2011 International Roofing Symposium
Emerging Technologies and Roof System Performance

Nighttime Radiative Cooling of Low-slope Roof Systems

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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

Membrane Type	Color	Thickness
EPDM	White	60 mils
TPO	White	60 mils
Polymer-modified bitumen	White	140 mils
EPDM	Black	60 mils
TPO	White	60 mils
PVC	Gray	45 mils
TPO	White	60 mils

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

$$q''_{net} = q''_{conduction} + q''_{convection} + q''_{radiation}$$

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

Heat Transfer

- Conduction
  - $q"_{Conduction} = \frac{\mathrm{k}\,(T_I - T_S)}{\mathrm{L}}$
- 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

$$q''_{radiation}$$

$$= E_{Solar} + E_{Sky} + E_{Terrestrial} - M_{Surface}$$

Heat Transfer

- E_{Solar} is zero at night!
- $E_{Terrestrial}$ is taken as zero for a low slope roof
  - More on this later
- Radiation

$$q''_{radiation} = E_{Sky} - M_{Surface}$$

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° 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

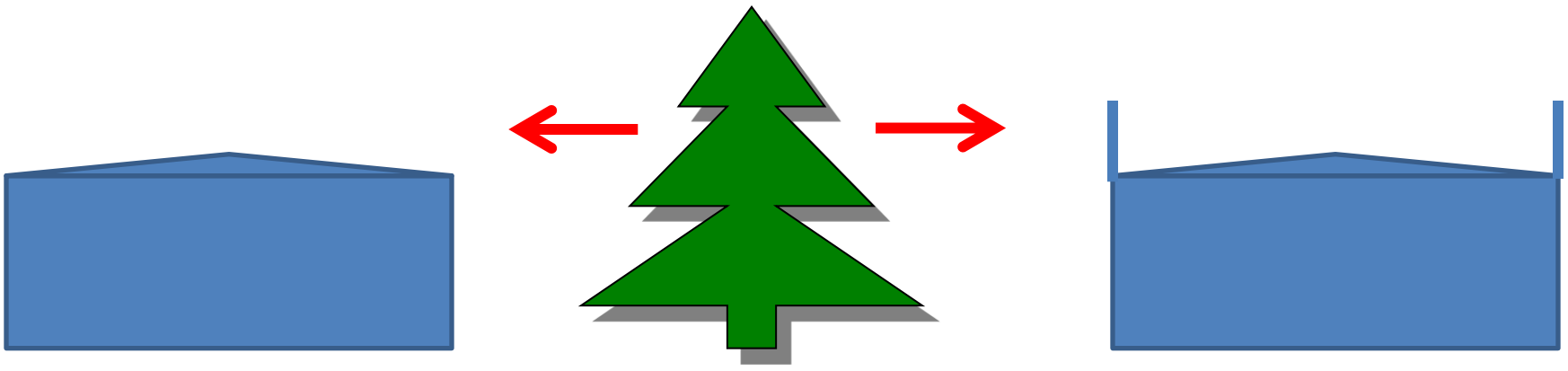
$$T_{Sky} = T_{Air}[0.711 + 0.0056T_{DP} + 0.000073T_{DP}^2 + 0.013\cos(15t_{midnight})]^{\frac{1}{4}}$$

Terrestrial Radiation

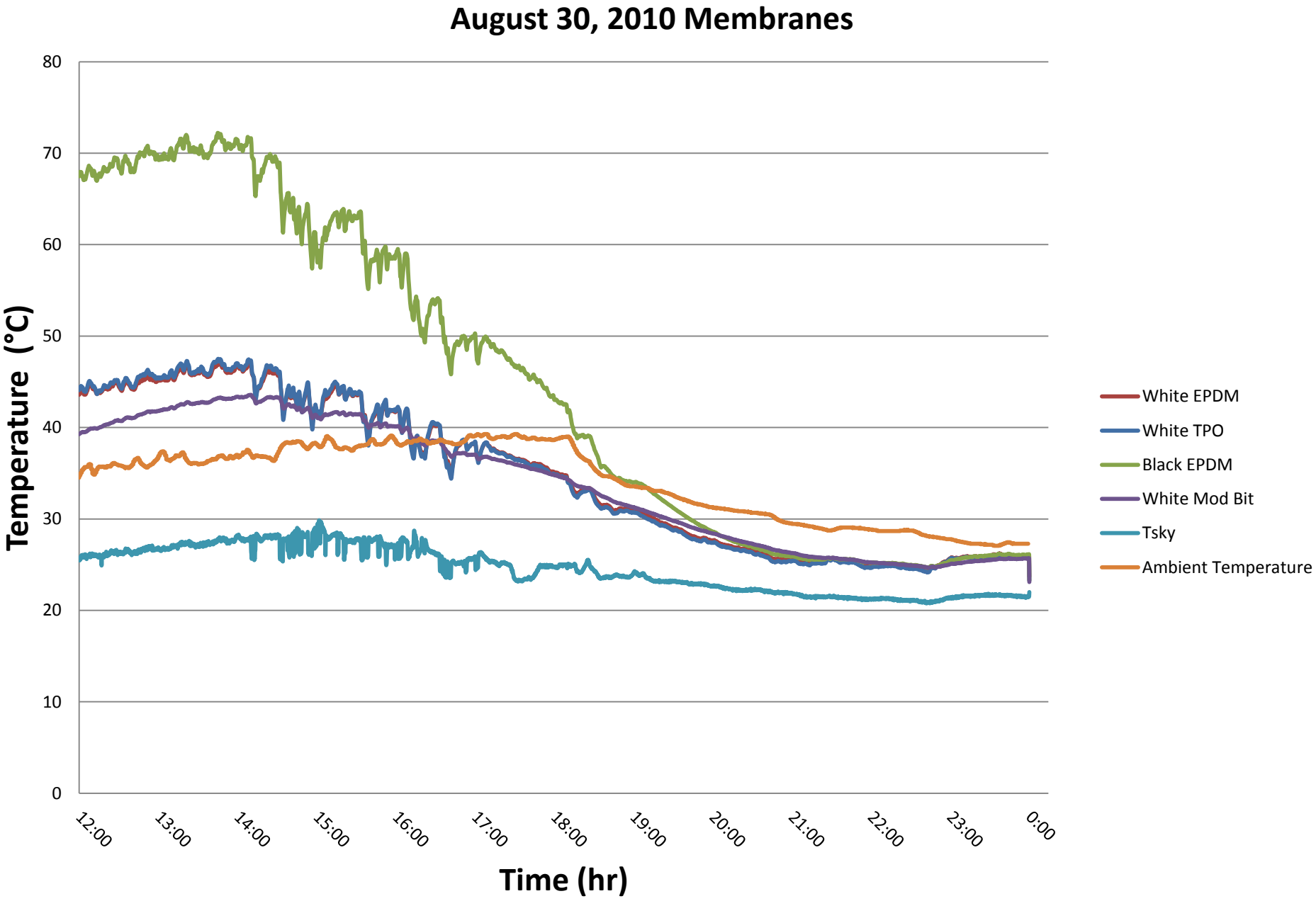
- All matter above absolute zero emits long wave
- To include
  - Other buildings
  - Trees
  - The ground
  - Pavement
  - Etc.

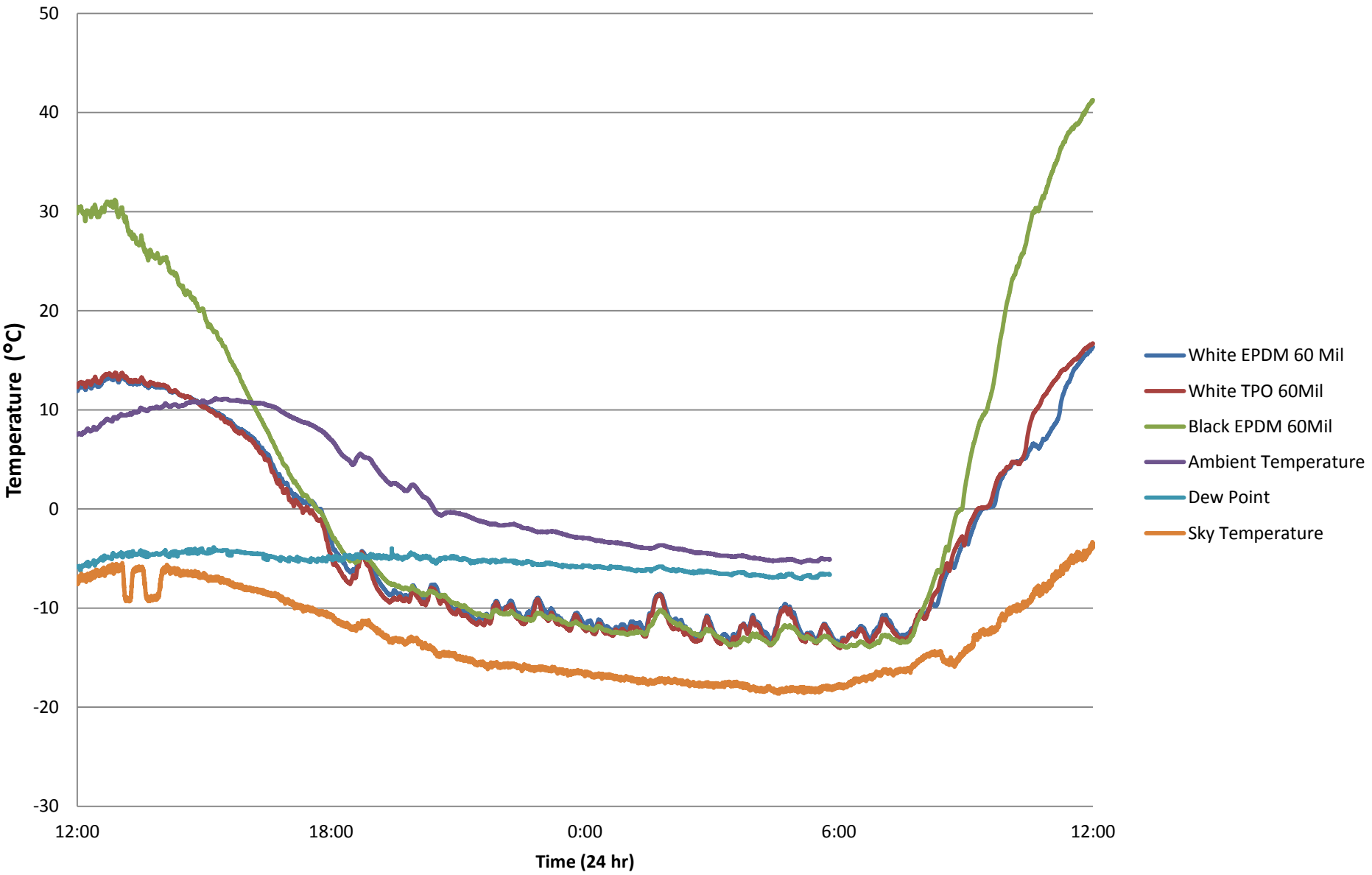
Terrestrial Radiation

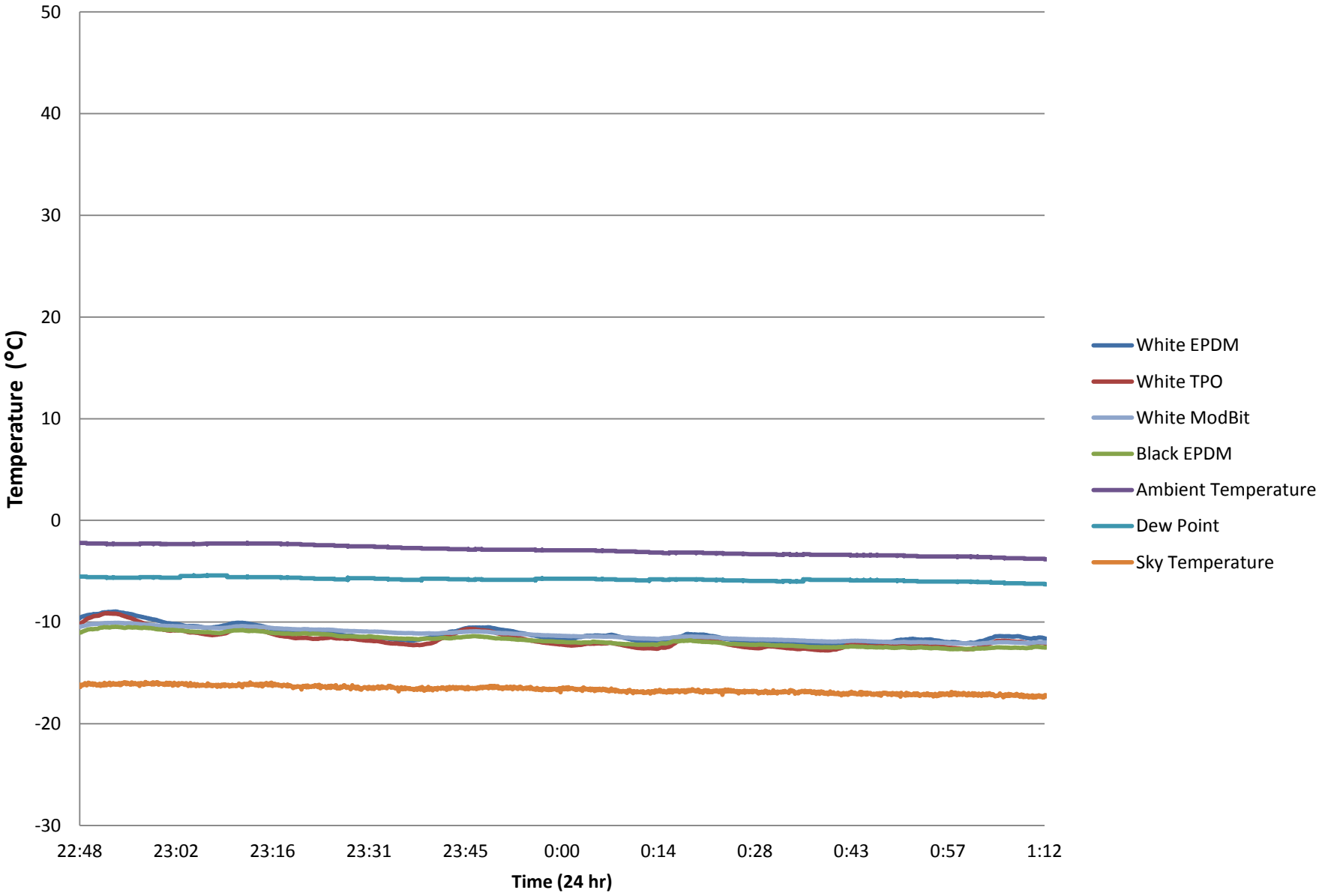
- Steep Roof obviously impacted
- Low slope roof
  - High parapet
  - Short or no parapet

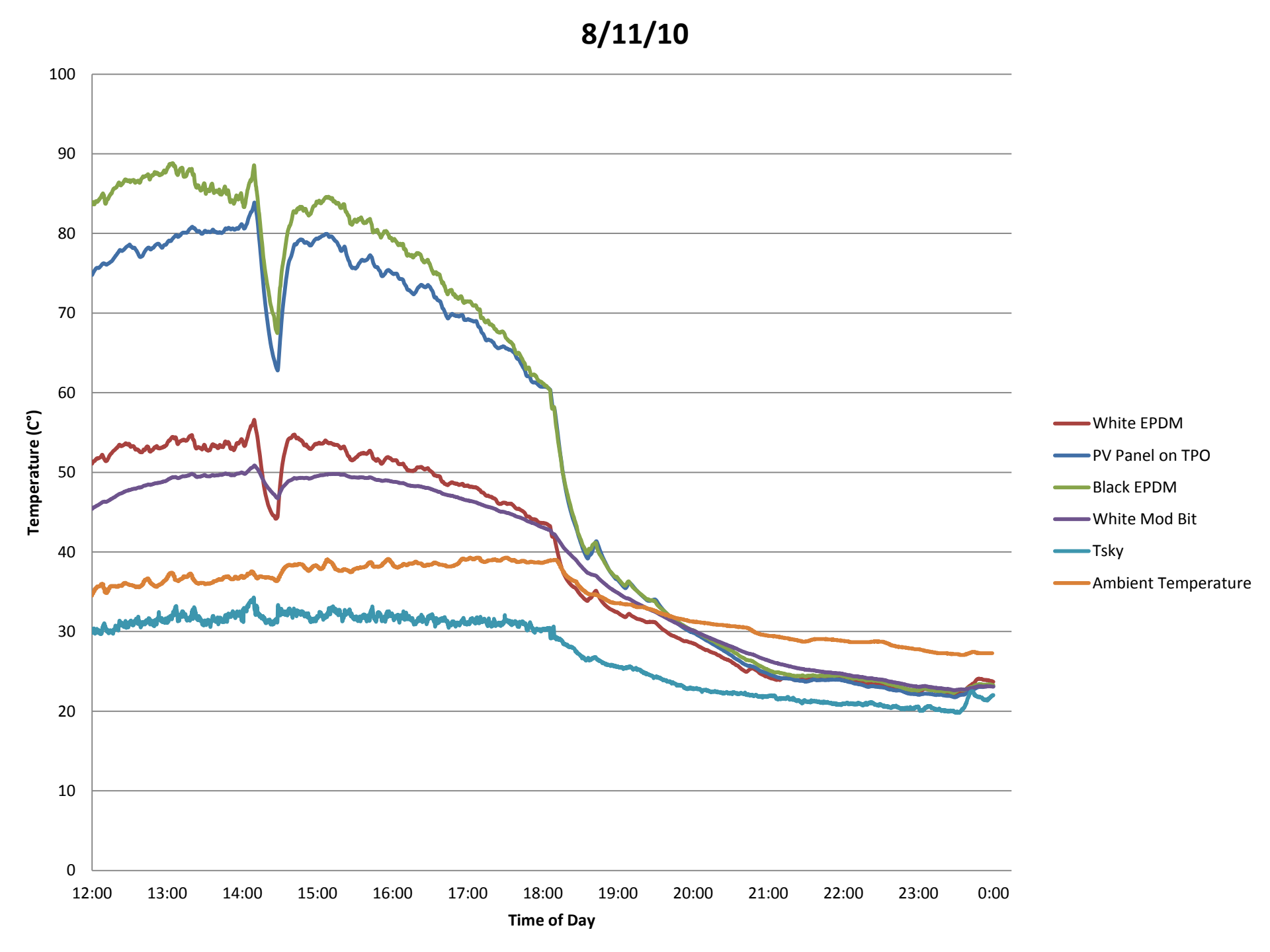


Field Data

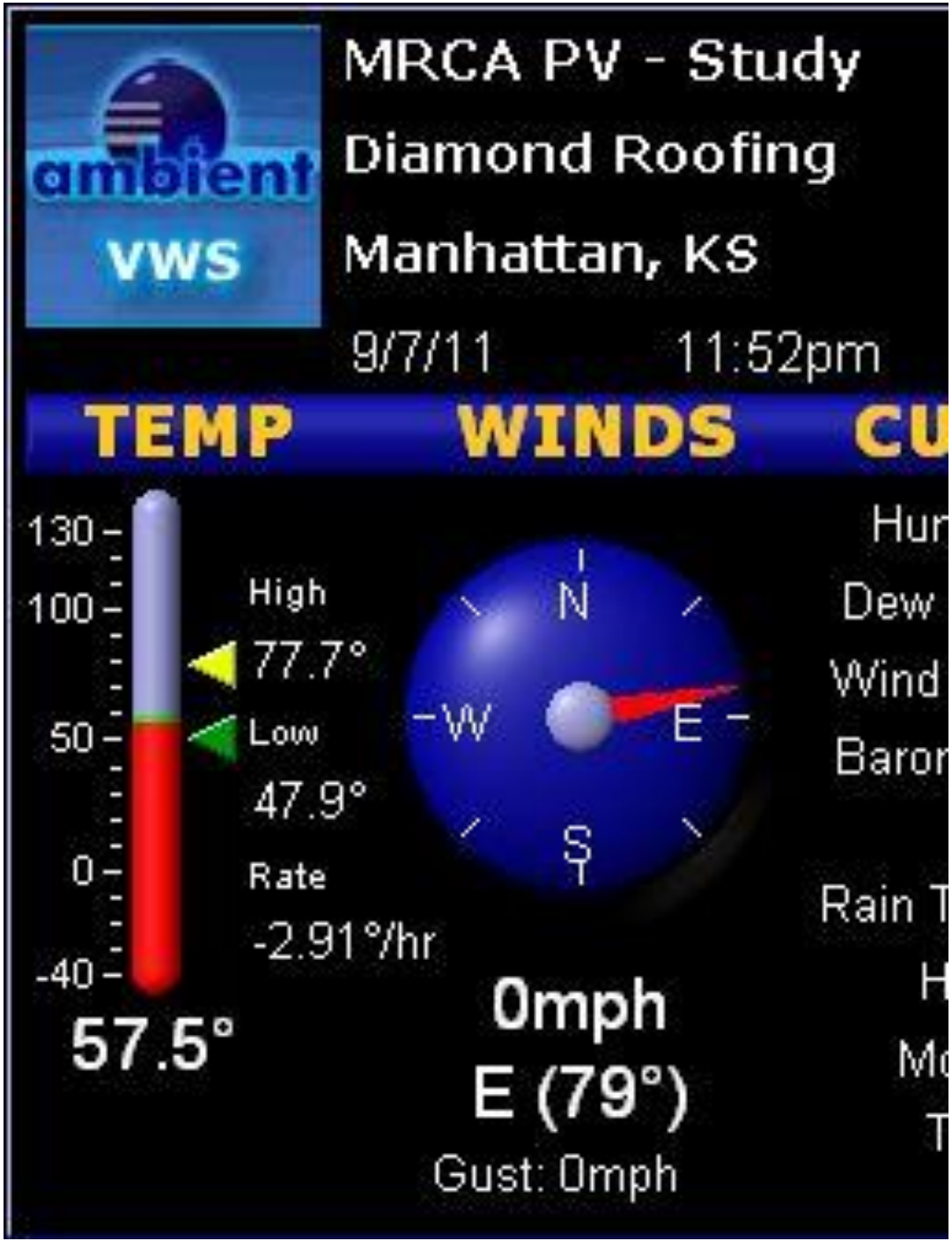

August 30, 2010 Membranes
Temperature (°C)
80
70
60
50
40
30
20
10
0
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00
Time (hr)
White EPDM
White TPO
Black EPDM
White Mod Bit
Tsky
Ambient Temperature


12PM 11/26/10 to 12PM 11/27/10
Temperature (°C)
50
40
30
20
10
0
-10
-20
-30
12:00
18:00
0:00
6:00
12:00
Time (24 hr)
White EPDM 60 Mil
White TPO 60Mil
Black EPDM 60Mil
Ambient Temperature
Dew Point
Sky Temperature


12PM 11/26/10 to 12PM 11/27/10
50
40
30
20
10
0
-10
-20
-30
Temperature (°C)
22:48
23:02
23:16
23:31
23:45
0:00
0:14
0:28
0:43
0:57
1:12
Time (24 hr)
White EPDM
White TPO
White ModBit
Black EPDM
Ambient Temperature
Dew Point
Sky Temperature


8/11/10
100
90
80
70
60
50
40
30
20
10
0
Temperature (C°)
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00
Time of Day
White EPDM
PV Panel on TPO
Black EPDM
White Mod Bit
Tsky
Ambient Temperature

Wednesday Night


ambient
VWS
MRCA PV - Study
Diamond Roofing
Manhattan, KS
9/7/11 11:52pm
TEMP
WINDS
CU
130
100
50
0
-40
High
77.7°
Low
47.9°
Rate
-2.91°/hr
57.5°
N
W
E
S
0mph
E (79°)
Gust: 0mph
Hur
Dew
Wind
Baror
Rain T

MRCA PV / Thermocouple Test Bed P
Manhattan, KS

White EPDM East	White TPO East	White Modbit East	Black EPDM East
Channel 1	Channel 5	Channel 9	Channel 13
43.9924	43.1913	44.9155	43.0764
Channel 2	Channel 6	Channel 10	Channel 14
44.4543 PV	44.3105 PV	44.9694 PV	43.7384 PV

Thursday Night

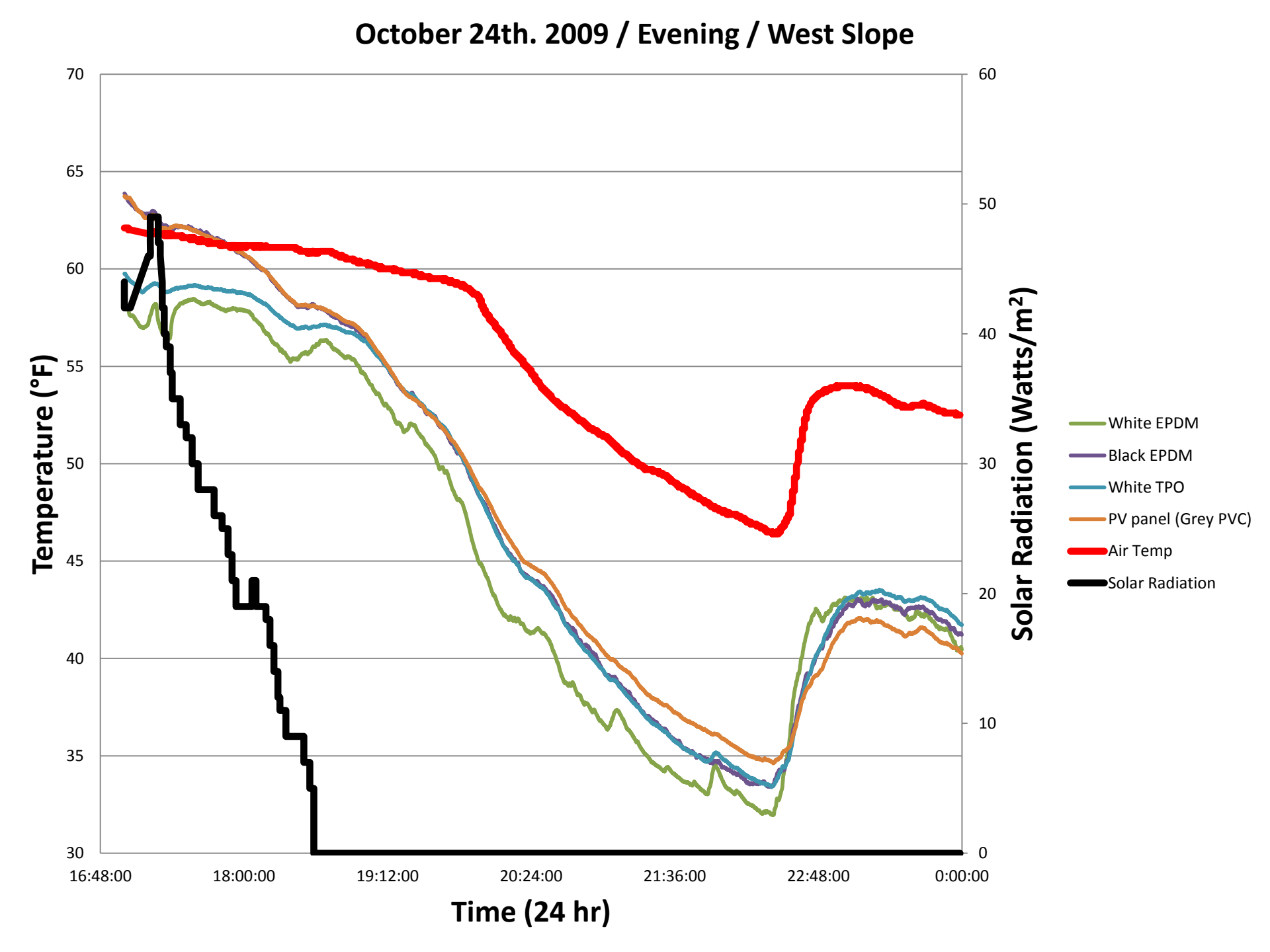

ambient
VWS
MRCA PV - Study
Diamond Roofing
Manhattan, KS
9/8/11
9:27pm
TEMP
WINDS
130
100
50
0
-40
High
77.6°
Low
47.4°
Rate
-3.92°/hr
66.2°
N
W
E
S
0mph
N (11°)
Gust: 5mph
Rain

MRCA PV / Thermocouple Test Bed
Manhattan, KS

White EPDM East	White TPO East	White Modbit East	Black EPDM East
Channel 1	Channel 5	Channel 9	Channel 13
47.2029	45.9544	49.8715	47.0301
Channel 2	Channel 6	Channel 10	Channel 14
47.1547 PV	46.8159 PV	49.9459 PV	47.4779 PV

Forced Convection!

- Night time increase in ambient air temperature


October 24th. 2009 / Evening / West Slope
Temperature (°F)
Solar Radiation (Watts/m²)
Time (24 hr)
70
65
60
55
50
45
40
35
30
60
50
40
30
20
10
0
16:48:00
18:00:00
19:12:00
20:24:00
21:36:00
22:48:00
0:00:00
White EPDM
Black EPDM
White TPO
PV panel (Grey PVC)
Air Temp
Solar Radiation

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