Urban Ecosyst (2008) 11:339–348
DOI 10.1007/s11252-008-0069-4

Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate

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Abstract Green roofs have the potential to retain stormwater on the roof surface and lower the thermal loading on buildings. Because of this, the greatest environmental benefits from green roofs might be achieved in subtropical climates characterized by high temperatures and intense rain events. There is, however, little research to support this. In a replicated study in Texas, we compared the performance of six different extensive green roof designs vegetated with native species, to non-reflective (black) roofs, and reflective (white) roofs. Preliminary hydrologic and thermal profile data indicated not only differences between green and non-vegetated roofs, but also among green roof designs. Maximum green roof temperatures were cooler than conventional roofs by 38°C at the roof membrane and 18°C inside air temperature, with little variation among green roofs. Maximum run-off retention was 88% and 44% for medium and large rain events but some green roof types showed very limited retention characteristics. These data demonstrate indicate that: 1. Green roofs can greatly affect the roof temperature profile—cooling surface layers and internal space on warm days. 2. Green roofs can retain significant amounts of rainfall, this is dependent on the size of the rain event and design and can fail if not designed correctly. We suggest that as green roofs vary so much in their design and performance, they must be designed according to specific goals rather than relying on assumed intrinsic attributes.

Keywords Green roofs · Subtropical climate · Native plants · Temperature · Storm water

Introduction

The technology underlying green roof design is complex, comprising many abiotic (substrate depth, weight, and composition, drainage layer and root barrier design) and biotic

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(plant species composition, substrate chemistry, and water availability) variables. Given the claimed intrinsic and extrinsic benefits of green roofs (see Getter and Rowe 2006 for review), there has been a desire by designers and building owners to adopt this new technology in spite of a limited understanding of the mechanisms which underlie the performance characteristics and therefore confusion about the broader potential benefits. Consequently, green roofs are increasingly being incorporated as a sustainable practice in building design, often without specific attention to designing the roof to achieve specific functions, or to the conditions of a specific climatic region.

Although the building and environmental benefits of green roofs in temperate systems have been documented in several countries (Kohler et al. 2002; Liu and Minor 2005; Getter and Rowe 2006), the investigation of similar benefits in other ecosystems have been somewhat neglected. In warmer, non-temperate systems where there are greater climatic extremes (e.g. high daytime temperatures, frequent flash flood events), green roofs may offer relatively larger intrinsic (e.g. cooling building, extension of roof membrane lifetime) and extrinsic (e.g. flash flood mitigation, reduction of heat island effect) benefits (Niachou et al. 2001; Kohler et al. 2002; Wong et al. 2003). While a general comparison of green versus conventional roofs has been addressed, and examination of a few of the major design variables such as substrate type and depth has been conducted (Rowe et al. 2003; VanWoert et al. 2005; Rowe et al. 2006), there are several variables and interactions between variables which have been overlooked. These include construction of drainage layer, monolithic versus modular construction, presence of retention blanket and other biotic effects such as plant effects on cooling and retention (Dunnett et al. 2005).

We set out to test suitability of green roofs in a subtropical climate and if the benefits ascribed to green roofs applied equally to all green roof designs or if different green roof designs in fact excel in different areas and have different limitations. To address some of these issues the goal of this project was to examine hydrologic, thermal and biotic responses and interactions of six different extensive green roof designs planted with identical native species, and two conventional (non-reflective black and reflective white roofs). The key questions tackled in this preliminary report are:

- What are the vertical temperature profiles of different green roofs, reflective and non-reflective roofs?
- What are the stormwater retention capacities of different green roofs, reflective and non-reflective roofs?

Methods

Experimental platforms were erected in a former pasture in Austin, Texas (30°11′ N, 97°52′ W; elevation 247 m; mean annual rainfall 810 mm). Climate is subhumid, subtropical with a bimodal rainfall pattern peaking in spring (April–June) and fall (September–October).

A total of 24 roof platforms were constructed representing black, non-reflective roofs, white reflective roofs (as defined by Cool Roof Rating Council), and six different green roof designs, each replicated three times. The coarse structure of the green roofs was identical across all types: membrane root barrier, drainage layer and 100 mm of substrate (growing media), however actual materials and some vertical arrangement varied among manufacturers (Table 1; Fig. 1). Where a rigid water retention cup system was installed, volumetric retention density was estimated by pipetting water into samples of the drainage structure, and proportion of drainage holes by physical measurement with vernier calipers. Specific substrate composition

Table 1 Green roof structural components by manufacturer

Roof	Black	White	A	B	C	D	E	F
Type								
Monolithic			Y	Y		Y	Y	Y
Modular					Y			
Substrate								
Decomposed granite						Y		
Expanded clay				Y	Y		Y	Y
Expanded shale			Y	Y			Y	Y
Sand			Y	Y	Y		Y	Y
Perlite					Y	Y		
Large size organic matter (>5 mm)				Y				Y
Small size organic matter (<5 mm)			Y	Y	Y	Y	Y	Y
Fertilizer						Y		
Drainage/membrane								
Volumetric soil water (%)±s.e.			34±2	37±4	43±4	46±3	38±4	32±1
Water retention mat								Y
Filter fabric/root barrier: polyester			Y					
Filter fabric: polyester				Y	Y	Y	Y	Y
Drainage layer: undulating spun plastic						Y	Y	
Drainage layer: plastic retention cups			Y	Y	Y			Y
Retention cup capacity (l m^{-2})			1.85^{a}	3.33^{a}	3.00^{ab}			3.64^{a}
Drainage hole area in retention layer (%)			8.73^{a}	0.06^{a}	0.68^{a}			11.72^{a}
Filter fabric/water retention: spun plastic						Y	Y	
Root barrier			Y					
PVC single ply membrane						Y		
Water retention mat				Y				
Root barrier plastic sheeting				Y				
Protection layer:1-ply modified bituminous membrane				Y			Y	Y
Membrane: 2-ply modified bituminous			Y				Y	
Membrane: hot-melt modified bituminous with polyester reinforcement				Y				Y
EPDM synthetic rubber membrane					Y			
Unsurfaced 2-ply APP modified bituminous membrane	Y							
Acrylic surfaced 2-ply APP modified bituminous membrane		Y						

Letter “Y” indicates roof structural components by manufacturer

[a] Data estimated by authors and not that provided by manufacturer

[b] Due to large shallow cup dimensions and overlying non rigid filter fabric, the actual cup capacity is reduced due to displacement by overlying substrate

was proprietary information, however each of the six substrate types contained one or more of the following: expanded shale/clay, vermiculite, sand, organic matter (Table 1).

Each test platform comprised 2.0 by 1.7 m metal platform with prefinished metal skinned insulated siding (*R* value of 30) with air gaps sealed, and two-layer extruded polystyrene ground-level insulation (*R* 30). Roof system assembly was 22 gauge galvanized metal deck, one layer of polyisocyanurate foam insulation (LTTR=12.1) mechanically attached with screws and plates with gypsum coverboard and membrane adding additional 0.5 and 0.3 *R*

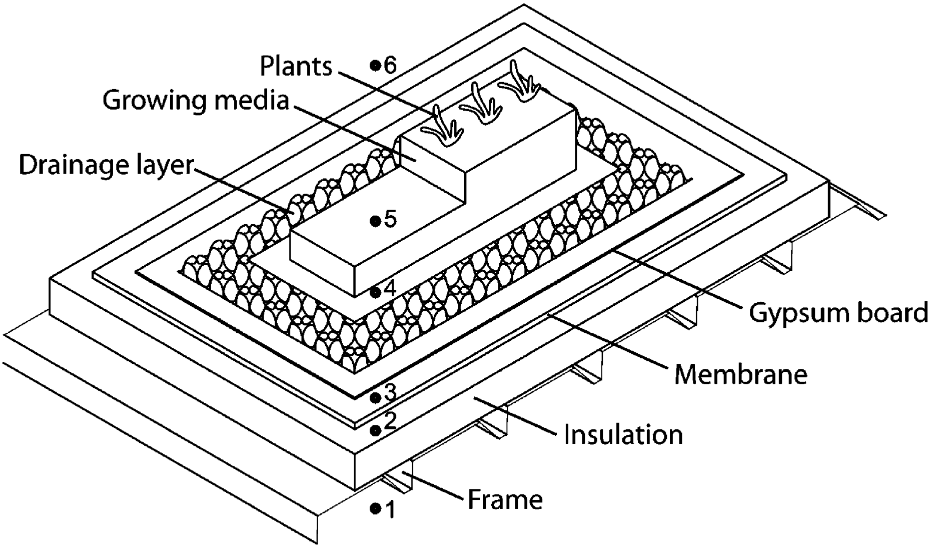


Fig. 1 Structural components of experimental green roof platform. *Solid circles* represent thermocouple locations: *1* inside platform, *2* on top of insulation, *3* on top of gypsum board, *4* on top of drainage layer, *5* inside growing media, *6* above plants in radiation shield

values respectively. Thermocouples placed throughout the roof strata on all 24 platforms measured the temperature profile for green roofs (50 mm inches below substrate surface, drainage layer, membrane, insulation, and inside the platform) and conventional roofs (membrane, insulation, and inside the platform) (Fig. 1) and signal fed to a Campbell Scientific CR23X data logger. Run-off was collected through a single 10×10 cm scupper and directed via PVC pipe through a SeaMetrics SPX flow meter connected to the data logger. Due to design constraints, anomalous values (single values tending toward zero) frequently occurred due to the flow meters becoming disabled due to particle blockage, these readings were removed from analysis limiting complete flow data to only a few rain events.

Native perennial plants (Table 2) were installed during August 2006 and hand watered to maintain an equivalent minimum 20 mm per week when there was inadequate rainfall during the 2006 and 2007 growing seasons. Climate data was taken from nearby (1.2 km) automatic weather recording station maintained by Weather Underground (www.wunderground.com). Performance data reflected in this report represents data recorded after initial plant establishment during fall (October through November) 2006 and spring (March through June) 2007 when the majority of the plants were physiologically active. For both thermal and run-off analyses three events are case studied to represent range of conditions and the roof performances throughout across this period. Repeated measures analysis of variance using statistical software package NCSS (Hintze 2001) were used for statistical analyses and the Tukey test used for multiple comparisons (α=0.05).

Results

Temperature profiles

Although there are significant diurnal temperature variations for all profile locations and roofs, the green roofs exhibited damped amplitude throughout the roof profile, and a shifted

Table 2 Plant species and associated physiological guild

	Physiological guild
Graminoids	
Bouteloua curtipendula	C4
Bouteloua gracilus	C4
Bouteloua rigidisete	C4
Carex texensis	C3
Hilaria belangerii	C4
Nassella tenuissima	C3
Forbs	
Bignonia capreolata	C3
Dalea greggii	C3
Echinacea purpurea	C3
Hesperaloe parviflora	CAM
Manfreda maculosa	CAM
Salvia farinacea	C3
Salvia greggii	C3
Scutellaria wrightii	C3
Stemodia lanata	C3
Tetraneuris scaposa	C3

temperature peak 1–3 h later than conventional roofs, particularly below the membrane. On warm sunny days the temperature of the roof membrane, insulation layer and inside the experimental platform was significantly modified (May 31; Fig. 2). Where black and white roof membrane temperatures reached 68°C and 42°C respectively in mid afternoon on a warm day when ambient air temperature reached 33°C, equivalent green roof membrane temperatures ranged between 31–38°C (Fig. 2). Similarly, where internal temperatures reached 54°C under black roofs, 50°C under white roofs, green roof internal temperatures ranged from 36–38°C (Fig. 2). On a moderately warm day (maximum ambient temperature= 27°C; March 12; Fig. 2) maximum membrane temperatures on black roofs peaked at 56°C, white roofs at 32°C and green roofs between 22–27°C. Inside air temperatures were 45°C and 40°C for black and white roofs respectively, compared with green roof temperatures ranged from 27–29°C. However, during cooler days (maximum ambient temperature 5°C; April 7; Fig. 2) membrane temperatures of black and cool roofs were significantly cooler than green roofs (by 2–5°C).

There were differences among green roofs within the profiles but these were not expressed inside the platforms. Green roofs D and C were somewhat cooler than the other green roof types through the upper part of the profile from membrane to substrate. Roof types A and B performed less well than others—marginally (2–5°C) warmer than types D and C through the profile during the temperature peak on moderate and hot days, with green roofs E and F intermediate between these temperatures.

Run-off

All three reported rain events had experienced some rainfall within the previous 3–4 days (Table 3). Green roofs generally delayed runoff (peak to peak) by approximately 10 min following medium to large rain events. Small rain events less than 10 mm were fully absorbed by all green roofs (data not shown). Generally the larger the rain event the less overall retention by the green roofs, however this was not consistent among green roof types. For the 12 mm rain event retention ranged from 88% (roof D) to 26% (roof A), for

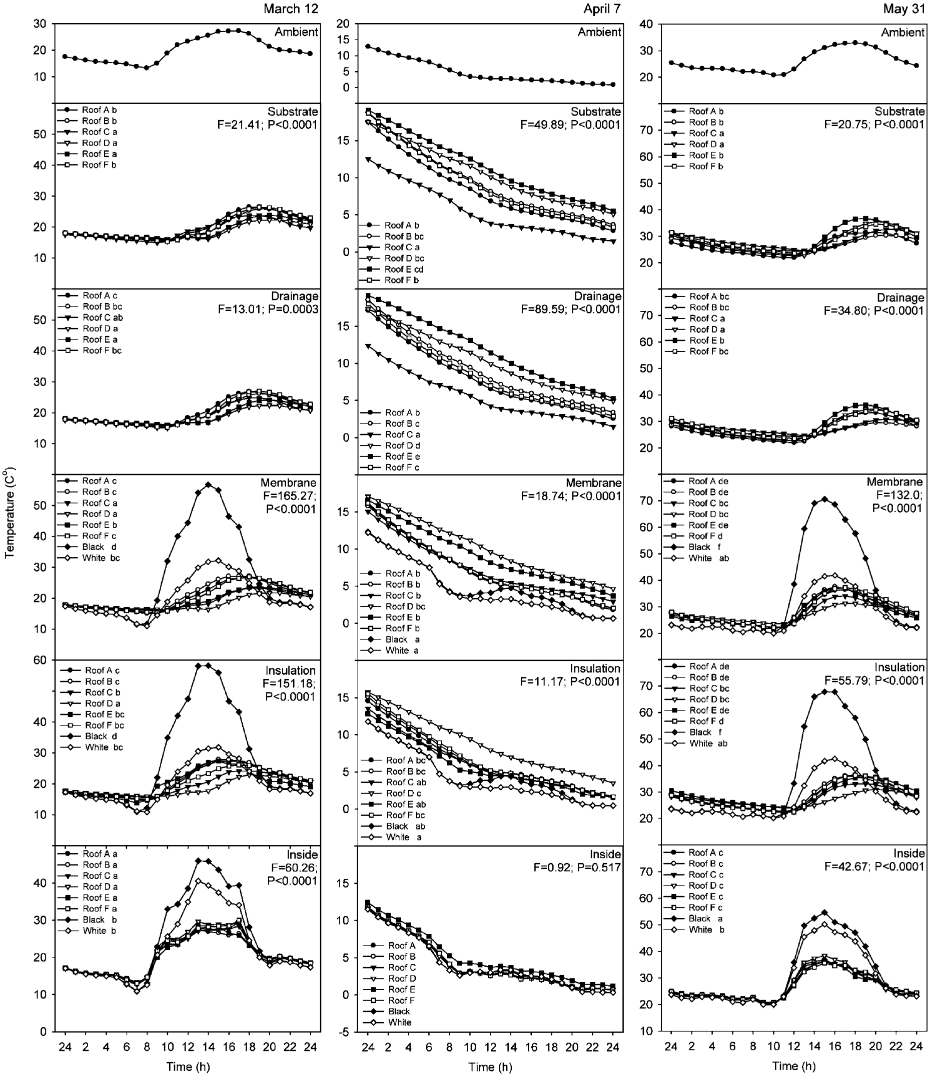


Fig. 2 Diurnal temperatures of structural layers of black, white and six manufactured green roofs during March 12, April 7, and 23 May 2007. *Error bars* are 1 standard deviation. Repeated measures ANOVA statistics are shown for each profile set. *Different lower case letters* for each roof type in legend indicate statistical difference at $P=0.05$ level

the 28 mm event the range was 43% (roof D) to 8% (roof F), and for the 49 mm event from 44% (roofs D and B) and 13% (roof F) (Fig. 3; Table 3).

Discussion

Temperature profiles

These data illustrate that all green roofs tested had significantly lower internal structural temperatures on warm days but and no difference during the cold event when compared to

Table 3 Rainfall amount and duration, time and amount of last previous rain event, and mean retention (% of mean of black and white conventional roofs) for each green roof type

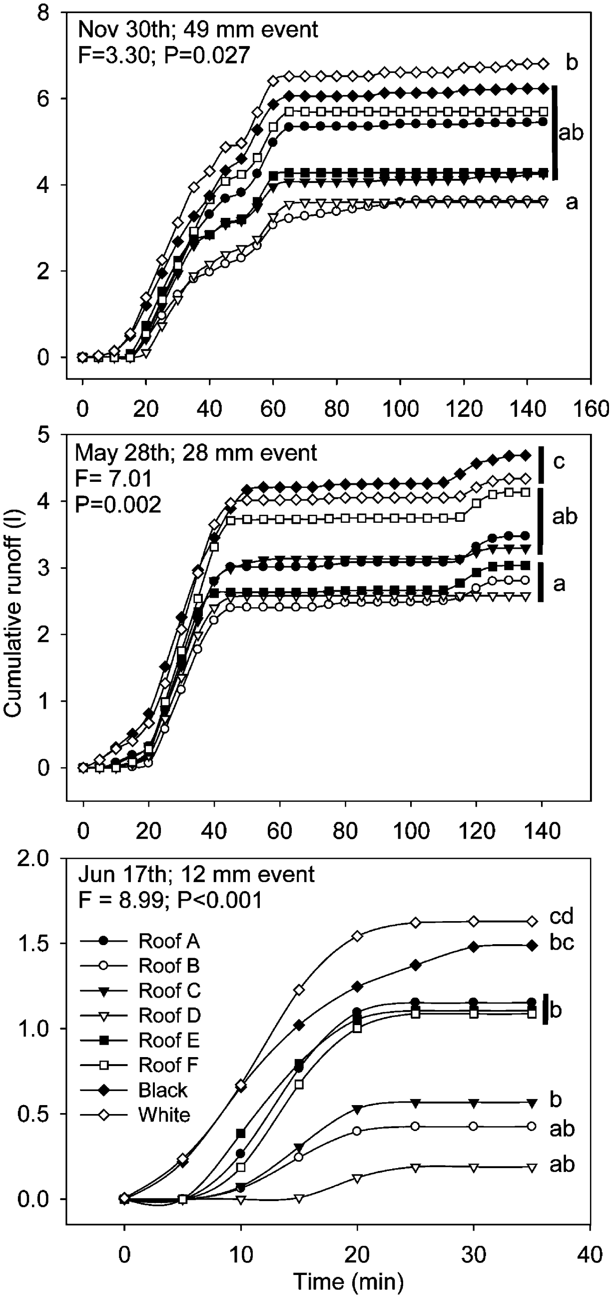
Date	Rainfall (mm)	Duration (min)	Previous rain event		Roof A (%)	Roof B (%)	Roof C (%)	Roof D (%)	Roof E (%)	Roof F (%)
			Amount (mm)	Time (days)						
November 30 2006	49.0	140	3	4	16	44	34	44	34	13
May 28 2007	28.4	140	7	3	23	38	27	43	33	8
June 17 2007	11.9	25	13	3	26	73	64	88	29	30

both conventional and cool roofs. There was also however, a significant difference in roof membrane temperatures among green roof types (Fig. 1). The depression of the membrane temperature (30–35°C) by the green roofs was significant enough to be transmitted through to the internal space (up to 18°C cooler than black roofs) even through standard roof insulation. The white reflective roofs were similarly able to significantly (28°C) cool the structural layers to the insulation layer, however the internal air temperatures had a maximum reduction of 5°C—significantly less than the green roofs. It is difficult to attribute the thermal performance of the different roofs to specific mechanisms to account for these patterns. While there were a wide range of green roof components, similarity in response was not always linked to the most obvious structural differences. Type C (modular) and type D (monolithic) had the two coolest roof membranes. However, type D had a high proportion of perlite in the substrate and this may have had a significant contribution to the overall thermal performance of this roof type. Further detailed quantification of all components such as thermal capacities and the thermal effect of moisture retention may eventually reveal underlying characteristics which explain these differences between thermal profiles. The contribution of the vegetative component of the green roofs is not discussed here and it has been argued that the overriding effect on green roof thermal properties may be insulative properties of the substrate (Palomo and Barrio 1998; Niachou et al. 2001; Velasco et al. 2007). However, it has been shown elsewhere that plants can further contribute to cooling through transpiration and increasing reflectivity, particularly in warmer regions and lower latitudes where solar angle of incidence is higher (e.g. Wong et al. 2003) and above-ground biomass (leaf area index) is higher (Theodosiou 2003).

Run-off

All green roofs consistently detained a greater amount of water than conventional and cool roofs. However, this difference was not always significant, and differences among green roof manufacturers was often more significant than between green roofs and conventional roofs (Fig. 2). During small (<10 mm) rain events the green roofs were able to retain most if not all runoff similar to that found by Bengtsson and Villarreal (2005) for a roof with 40 mm of substrate, and by Macmillan (2004) with a substrate depth of 140 mm, but better than that in other studies (Teemusk and Mander 2007). Rain events greater than 10 mm this resulted in a range of responses in line with similar studies elsewhere depending on green roof type (Getter and Rowe 2006; Seters et al. 2007), except that in this study, total runoff from some green roof types was not significantly different from the conventional roofs. Retention could be attributed to several mechanisms. The substrate and drainage layers (either retention mat or

Fig. 3 Cumulative runoff hydrographs for black, white, and six manufactured green roofs for three independent rain events. Repeated measures ANOVA statistics are shown for each hydrograph. *Different lower case letters* for each roof type indicate statistical difference at $P=0.05$ level. Note that both *axes scales* are not consistent across graphs



retention cup structure) potentially played the largest role in detaining water. There is some correlation with retention cup capacity and drainage layer weep area with mean retention. Type B, which along with D, exhibited the overall highest retention, had a high retention cup capacity with lowest drainage hole area. Two other roof types also had high drainage cup capacity, but did not retain as much water. Type F which had consistently low retention, had larger drainage holes in this layer, and the cups in type C were designed (i.e. shallow and wide) such that the retention volume could be displaced by overlying media (Table 1). Green roof type D, which exhibited high retention, contained only a retention blanket and had no rigid structure for water retention at all. However, type D did have a high proportion (95% by volume) of perlite in the substrate and this could account for the improved overall retention capacity. Microstructures in the substrate and root barrier (pores, irregularities, high surface area) and micro and meso structures in the drainage area which can all contribute to the retention characteristics and are not quantified in this report. However, these attributes are easily engineered to maximize this response (Getter and Rowe 2006). Similarly, increasing root density and soil biota will affect both water uptake and substrate retention characteristics (Larcher 1995). As data were collected within the first 8 months of planting, results largely reflect the insulation and evaporative cooling characteristics of the abiotic component of the green roof. It is expected that as the plants establish further over the subsequent years there will be associated differences in green roof performance.

From an engineering perspective green roofs have a high degree of complexity and added unpredictability of incorporating a biological system. However, it is evident that many different attributes can alter performance both thermally (Palomo and Barrio 1998) and hydrologically (Bengtsson and Villareal 2005; Teemusk and Mander 2007). Further data collection as these roofs become established will hopefully reveal the characteristics of a mature green roof and responses to different rainfall events and diurnal temperature patterns peculiar to this subtropical region. Similarly, the continued examination of plant responses (including growth performance and transpirational rates), and quantification of all aspects of the substrate and structural components of the different green roofs not included in this report, are ongoing and will help identify the trade-offs in performance characteristics between green roof design elements and help to engineer green roofs to achieve specific performance goals.

Conclusions

These data indicate that: 1. Green roofs can greatly affect the roof temperature profile—cooling surface layers and internal space on warm days. 2. Green roofs can retain significant amounts of rainfall, however this is dependent on the size of the rain event and design and can fail if not designed correctly. We suggest that as green roofs vary so much in their design that they must be designed according to specific performance goals, and not on assumed performance attributes. These will vary among geographic location and client needs, but must be stated early in the design process to assess whether or not the green roofs are a suitable option, and if so then dictate the biotic and abiotic components of the design.

Acknowledgments The authors wish to thank City of Austin, Watershed Protection and Development Review Department, Austin Energy, RCI (Institute of Roofing, Waterproofing, and Building Envelope Professionals) Foundation, and TBG Partners for sponsoring this project. We also wish to thank Ken Ollinger RRC, CCCA who constructed the steel test assembly structures, roofing contractors who provided material and thousands of hours in labor, including: Dean Contracting, D. R. Kidd Roofing, Empire Roofing, Fifth Wall Roofing, L. S. Decker, Port Enterprises and Texas Roofing.

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