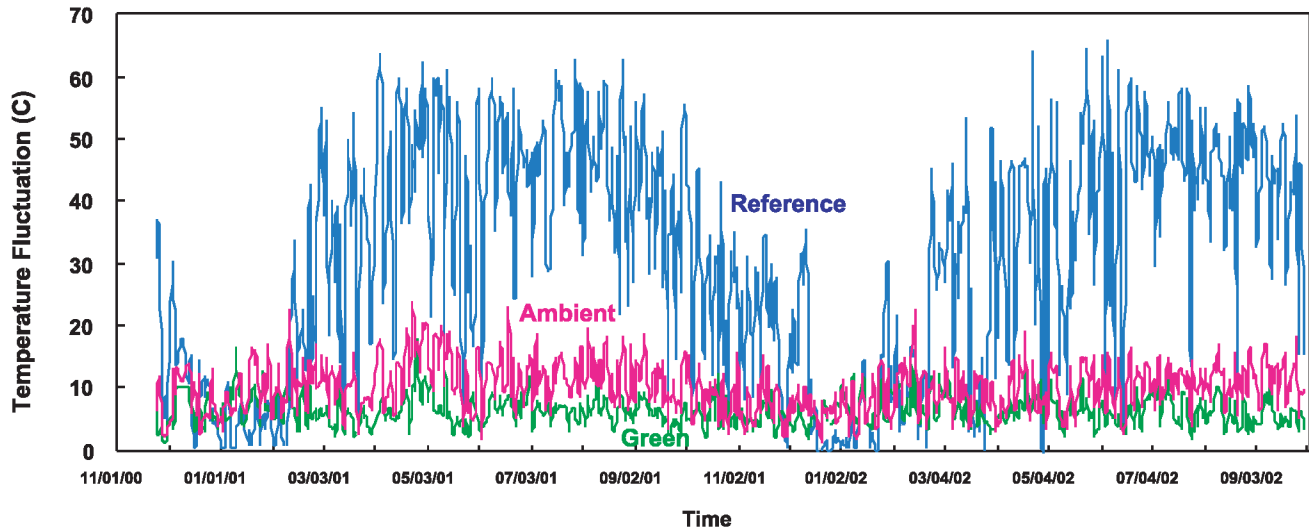


Figure 6 – Temperature measurements showed that the green roof significantly reduced the daily temperature fluctuations experienced by the membrane.

### Temperature Fluctuations

An exposed membrane absorbs solar radiation during the day and its surface temperature rises. It re-radiates the absorbed heat at night and its surface temperature drops. Diurnal (daily) temperature fluctuations create thermal stresses in the membrane, affecting its long-term performance and its ability to protect a building from water infiltration. *Figure 6* shows the daily membrane temperature fluctuation (daily maximum temperature - daily minimum temperature) of the reference roof and the green roof and the daily ambient temperature fluctuations.

The green roof moderated the daily temperature fluctuations that the membrane experienced during early winter (November and December), while the membrane temperature of the reference roof followed the daily ambient temperature fluctuations. This protection was somewhat dissipated during the accumulation of

snow, and once heavy snow coverage was established (January and February), both roofing membranes were protected from temperature fluctuations. The green roof significantly moderated the daily temperature fluctuations experienced by the membrane during the spring and the summer. The daily membrane temperature fluctuations of the green roof were consistently lower than the diurnal ambient temperature fluctuations. *Table 2* summarizes the daily temperature fluctuations in the roof membrane and the atmosphere over the observation period. The exposed membrane in the reference roof experienced high daily temperature fluctuation, with a median of 42 - 47°C (76 - 85°F). However, the green roof reduced the temperature fluctuation in the membrane throughout the year, keeping a median fluctuation of 5 - 7°C (9 - 11°F) only.

### Energy Efficiency

The green roof was found to be effective in helping to keep the building cool in the summer. The plants and the growing medium in the green roof kept the membrane cool by direct shading, evaporative cooling from the plants and the growing medium, additional insulation values from both the plants and the growing medium, and the thermal mass effects of the growing medium.

Heat flow through the building envelope creates energy demand for space conditioning in a building. *Figure 7* shows the heat flow through the roof on a summer day as measured by the three heat flux transducers embedded in each roof section. These transducers were calibrated such that positive heat flow represents heat entering the roof at the installed

Observation Period	Median Daily Temperature Fluctuation (daily maximum temp - daily minimum temp)		
	Reference Roof Membrane	Green Roof Membrane	Ambient
Winter 2001	9°C (16°F)	6°C (11°F)	10°C (18°F)
Spring 2001	46°C (83°F)	6°C (11°F)	13°C (23°F)
Summer 2001	47°C (84°F)	7°C (13°F)	12°C (22°F)
Fall 2001	23°C (41°F)	5°C (9°F)	8°C (14°F)
Winter 2002	9°C (16°F)	7°C (13°F)	9°C (16°F)
Spring 2002	42°C (76°F)	6°C (11°F)	10°C (18°F)
Summer 2002	47°C (84°F)	6°C (11°F)	12°C (22°F)

Table 2: Median daily temperature fluctuation of the roof membranes on FRF during the observation period (Nov. 22, 2000 - Sep. 30, 2002).

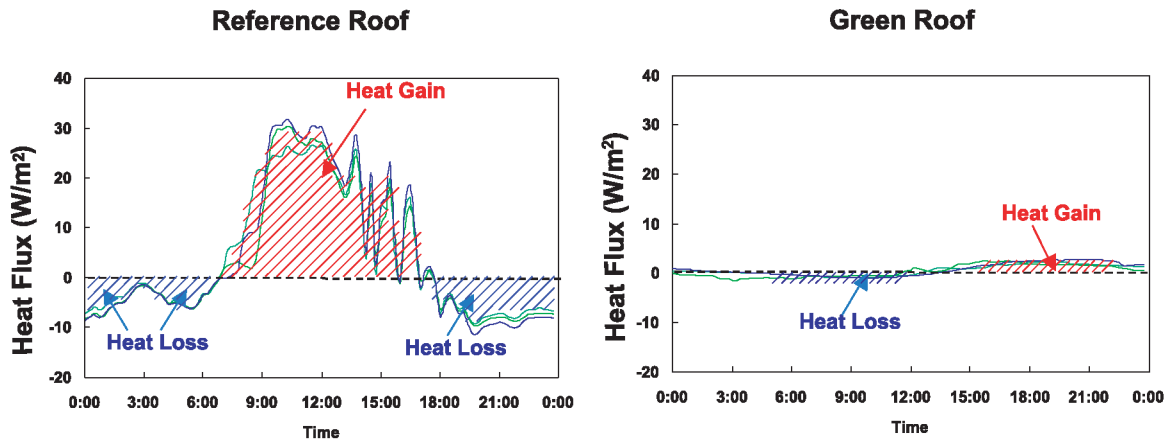


Figure 7 – Heat flow through the roofing systems on a summer day (July 16, 2001) indicated that the green roof reduced the heat flow significantly through the system.

location, while negative heat flow means heat leaving the roof. The membrane on the reference roof, being exposed to the elements, absorbed solar radiation during the day and re-radiated the absorbed heat at night, creating positive heat flow in the afternoon and negative heat flow in the early morning and evening. The green roof significantly moderated the heat flow between the building and its surroundings through the system. In the winter, data from the FRF showed that once the snow cover was established, the heat flow through both the reference roof and the green roof became the same, as snow provided good insulation and stabilized heat flow through the roof.

Figure 8 summarizes the average daily energy demand for space conditioning due to heat flow through the roof only. The energy efficiency of the green roof was slightly better than that of the reference roof in the fall and early winter, as the green roof system acted as an insulation layer. However, as the growing medium froze, its insulation value was greatly diminished. Snow cover provided excellent insulation for the roofing system and stabilized the heat exchange between the building and its surroundings. The snow cover on the roof was not uniform in early winter, due to wind and the influence of the high parapet. Once snow cover was established, heat flow through both roofs was almost the same.

The green roof significantly outperformed the reference roof in spring and summer (April to September). Solar radiation has a strong influence on the heat flow through the roof. The membrane on the reference roof, being exposed to the elements, absorbed solar radiation during the day and re-radiated the absorbed heat at night, creating high energy demand for space conditioning. On the other hand, the growing medium and the plants enhanced the thermal performance of the green roof by providing shading, insulation, and evaporative cooling. It also acted as a thermal mass, which effectively damped the thermal fluctuations going through the roofing system. The average daily energy demand due to the heat flow through the reference roof was 6.0-7.5 kWh/day (20,500-25,600 BTU/day), as shown in Figure 8.

**Average Daily Heat Flow Through Roof Systems  
(Nov 22, 2000 - Sep 30, 2002)**

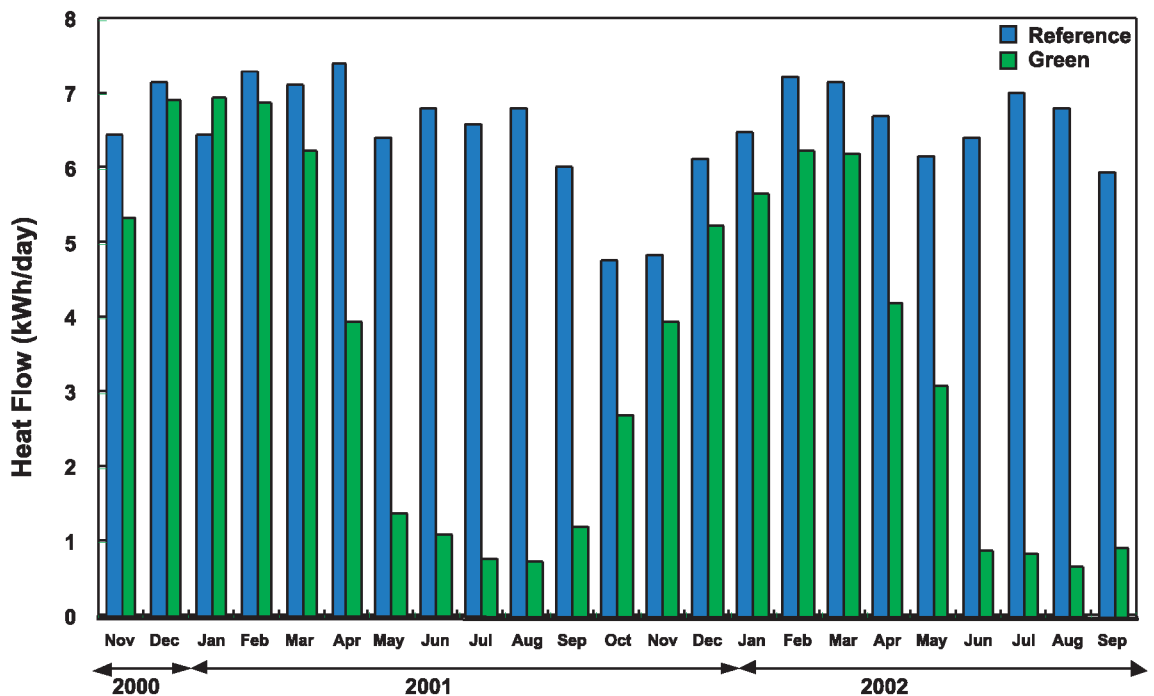


Figure 8 – Heat flow measurement showed that the average daily energy demand due to the heat flow through the green roof was significantly less than that of the reference roof in the spring and summer.

The green roof sig-



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	Reference Roof	Green Roof	Reduction
<b>Heat Gain</b>	19.3 kWh/m <sup>2</sup> (5900 BTU/ft <sup>2</sup> )	0.9 kWh/m <sup>2</sup> (270 BTU/ft <sup>2</sup> )	95%
<b>Heat Loss</b>	44.1 kWh/m <sup>2</sup> (13500 BTU/ft <sup>2</sup> )	32.8 kWh/m <sup>2</sup> (10100 BTU/ft <sup>2</sup> )	26%
<b>Total Heat Flow</b>	63.4 kWh/m <sup>2</sup> (19400 BTU/ft <sup>2</sup> )	33.7kWh/m <sup>2</sup> (271 BTU/ft <sup>2</sup> )	47%

Table 3 – Normalized (per unit area) heat flow through the roof surfaces of FRF during the observation period (Nov 22, 2000 - Sep 30, 2002).

However, the growing medium and the plants of the green roof modified the heat flow and reduced the average daily energy demand to less than 1.5 kWh/day (5,100 BTU/day), a reduction of over 75%. Note that these values were due to the heat flow through the roof only (36 m<sup>2</sup> or 400 ft<sup>2</sup>) and did not include heat flow through other parts of the building envelope.

The green roof was more effective in reducing heat gain in the spring/summer than heat loss in the fall/winter. This is because the green roof can reduce heat gain through shading, insulation, evapotranspiration, and thermal mass. However, it can reduce heat loss only through improved insulation and decreased radiation heat losses. This is effective on summer evenings but not in winter, when the growing medium is frozen and the improved insulation and decreased radiation heat loss effects are dominated by snow cover.

Table 3 shows the total heat flow through the assemblies of FRF normalized with the roof area from November 2000 to September 2002. During the 22-month observation period, the green roof reduced 95% of the heat gain and 26% of the heat loss as compared to the reference roof, with an overall heat flow reduction of 47%. Since an extensive green roof was more effective in reducing heat gain than heat loss, and Ottawa is in a predominantly heating region, it is expected that its effectiveness will be more significant in warmer regions.

### Stormwater Runoff

The green roof delayed stormwater runoff and reduced both the peak runoff rate and the runoff volume. The extent of the reduction depends on many factors, such as the rain intensity, duration, and the wetting history of the growing medium (the moisture content of the growing medium before the rain event). For example, during a light rain of 19 mm (0.75 in.) in 6.5 h, the green roof delayed the runoff by 95 minutes and the runoff volume was 2.9 mm (0.11 in.) – a reduction of 85% (Figure 9a). On the other hand, during a heavy rain of 21 mm (0.83 in.) in 21 minutes, the green roof delayed the runoff only by four minutes and the runoff volume was 5.7 mm (0.22 in.) – a reduction of 73% (Figure 9b).

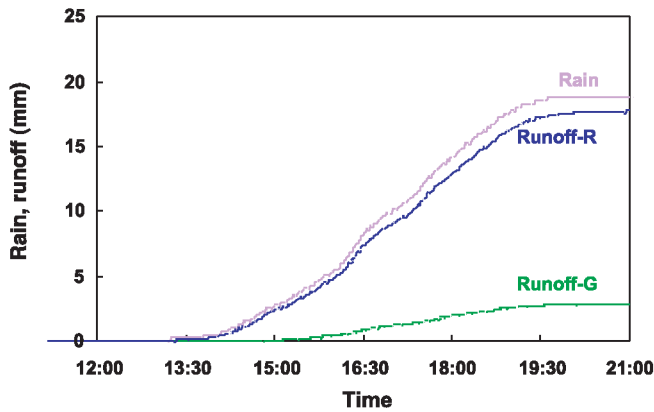
Figure 10 shows the total rain and runoff measured at the FRF during spring and summer 2002. Note that the green roof was not as effective in June as in the other months. This was because it rained steadily during June, so the growing medium did not have enough time to dry out between rainfall and was saturated with water. This reduced the runoff retention efficiency significantly. In total, the green roof retained (and diverted through evaporation/evapotranspiration) 245 mm (9.64 in.) out of the 450 mm (17.72 in.) of rain that fell during April to September 2002 - a runoff reduction of 54%.

The green roof was an extensive system with grass growing in 150 mm (6 in.) of light-weight soil. It is expected that green roof systems could be designed with deeper and more absorbent soil and more vegetation to deliver even greater stormwater retention.

### CONCLUSIONS

Observation from the Field Roofing Facility showed that a generic extensive green roof with 150 mm (6 in.) of growing medium could reduce the temperature of the membrane significantly in the summer. The exposed membrane on the reference roof exceeded 70°C (158°F) in the summer, but that under the green roof rarely reached over 30°C (86°F). Also, the green roof moderated the temperature fluctuations that the roof membrane experienced, especially in the warmer months. The median daily temperature fluctuation of the mem-

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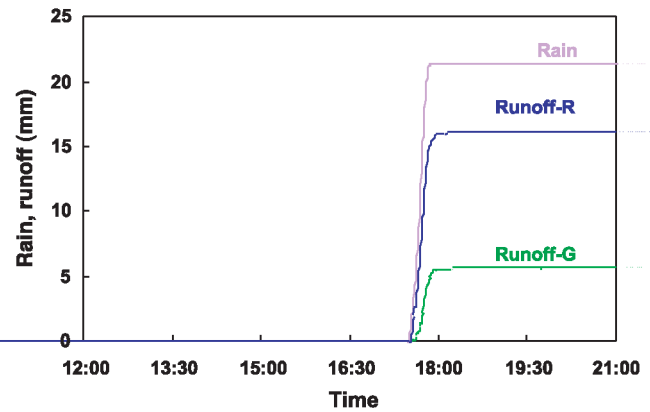


Figure 9 - Hydrographs (cumulative rainfall plots) of two rain events of different rain intensity (a) light rain and (b) heavy rain.

brane on the reference roof in spring and summer ranged from 42 to 47°C (76 to 85°F). However, the green roof reduced the temperature fluctuation to 5 - 7°C (9 - 11°F). The green roof also significantly moderated the heat flow through the system in the warmer months. The average daily energy demand for space conditioning due to the heat flow through the roof was reduced from 6.0 - 7.5 kWh/day (20,500 - 25,600 BTU/day) to less than 1.5 kWh/day (5,100 BTU/day) as measured on the reference roof and the green roof, respectively. This corresponded to a reduction of over 75%. The green roof was shown to delay runoff and reduce peak runoff rate and volume. It retained 245 mm (9.64 in.) out of the 450 mm (17.72 in.) of rain that fell from April to September 2002 - a reduction of 54%.

### Implications from the Study

Analysis of the data collected from the Field Roofing Facility suggests that an extensive green roof can lower the temperature and modify the temperature fluctuations that are experienced by roof membranes. The reduction in temperature reduces the effects of heat aging from natural exposure and the moderation in temperature fluctuations decreases the thermal stress on the membrane. Both mechanisms can possibly extend the life of the roof membrane. The reduction in surface temperature can help to lower the urban heat island effects as well. Green roofs can moderate heat flow through the roof by shading, insulation, evapotranspiration, and thermal mass effects. This reduces the energy demand for space conditioning, most significantly in spring and summer. Green roofs can also delay runoff and reduce both the peak runoff rate and volume. This delay in peak flow and reduction in runoff volume suggest that green roofs can reduce the load on stormwater sewage infrastructure and help minimize the frequency of combined sewage overflow (CSO) events in urban areas. ■

### Acknowledgement

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### Rain and Runoff Measured at FRF (April 2002 - September 2002)

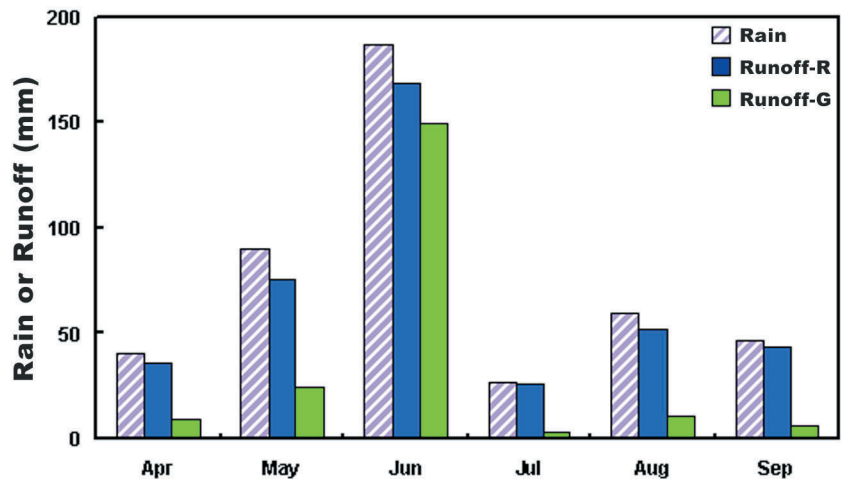


Figure 10 - Rainfall and runoff measured at the FRF during April to September 2002.

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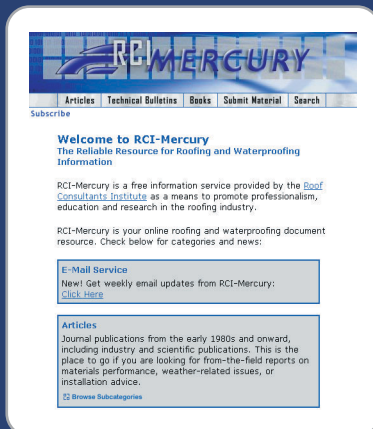
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## ABOUT THE AUTHOR

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