High Performance Roofs
How to Beat the Heat

Building Envelope Program
Oak Ridge National Laboratory


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Efficiency Vermont
OBJECTIVES

1. Merge strategies into Next Generation Attics
   - Cool color roofs
   - Ventilation
   - Radiant barrier
   - Thermal mass

2. Energy impact of alternative attic ventilation schemes

3. Energy benefit of thermal mass (PCM)

4. Consensus based calculator
WHAT ARE COOL COLOR ROOFS?

- Cool color, sub-tile venting and thermal mass concrete and clay tile
  - Key Find: Cool color and sub-tile venting eliminated 70% of peak heat transfer penetrating roof deck (asphalt shingle control)

- Demonstration homes showcasing cool color medium profile concrete tile (Hanson Roof Products) and painted metal shakes (Custom-Bilt Metals)
  - Key Find: Cool color roofs reduced summer electricity ≈ 3 to 5%

- Demonstration homes with cool color asphalt shingles (GAF/ELK Group)
  - Key Find: Peak shingle temperature drops 3°C (5.4°F)
COOL COLOR PAINTS ARE HIGHLY REFLECTIVE IN INFRARED SPECTRUM

Solar Energy Distribution
- 5% ultraviolet (300-400 nm)
- 43% visible (400-700 nm)
- 52% near-infrared (700-2500 nm)

Heat Build Up per ASTM D-4803-97
- Typical Black Pigment: 102°C
- V-799 High IR Black: 76°C

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CAMOUFLAGE INVISIBLE TO IR NIGHT VISION

Conventional Film

Near Infrared Film

Wavelength

400nm 500nm 600nm 700nm

0.01nm 0.1nm 1nm 10nm 100nm

Gamma Rays X-Rays Ultraviolet Visible Infrared Microwave Radio

Shorter Wavelength Longer Wavelength
Cool Tile IR Coating™ Applied to Concrete Tile

○ COOL TILE IR COATING™ technology was developed by Joe Reilly of American Rooftile Coatings
S-Mission Tile Have Lowest Heat Transfer Penetrating the Roof Deck
Demonstration Showcasing Painted Metal Shakes at Fair Oaks, CA

Custom-Bilt Painted Metal Shakes and Stucco

South facing roof

House-4 4991 Mariah Place

Ultra Cool 31% reflectance

House-2 4983 Mariah Place
Cool Coating Reduces Heat Flux Through South Facing Roof Deck

**Painted Metal Roofs**

- Standard Color SR08
- CRCM SR31

*Heat Flux (Watts/m²)*

*Heat Flux (Btu/hr·ft²)*

*Time of Day (hrs)*

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Demonstration Showcasing Hanson Concrete Tile at Fair Oaks, CA

 Finished with Medium-profile Concrete Tile and Stucco

House-1 4979 Mariah Place

House-3 4987 Mariah Place

COOL TILE IR COATING™
41% reflective

House-1 4979 Mariah Place

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Medium-profile concrete tile

Same setup used at Fair Oaks Demonstration

Batten

Direct-to-Deck

Batten and Counter-Batten

(ESRA) Envelope Systems Research Apparatus
Medium-profile conventional concrete tile on double batten performs as well as cool-color tile direct-to-deck
Fair Oaks Demonstrations Show Positive Benefits of Cool Colors

![Diagram showing energy savings with cool colors]
## Squares of Roof Products F.W. Dodge Report 2003

<table>
<thead>
<tr>
<th>United States</th>
<th>Asphalt Shingles</th>
<th>Wood Shakes</th>
<th>Clay tile</th>
<th>Concrete tile</th>
<th>Metal</th>
<th>Other</th>
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<td>New Construction</td>
<td>29,955,734</td>
<td>280,821</td>
<td>323,763</td>
<td>1,965,500</td>
<td>889,134</td>
<td>461,263</td>
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<tr>
<td>Reroof</td>
<td>115,054,533</td>
<td>6,445,277</td>
<td>892,926</td>
<td>1,657,307</td>
<td>466,234</td>
<td>4,400,195</td>
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<td><strong>Total</strong></td>
<td><strong>145,010,267</strong></td>
<td><strong>6,726,098</strong></td>
<td><strong>1,216,689</strong></td>
<td><strong>3,622,807</strong></td>
<td><strong>1,355,368</strong></td>
<td><strong>4,861,457</strong></td>
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</table>

- **Asphalt Shingles**: 88%
- **Wood Shakes**: 3%
- **Clay tile**: 1%
- **Concrete tile**: 6%
- **Metal**: 1%
- **Other**: 1%
Hurdle: optimize reflectance of Cool Shingles and Stone Coated Metals

Green [(Cr,Fe)$_2$O$_3$]

(G) coating on glass
(S) coating on shingle

Reflectance (R)

Wavelength (nm)

R$_G$, R$_S$

solar 0.37 0.17
uv 0.07 0.05
vis 0.11 0.08
nir 0.61 0.26

(G) coating on glass
(S) coating on shingle
Demonstration Homes Provided by Elk Corp and Ochoa & Shehan Custom Homes

2605 Eel Street, Redding CA  2605 Loggerhead St., Redding CA

SR ~ 0.090  SR ~ 0.255

Temperature Difference (OD Air-to-Return Air) [°C]
Heat Flux Penetrating West Roof Reduced 25% of Conventional Shingle
110 Million Existing Homes in U.S. that Require Improvements in Building Envelope

Retrofit Shingle Roof

Envelope Systems Research Apparatus
WHAT ABOUT ROOF/ATTIC VENTILATION?

- Develop empirical algorithms to capture energy benefits of above-sheathing ventilation
  - Status: heat transfer correlations checked against field data, tracer gas used for airflow measures, algorithm formulated & validated

MCA installing stone-coated metal roofs on ESRA
Clay tile, concrete tile, painted metal shake, asphalt shingle, and stone-coated metal roofs field tests

Formulate and Validate AtticSim for Cool Color and Above-Sheathing Ventilation
Attic Assembly Construction and Instrument Setup

Diagram showing the construction details:
- Metallic layer
- Moisture shield
- 5/8 in. Oriented Strand Board
- 1/2 in. (12.7-mm) Wood Fiberboard
- 1 in. (25.4-mm) Wood Fiberboard
- Heat Flux Transducers (2)
- Thermocouples (9)

Formulas:
- $q$ (heat flux)
- $q_{\text{Lat}}$ (latent heat flux)
- $q_{\text{iR}}$ (infrared heat flux)
- $q_{\text{deck}}$ (deck heat flux)
- $(\rho \cdot l)_{\text{solar}}$ (solar density)
- $I_{\text{solar}}$ (solar intensity)
- $\varepsilon \alpha(T_m)^4$ ( Stefan-Boltzmann law for infrared radiation)

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ASV Reduced Heat Flow Crossing Deck by 30% of Asphalt Shingle

August 2005
Deck Heat Flow Reduced 45% by IRR pigments and ASV

- Above Sheathing Ventilation ~ 30% of control
- SR increase of 0.17 ~ 15% of control

### Roof Deck and Attic Floor Heat Flows (Btu/ft^2) summed over the daylight hours for a July week

<table>
<thead>
<tr>
<th>During Daylight Hours¹</th>
<th>Shingle (SR093E89)</th>
<th>Shk-LG-IRRagg-Upt-CB (SR246E90)</th>
<th>Shk-DG-CNVagg-Upt-CB (SR08E90)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Abs (Btu/ft^2)</td>
<td>3723.2</td>
<td>2095.2</td>
<td>3714.5</td>
</tr>
<tr>
<td>Roof Deck (Btu/ft^2)</td>
<td>1216.4</td>
<td>670.3</td>
<td>853.9</td>
</tr>
<tr>
<td>Attic Floor (Btu/ft^2)</td>
<td>326.6</td>
<td>95.5</td>
<td>112.2</td>
</tr>
<tr>
<td>Q_{Attic Vent} (Btu/ft^2)</td>
<td>889.7</td>
<td>574.8</td>
<td>741.8</td>
</tr>
<tr>
<td>Q_{Deck Vent} (Btu/ft^2)</td>
<td>1280.6</td>
<td>2703.8</td>
<td></td>
</tr>
</tbody>
</table>

¹ Daylight defined as period when solar flux normal to roof exceeds 30 Btu/hr ft^2

\[
Q_{\text{Attic vent}} = \frac{Q_{\text{HFT, Roof Deck}}}{\text{COS}(\theta)} - Q_{\text{HFT, Attic floor}}
\]

\[
Q_{\text{Deck vent}} = \frac{Q_{\text{Solar Abs}} - Q_{\text{Mass}} - Q_{\text{HFT, Roof Deck}}}{\text{COS}(\theta)}
\]
Above-sheathing ventilation accelerated the removal of unwanted moisture

- reduced moisture content in OSB well below that of OSB in a non-vented cavity
■ Regional Criteria for Above-Sheathing Ventilation
  - Develop Recommendations for above-Sheathing Ventilation and submit for public review and acceptance as standards practice

■ Maximize attic contribution to energy savings through integration of key strategies into Next Generation Attic
  - PCM, cool roofs (IRR), above sheathing ventilation and radiant barriers combined into Next Generation Attic

■ Computer Tool Benchmarking
# MCA Field Testing of Painted Metal

**ESRA**

<table>
<thead>
<tr>
<th>Lane</th>
<th>Installation</th>
<th>Radiant Barrier</th>
<th>Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^1)</td>
<td>Offset from deck 4.0-in, dual air channel</td>
<td>Low-e foil on deck facing up</td>
<td>Hardy Board (0.5-in)(^2)</td>
</tr>
<tr>
<td>11</td>
<td>Offset from deck 4-in using clips</td>
<td>Backer on metal underside</td>
<td>No insulation above deck</td>
</tr>
<tr>
<td>12</td>
<td>Offset from deck 2-in using clips</td>
<td>Low-e paint on underside</td>
<td>No insulation above deck</td>
</tr>
<tr>
<td>13(^1)</td>
<td>Offset from deck 4.0-in, forced ventilation</td>
<td>Low-e foil on deck facing up</td>
<td>No insulation above deck</td>
</tr>
<tr>
<td>14</td>
<td>Offset from deck 0.75-in using clips</td>
<td>Backer on metal underside</td>
<td>≈ R-1.0 above deck</td>
</tr>
<tr>
<td>15</td>
<td>Offset from deck 0.75-in using clips</td>
<td>Low-e paint on underside</td>
<td>No insulation above deck</td>
</tr>
</tbody>
</table>

\(^1\)Roof and attic assemblies already under evaluation.

\(^2\)Hardy board used to separate two air channels above roof deck.
Roof with \( \frac{3}{4} \)- and 2-in airspace yield similar roof heat flows to roof with 4-in airspace.
Roof with R-1 insulation placed above deck yields similar thermal performance to roof with ¾-in airspace above deck.
AtticSIM II (Attic Simulation) Model

Table 1. Data for daylight hours with average outdoor air temperature of 84°F; 0.75-in air space.

<table>
<thead>
<tr>
<th>System</th>
<th>Nu number</th>
<th>Temperature (°F)</th>
<th>Heat Flux (Btu/hr ft²) over Daylight hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Roof Underside</td>
</tr>
<tr>
<td>Open Cavity</td>
<td>0.9</td>
<td>137.9</td>
<td>124.9</td>
</tr>
<tr>
<td>Louvre in Open Cavity</td>
<td>1.1</td>
<td>141.7</td>
<td>115.9</td>
</tr>
</tbody>
</table>

Solar reflectance 0.28, emittance 0.95; air space 4.0-in.

\[
\dot{h} = \frac{k}{\Delta}
\]
1st Generation Roof and Attic

Painted metal roof (SR28E81, 4-in air gap, 2 Low-e, PCMs)
Advanced Attic with PCM Shaves Peak Demand and Reduces Night Sky Losses

![Graph showing roof heat flux over time into week (hours) with peak demand reduction highlighted.]

- **Control - Asphalt Shingle (SR093E89)**
- **Painted Metal (SR28E81), 4-in Airgap, PCM, 2-RB**
Effect of Cool Color, Above-Sheathing Ventilation, PCMs, and Low-e Reflective Insulation

Full System Integration

Time into Week (hrs)

- Control - Asphalt Shingle (SR093E89)
- IRR Shingle (SR26E90) with RB
- Clay S-Mission (SR54E90)
- Painted Metal (SR28E81), 2-in Airgap, 1-RB
- Painted Metal (SR28E81), 4-in Airgap, PCM, 2-RB

July 28, 2006
Above Sheathing Ventilation Roofs Negate Heating Penalty
Cool Color painted metal with ASV, Low-e surface and PCM [2nd Generation prototype]

- ESRA
- 2-in Air space
- IRR Shingle with RB
- Clay and Concrete tile with above deck EPS insulation
- 4-in Air space PCM Roof
- Conventional Shingle
Next Generation Attics (in progress)

- Asphalt Shingle (SR093E89) - Control
- Asphalt Shingle (SR11E89) with Radiant Barrier
- Painted Metal (SR28E81), 4-in Airspace, 1-Low-e
- Painted Metal (SR28E81), 2x (2-in) Airspace, PCM, Astroboard, 2x-Low-e
- -- - Clay High profile (SR54E90) DD with EPS

Graph showing Roof Heat Flux (Btu/hr ft²) vs Time into Week (hrs)
Surface and Underside Temperatures of tooth and valley not affected by RB
OSB Deck Temperature Increases

- Sheathing 4°F increase
- OSB Underside 15°F increase

---

Graph showing temperature changes over time for different materials:
- Asphalt Shingle (SR093E89) - Control
- Asphalt Shingle (SR11E89) - Radiant barrier
- Asphalt Shingle (SR28E94) - Cool Color

Y-axis: Sheathing Temperature (°F)
X-axis: Time (hrs)
2nd Generation Roof and Attic
Conventional thermal mass works well when combined with foam insulation placed above sheathing.
Energy Plus Simulation: PCM in Fiberglass Insulation Blown on Attic Floor

About $1.30 per ft² of attic floor would be spent to increase thermal resistance of conventional blown-in fiberglass insulation.
AtticSIM (Attic Simulation) Model


Miller et al. (2007), “Natural Convection Heat Transfer in Roofs with Above-Sheathing Ventilation.”

Florida Solar Energy Center
AtticSIM II Validations
Asphalt Shingle (SR093E89)

Ceiling Heat Flux

Graph showing the comparison of Ceiling Heat Flux between AtticSim and ESRA 1.5" WFB k' DT/D over time.
Asphalt Shingle (SR093E89) with radiant barrier facing attic space

OSB with RB facing attic
AtticSIM II Validations
Flat Concrete tile (SR13E83) on double batten system

Ceiling Heat Flux
AtticSIM II Validations
S-Mission Clay Tile (SR54E90)

Heat flux through roof deck
S-Mission Clay Tile (SR54E90) with 1¼-in EPS insulation on roof deck (Ecoset)

Heat flux through roof deck
AtticSIM Simulations Include Duct System

- Summer Duct Loss Cools Attic
- Winter Duct Loss Heats Attic

Supply Duct 309 ft²
Return Duct 176 ft²
AtticSim Duct Validation

Equivalent R-Value of Ceiling Insulation for SR25E75 Roof with Inspected Ducts

Zone 09: Attic Contains R-30 Insulation and AC Ducts with R-6 Insulation

$700 for 1400 ft² attic footprint by BNI (2008)
Equivalent R-Value of Insulation for SR25E75 Roof with Inspected Ducts

Zone 15: Attic Contains R-38 Insulation and AC Ducts with R-8 Insulation

$1200 for 1400 ft² attic footprint by BNI (2008)
Annual Cost of Ceiling and Duct Energy based on TDV 30-yr forecast of $0.145 per kBtu NG

Zone 15: Attic Contains R-38 Insulation and AC Ducts with R-8 Insulation
Radiant Barrier Yields Greater Return on Investment than ASV and or Low-E in Airspace

Zone 15: Attic Contains R-38 Insulation and AC Ducts with R-8 Insulation

Heating and Cooling TDV Load

Attic Footprint 1250 ft² (≈115 m²)
<table>
<thead>
<tr>
<th>City</th>
<th>Zone</th>
<th>ASHRAE</th>
<th>Above-Sheathing</th>
<th>Attic Plenum(^2)</th>
<th>Duct System</th>
<th>Load Due to Roof &amp; Attic</th>
<th>Energy(^5) Costs Attributable to Roof &amp; Attic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R-value</td>
<td>FB (TE)</td>
<td>R-Value</td>
<td>Air Leakage</td>
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<tr>
<td>Chicago</td>
<td>05</td>
<td>0.05 / 0.75</td>
<td>NA</td>
<td>19</td>
<td>0.90</td>
<td>4.2</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25 / 0.75</td>
<td>NA</td>
<td>19</td>
<td>0.90</td>
<td>4.2</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.28 / 0.81</td>
<td>1-in airspace</td>
<td>19</td>
<td>0.90</td>
<td>4.2</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.54 / 0.90</td>
<td>High profile(^3)</td>
<td>19</td>
<td>0.90</td>
<td>4.2</td>
<td>14%</td>
</tr>
<tr>
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<td>0.54 / 0.90</td>
<td>High profile(^3)</td>
<td>19</td>
<td>0.05</td>
<td>4.2</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.54 / 0.90</td>
<td>High profile(^3)</td>
<td>38</td>
<td>0.05</td>
<td>4.2</td>
<td>14%</td>
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<tr>
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<td>0.54 / 0.90</td>
<td>High profile(^3)</td>
<td>38</td>
<td>0.05</td>
<td>8</td>
<td>4%</td>
</tr>
</tbody>
</table>

\(^1\) Air space fitted with one low-emittance surface. \(^2\) Annual loads based on attic footprint of 1261 square feet (117.2 m\(^2\)).
\(^3\) High profile clay tile spray adhered to 1/2-in (0.32-m) EPS foam; spray foam adhered EPS to roof deck.

\(^5\) Energy is converted to a net present value cost ($NPV) using a 30-year projection based on EIA fuel price data for Chicago of 11.07\$ per kWh and 1.03\$ per therm NG.

Annual cost ($PV$) computed using 3% discount rate over 30-yrs.
Prototype Roof on Post-1980 Construction Yields Energy Savings of about 5 MBtu NG/yr

<table>
<thead>
<tr>
<th>City</th>
<th>Zone</th>
<th>Climate</th>
<th>SR / TE</th>
<th>Above-Sheathing</th>
<th>Attic Plenum</th>
<th>Duct System</th>
<th>Annual Load (kBtu per yr)</th>
<th>TDV Energy Costs</th>
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<td>1,316</td>
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<td>0.81</td>
<td>1-in airspace</td>
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<td>0.05</td>
<td>6</td>
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<td>1,182</td>
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<td>Sacramento</td>
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<td>4%</td>
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<td>0.81</td>
<td>1-in airspace</td>
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<td>8</td>
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<td>0.05</td>
<td>6</td>
<td>0%</td>
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<td>El Centro</td>
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<td>4-in airspace</td>
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<td>8</td>
<td>4%</td>
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<td>0.90</td>
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<td>0.90</td>
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<td>8</td>
<td>4%</td>
<td>1,751</td>
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<td>0.05</td>
<td>6</td>
<td>0%</td>
<td>2,198</td>
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1 Air space fit with one low-emittance surface. 2 Annual loads based on attic footprint of 1,251 square feet (117.2 m²).
3 High profile clay tile spray adhered to 1.25-in (32-mm) EPS foam; spray foam adhered EPS to roof deck.
4 TDV energy is converted to a net present value cost based on a 30-year fuel price forecast of $0.145 per kBtu NG. Annual cost computed using 3% discount rate over 30-yrs.
Space conditioning energy attributable to attics reduced almost by 50% of Post-1980 Construction

Ranking of Roof and Attic Strategies

Annual Cooling Load

Attic Footprint 1250 ft² (≈115m²)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Cooling Load (KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base SR10E75</td>
<td>1301</td>
</tr>
<tr>
<td>SR10E75, RB</td>
<td>1069</td>
</tr>
<tr>
<td>SR25E75, RB, IRR</td>
<td>1004</td>
</tr>
<tr>
<td>SR28E75, RB, IRR, ASV(1'')</td>
<td>842</td>
</tr>
<tr>
<td>Base + Ecoset</td>
<td>739</td>
</tr>
</tbody>
</table>

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CONCLUSIONS

Ductwork in Attics Are the Predominant Energy Loss

Radiant Barrier provides best opportunity for return on Investment

Smart Integration yields positive gains in roof and attic performance (regional design)

- Reflective surfaces (low-e)
- Conventional insulations
- PCM insulations
- Above Sheathing Ventilation
- Cool Color Roofs

GOAL

Reduce space conditioning attributable to attics by 50% of Building America regional benchmark (R50 Roof, R30 Wall.)