Nighttime Radiative Cooling of Low-slope Roof Systems

Presented by
Matt Dupuis
Structural Research Inc.
Topics to Cover

• Background
• Test Bed Details
• Heat Transfer
• Sky Temperature
• Terrestrial Radiation
• Field Data
• Conclusions
• Questions
Background

• MRCA PV Project
  – Observed roof surface temperatures at night below ambient every night

• Radiative Behavior of Building Surfaces
  – Basic Temperature (Goodman 1938)
  – Ponded Roofs (Clark 1981)
  – Cool Roofs and Moisture (Rose 2007)
Test Bed Details

• Constructed in 2009
• Initial goal was to observe temperature differentials created by fully adhered photovoltaic panels on varying membranes
• 3yr project
• Live data stream
  – www.sri-engineering.com/mrca
Test Bed Details
Test Bed Details
## Test Bed Details

<table>
<thead>
<tr>
<th>Membrane Type</th>
<th>Color</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPDM</td>
<td>White</td>
<td>60 mils</td>
</tr>
<tr>
<td>TPO</td>
<td>White</td>
<td>60 mils</td>
</tr>
<tr>
<td>Polymer-modified bitumen</td>
<td>White</td>
<td>140 mils</td>
</tr>
<tr>
<td>EPDM</td>
<td>Black</td>
<td>60 mils</td>
</tr>
<tr>
<td>TPO</td>
<td>White</td>
<td>60 mils</td>
</tr>
<tr>
<td>PVC</td>
<td>Gray</td>
<td>45 mils</td>
</tr>
<tr>
<td>TPO</td>
<td>White</td>
<td>60 mils</td>
</tr>
</tbody>
</table>
Test Bed Details

• Type T thermocouples
  – 58
• Weather station
• Radiometric Sensors
  – Pyranometer
  – Pyrgeometer
• Data Acquisition
  – NI cRIO and Lab View
Heat Transfer

• Just the very basics
  – Conduction
  – Convection
  – Radiation
Heat Transfer

- Net heat flux per unit area

\[ q''_{\text{net}} = q''_{\text{conduction}} + q''_{\text{convection}} + q''_{\text{radiation}} \]

- Units of \( \frac{W}{m^2} \)
Heat Transfer

• Conduction
  \[ q''_{Conduction} = \frac{k(T_I-T_S)}{L} \]

• Convection
  - Natural convection
  - Forced convection
  - Convective Heat Transfer Coefficient
    • Jiantao, Jing et al. 2009
  \[ q''_{Convection} = h_{Convection}(T_S - T_A) \]
Heat Transfer

• Radiation

\[ q_{\text{radiation}} = E_{\text{Solar}} + E_{\text{Sky}} + E_{\text{Terrestrial}} - M_{\text{Surface}} \]
Heat Transfer

- $E_{Solar}$ is zero at night!
- $E_{Terrestrial}$ is taken as zero for a low slope roof
  - More on this later
- Radiation
  \[ q_{\text{radiation}} = E_{\text{Sky}} - M_{\text{Surface}} \]
Sky Temperature

• **Short Wave Irradiance**
  • Originates from the sun
  • Includes
    • Ultraviolet (7%)
    • Visible (45%)
    • Infrared (48%)

• **Wavelengths from 300nm-2500nm**
Sky Temperature

• **Long Wave Irradiance**
  - Covers approximately 4500nm - 50,000nm
  - Emitted by all matter above absolute zero

• **Sky Radiation**
  - Long Wave
  - Emitted by
    - Atmospheric gases
    - Water vapor (humidity and clouds)
    - Dust and Pollutants
Sky Temperature

• Pyrgeometer
  – Sensitive to 4500nm - 50,000nm
  – $150^\circ$ cone
  – Reads incoming Sky Irradiance ($E_{Sky}$)
    • Units of ($\frac{W}{m^2}$)
Sky Temperature

• Typical ranges $100 \frac{W}{m^2}$ to $400 \frac{W}{m^2}$

• Varies with
  – Air temperature
  – Cloud cover
  – Pollution

• Irradiates the roof 24 hours a day

• During the day it is masked / overwhelmed by incoming solar irradiance
Sky Temperature

- Sky Irradiance is typically discussed as a Sky Temperature
  - Black body radiator
  - Stefan-Boltzmann Law
    \[ P = \sigma T^4 \]
- Cloudy night
  - High Irradiance / High Temperature
- Clear Night (low humididty)
  - Low Irradiance / Low Temperature (feels cold)
Sky Temperature

- At night, Sky Irradiance and Surface Radiation generally dominate
  - Surface Radiation (grey body)
    \[ P = \varepsilon \sigma T^4 \]
- Berdahl and Martin 1984

\[ T_{Sky} = T_{Air} \left[ 0.711 + 0.0056T_{DP} + 0.000073T_{DP}^2 + 0.013 \cos(15t_{midnight}) \right]^{\frac{1}{4}} \]
Terrestrial Radiation

• All matter above absolute zero emits long wave

• To include
  – Other buildings
  – Trees
  – The ground
  – Pavement
  – Etc.
Terrestrial Radiation

- Steep Roof obviously impacted
- Low slope roof
  - High parapet
  - Short or no parapet
Field Data
Starting Temperature:
- White EPDM 60 Mil: 30°C
- White TPO 60 Mil: 31°C
- Black EPDM 60 Mil: 33°C
- Ambient Temperature: 29°C
- Sky Temperature: -5°C

Dew Point: 11°C

Graph shows temperature changes from 12PM 11/26/10 to 12PM 11/27/10.
8/11/10

Temperature (°C) vs. Time of Day

- White EPDM
- PV Panel on TPO
- Black EPDM
- White Mod Bit
- Tsky
- Ambient Temperature

Graph showing temperature variations for different materials and conditions throughout the day on 8/11/10.
Wednesday Night
Thursday Night
MRCA PV / Thermocouple Test Bed
Manhattan, KS

White EPDM East
Channel 1
47.2029

White TPO East
Channel 5
45.9544

White Modbit East
Channel 9
49.8715

Black EPDM East
Channel 13
47.0301

Channel 2
47.1547

Channel 6
46.8159

Channel 10
49.9459

Channel 14
47.4779
Forced Convection!

• Night time increase in ambient air temperature
October 24th, 2009 / Evening / West Slope

Temperature (°F)

Solar Radiation (Watts/m²)

- White EPDM
- Black EPDM
- White TPO
- PV panel (Grey PVC)
- Air Temp
- Solar Radiation

Time (24 hr)
Conclusions

• Night time radiative cooling
  – Super cooling
  – Over cooling

• Appears to occur almost every night
  – Exceptions such as precipitation and snow cover

• Cooling observed in excess of 10° C / 20° F

• May need to reconsider minimum service temperatures for system design and energy calculations
Questions