Beyond the Envelope

Subambient Sky-Facing Surfaces under Sunlight & their Potential

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CRRC Annual Meeting 2015
The cool roof picture

What is a Cool Roof?
A cool roof reflects and emits the sun's heat back to the sky instead of transferring it to the building below. "Coolness" is measured by two properties, solar reflectance and thermal emittance. Both properties are measured from 0 to 1 and the higher the value, the "cooler" the roof.

What are the Benefits of a Cool Roof?
- COOL ROOF CAN:
  ■ Increase occupant comfort by keeping the building cooler during hot summer months.
  ■ Cut costs by:
    • reducing the need for air-conditioning, and extending the life of cooling equipment. Studies have shown typical cooling energy savings of 10-30% in cooling energy and an extension in the life of cooling equipment.
    • decreasing roof maintenance costs (cool roofs are expected to last longer than the average roof).
  ■ Address air pollution and Global Warming concerns by lowering CO₂ and other emissions associated with fossil fuel-generated electricity used for air-conditioning.
  ■ Reduce the "Urban Heat Island Effect" by reflecting heat back to the atmosphere.
  ■ Help with local code compliance since a growing number of building codes have cool roof requirements.

Black surfaces in the sun can become up to 90°F hotter than the most reflective white surfaces (LBNL Heat Island Group).

These values reflect 1997 energy prices; current values are higher. Nationwide implementation of cool roofs could mean an annual savings of $1 billion in cooling costs! (LBNL Heat Island Group).

Cool Roof Rating Council Website
Thermal emittance accesses another ‘resource’

The sun’s radiation hits the roof surface.

Solar Reflectance: the fraction of solar energy that is reflected by the roof.

Some heat is absorbed by the roof and transferred to the building below.

Thermal Emittance: the relative ability of the roof surface to radiate absorbed heat.

Some heat is absorbed by the roof and transferred to the building below.

Los Angeles: $9M
Phoenix: $9M
Houston: $35M
New Orleans: $10M
Chicago: $20M
Atlanta: $8M
Dallas/Ft. Worth: $20M
Miami/Ft. Lauderdale: $37M
New York: $16M
Baltimore: $27M
Philadelphia: $3M
Washington, DC: $10M

The benefits of a cool roof include:

- Increased occupant comfort by keeping the building cooler during hot summer months.
- Cutting costs by reducing the need for air-conditioning and extending the life of cooling equipment.
- Addressing air pollution and global warming concerns by lowering CO₂ and other emissions associated with fossil fuel-generated electricity used for air-conditioning.
- Reducing the “Urban Heat Island Effect” by reflecting heat back to the atmosphere.
- Helping with local code compliance since a growing number of building codes have cool roof requirements.

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Nationwide implementation of cool roofs could mean an annual savings of $1 billion in cooling costs!
Radiative cooling to below ambient air temperature

**Thermal emission** > **Solar absorption** = Cooling below ambient

**Solar Reflectance:**
the fraction of solar energy that is reflected by the roof

**Thermal Emittance:**
the relative ability of the roof surface to radiate absorbed heat

The sun’s radiation hits the roof surface.

Some heat is absorbed by the roof and transferred to the building below.
Talk Outline

• Radiative Cooling Fundamentals & History
• Cooling Under Sunlight: The Challenge
• Our Solution: Design & Results
• Outlook
Electromagnetic waves carry energy: Thermal Radiation

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Wavelength (m)</th>
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<tr>
<td>$10^6 - 10^9$</td>
<td>$10^2 - 10^{-1}$</td>
</tr>
<tr>
<td>$3 \times 10^{13}$</td>
<td>$10 \times 10^{-6}$</td>
</tr>
<tr>
<td>$6 \times 10^{14}$</td>
<td>$\sim 0.5 \times 10^{-6}$</td>
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Photonics: Controlling Light with Nano-/Micro-structures

Reflectance and Thermal Emittance are not just single numbers: We can design photonic structures to cause them to vary over the above spectrum in remarkable ways.
Sky-facing surfaces at night

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  - Address air pollution and Global Warming concerns by lowering CO$_2$ and other emissions associated with fossil fuel-generated electricity used for air-conditioning.
  - Reduce the “Urban Heat Island Effect” by reflecting heat back to the atmosphere.
  - Addressing the Urban Heat Island occurs when a city is hotter than the surrounding rural areas due to dark surfaces, like roofs and roads that absorb heat from the sun, and less shading vegetation.
  - Help with local code compliance since a growing number of building codes have cool roof requirements.

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Radiative Cooling Mechanism

Sky-facing surface

\[ T_{\text{surface}} = 28^\circ \text{C} \]
Radiative Cooling Mechanism

In the infrared transparency window the sky’s thermal radiation is much cooler
Radiative Cooling Mechanism

In the infrared transparency window the sky’s thermal radiation is much cooler: The sky has low emittance!
Humidity affects infrared atmospheric properties

- Radiative cooling works best in dry climates
- But, it works even better when it’s hotter
Atmospheric transparency window

Blackbody @ 28°C

Sky: -21.6°C

Room: 23.9°C
When going subambient the benefits of a selective thermal emitter

Target emissivity spectrum
Power balance equation

\[ P_{\text{cool}}(T) = P_{\text{rad}}(T) - P_{\text{atm}}(T_{\text{amb}}) \]

**Cooling Power:** Net radiating flux out of surface

**Steady-State Temperature:** \( T \) when \( P_{\text{cool}} = 0 \)
Radiative (sky) cooling: A long history


Granqvist & Hjortsberg (1980)


The challenge: going subambient under sunlight

Sun: $\sim$1000 W/m$^2$

Net infrared radiation out: $\sim$50-100 W/m$^2$

To get meaningful cooling in typical conditions:

Solar reflectance $> 95$-96%
Our approach

- Deliberately chosen materials and thicknesses to make possible both high solar reflectance and selective thermal emission
- Deposited by e-beam evaporation on 200 mm Si wafers

Spectral characteristics

- 97% solar reflectance
- Selective emissivity within the atmospheric window

**Strong solar reflection**

**Strong and selective thermal emission**
Spectral characteristics

- Strong selective emissivity to relatively large angles for a thin-film stack
Rooftop testing

- Wood frame
- Clear acrylic
- Aluminized mylar
- Polystyrene
- Low-density Polyethylene
- Photonic Radiative Cooler
- Air pocket

Diagram showing the components of the rooftop testing setup.
Performance under direct sunlight

Exposed to sky

Temperature (°C)

Solar irradiance (W/m²)

Time of Day

Black paint

Aluminum

Ambient air

Photonic radiative cooler
Performance under direct sunlight

Exposed to sky

Ambient air temperature

Photonic radiative cooler temperature

5°C below ambient under > 800 W/m² solar irradiance

Cooling power measurement

40 W/m² net radiative flux at ambient under > 800 W/m² solar irradiance

Gray line denotes theoretical model whose bounds are defined by varying atmospheric transmittance
Theoretical model: cooling power

\[ P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{cond+conv} \]

With better packaging and insulation:

**20°C below ambient under direct sunlight**
Theoretical model: temperature

\[ P_{\text{cool}}(T) = P_{\text{rad}}(T) - P_{\text{atm}}(T_{\text{amb}}) - P_{\text{sun}} - P_{\text{cond+conv}} \]
Recent demonstrations by other researchers:

Outlook

- **Challenges** to direct application for roofing: **cost, durability, appearance, wind shielding**

- **What’s new:** Electricity and water-free way of dissipating heat loads to *below* ambient

- Rejecting interior heat loads and directly substituting for A/C electricity and water use: *beyond the envelope*
Tuning thermal emittance by design

• Tuning and optimizing thermal emittance makes possible new efficiency gains by using the sky’s ‘resource’ more effectively: new energy opportunities!

• One example: cooling solar cells
  (lower operating temperature 10+°C)

A. Raman*, L. Zhu* and S. Fan (in review)
L. Zhu, A. Raman, K. Wang, M. Anoma & S. Fan,
Optica, 1 (1), 32 (2014)
Direct roof applications?

Uninsulated structures, especially off-grid could directly benefit from a subambient cool roof: direct air flow beneath a sub-ambient cooling roof surface

(in western Kenya)
Some potential takeaways to consider for cool roofs

- Recent developments from the photonics and optics world could be leveraged to assist or improve cool roofs.
- Deterministically manipulating (and increasing/decreasing) thermal emittance at certain wavelengths while increasing solar reflectance: new possibilities.
- Subambient cooling by a module would be best achieved on a cool roof: complementary.
- Night sky radiative cooling is already accessible and prominent in arid climates: opportunities to reconsider in today’s energy and buildings landscape?
Acknowledgments

Prof. Shanhui Fan  Dr. Eli Goldstein
Dr. Eden Rephaeli  Danielle Cotugno
Zach Weiner  Linxiao Zhu
Tesh Shrestha  Marc Anoma
Ben Jensen

Advanced Research Projects Agency - Energy
OPEN 2012 Awardee
Summary

• Recent developments from the photonics and optics world could be leveraged to assist or improve cool roofs
• Subambient surfaces can benefit from having spectrally selective thermal emittance behavior
• The coldness of the universe is an under-exploited thermodynamic resource for energy processes on Earth