White Roofs in Northern Climates

ASHRAE Tech. Paper: *Simulated Influence of the Roof Reflectance on the Building Energy Balance in Two Northern Cities*

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Learning Objectives

1) Identify and evaluate applications where a white roof is effective and ineffective
2) Recognize common misconceptions for the use of white roof technology
3) Understand the technology and savings benefits of white roofs in northern climates

Definition

- Here, we define a “white roof” is one that is highly reflective of incident solar radiation

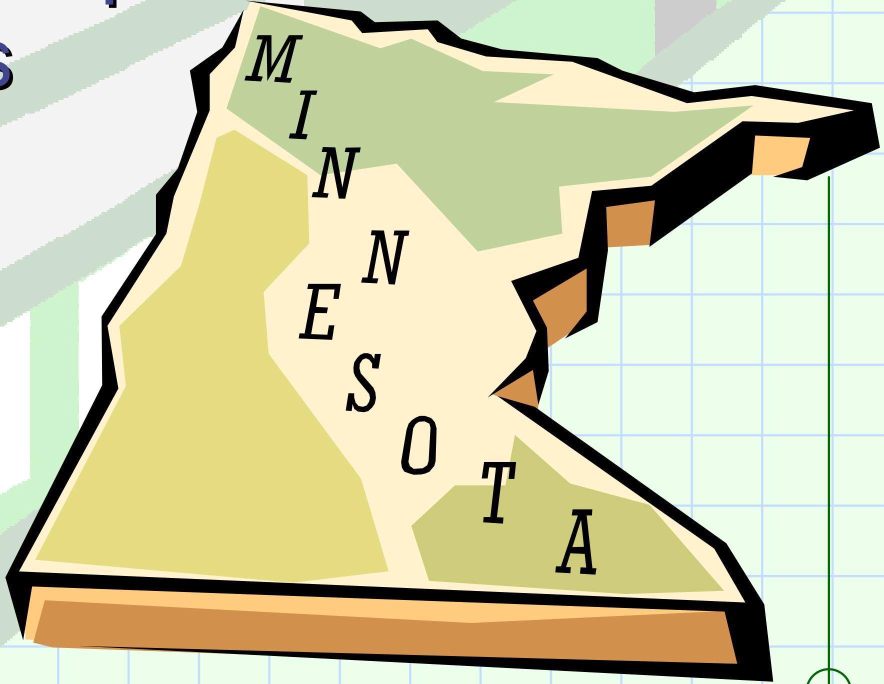
EPA’s requirements for a “Reflective Roof”

Equipment	Specification
Roofing	•Low Slope roofs must have an initial solar reflectance of >= 0.65. After 3 years, the solar reflectance must be >= 0.50. •Steep Slope roofs must have an initial solar reflectance of >= 0.25. After 3 years, the solar reflectance must be >= 0.15.

Source: www.energystar.gov/index.cfm?c=roof_prods.pr_crit_roof_products

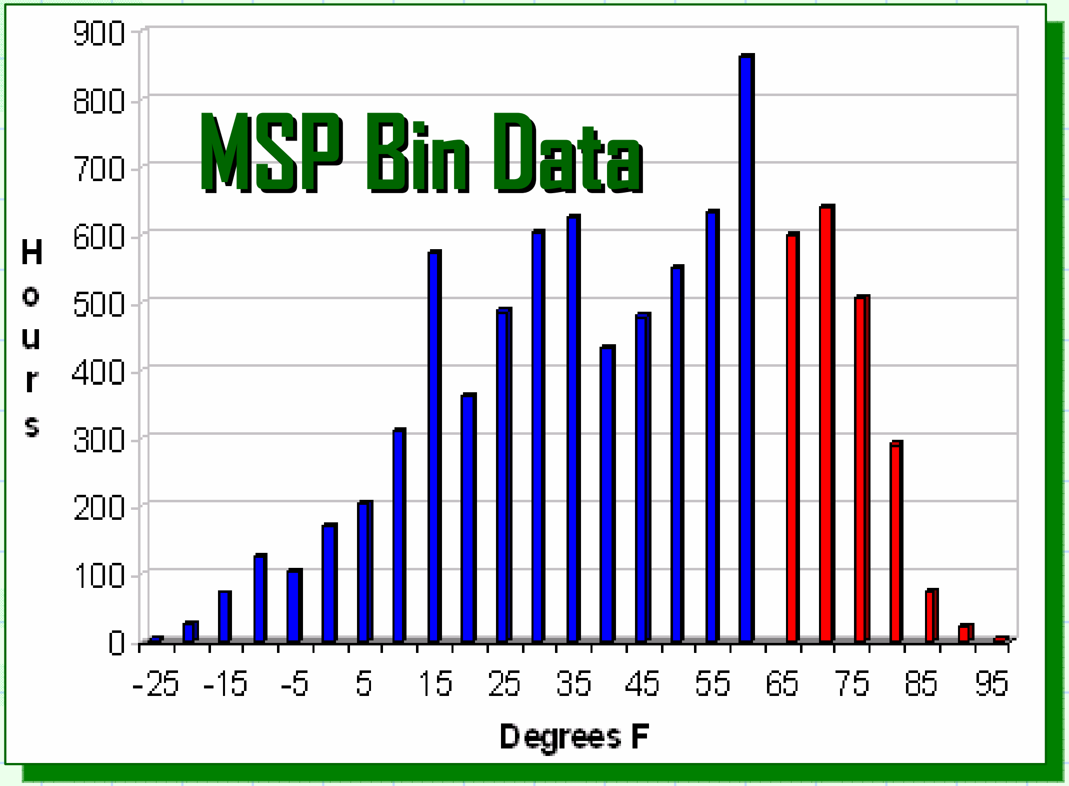
Why Northern Climates?

- Minnesota utility offered a rebate for installing high albedo (white) roof on "big box" retail buildings
  - Primarily targeted at roof replacements of poorly insulated buildings
- Rebate was challenged due to climate
  - *MANY* more heating hours than cooling hours



Why Northern Climates?

- Is there monetary savings?
  - Is electric (A/C) savings being achieved at the expense of extra gas (heating) use?
  - Is heat/cooling season balance to skewed?
  - Or does reflective nature of snow cover negate the differences between white and black roofs?



Previous Work

- *Cool Roofs Save Energy*, Hashem Akbari, ASHRAE Transactions 1998.
- *Measured Performance of a Reflective Roofing System in a Florida Commercial Building*, Danny S. Parker, John R. Sherwin, Jeffrey K. Sonne, ASHRAE Transactions 1998.
- *High-Albedo Roof Coatings—Impact on Energy Consumption*, James M. Akridge, ASHRAE Transactions 1998.
- *Measured and Simulated Performance of Reflective Roofing Systems in Residential Buildings*, D. S. Parker et al, ASHRAE Transactions 1998.

Previous Work

- *Cool Roof* ... Transactio...
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- *High* ... *on Energy* ... , ASHRAE
- *... Performance of Reflective ... uildings*, D. S. ... SHRAE Transactions 1998.

California &

st Florida

Very little work done on heating dominated climates

Previous Work

- *Measured and Simulated Performance of Reflective Roofing Systems in Residential Buildings*, D. S. Parker et al, ASHRAE Transactions 1998.
  - DOE-2 simulations said residential white roof would have negative impacts in northern climates
- *Calculations for Reflective Roofs in Support of Standard 90.1*, Hashem Akbari et al., ASHRAE Transactions 1998.
  - Again, DOE-2.1E simulations said roofs in cold climates should not be reflective, but assumptions made from warm weather data
- *Cool Roofs Save Energy, H.* Akbari, ASHRAE Transactions 1998.
  - DOE-2 based simulations may underestimate the effect of roof reflectance on energy usage

Parameters

- Architectural/ Envelope Characteristics
  - Building type: 1 story commercial retail – “big box”
  - Location: Minneapolis
  - Floor area: 100,000 ft^2
  - Height: 25 ft
  - Length: 316.2 ft
  - Width: 316.2 ft
  - Windows: 400 ft^2 each wall, facing N, S, E and W
  - Window Type: Standard clear double glazed
  - Wall insulation level: R-11
  - Floor construction: Concrete slab on grade

Parameters

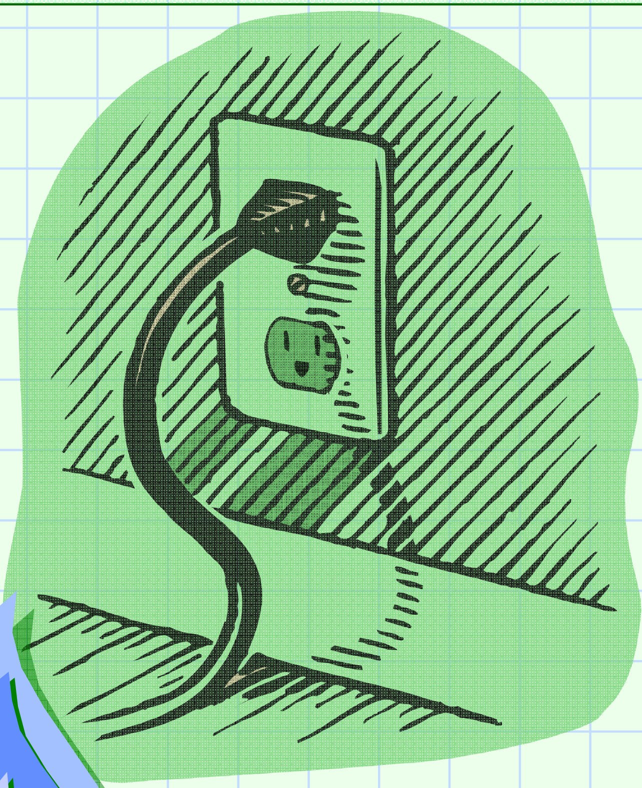
- Operation and Use
  - Occupied periods: 7AM to 10PM all days
  - Heating set point: 72°F
  - Cooling set point: 76°F and max of 60% RH
- Internal Load Characteristics
  - Light: 2.5 w/ft^2 Occupied & 0.50 W/ft^2 unoccupied
  - Light Schedule: 100% occupied time, 20% unoccupied time
  - People: Maximum 400, varies throughout the day and week vs. weekend
  - Activity level: ISO 7730-05 (315/325 Btu/h sensible/latent), only during occupied
  - Equipment load/schedule: 0.3 W/ft^2/24 x 7

Parameters

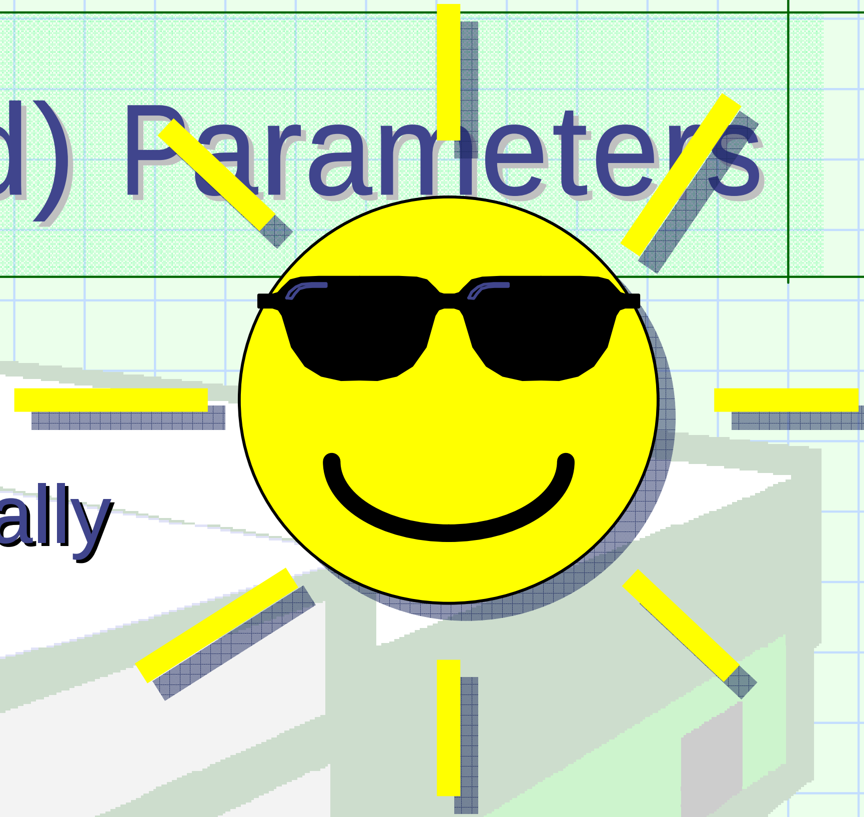
- Mechanical System Characteristics
  - Cooling Equipment: DX Rooftop
  - Cooling EER: 9.0
  - Heating system 80% Rooftop gas fired unit
  - Air handler type: Constant volume
  - Supply CFM/sf: 1.5 cfm/ft^2
  - Outside air: 0.2 cfm/ft^2
  - Supply/return fan power: 70 kW
  - Pressure drop: 1 inH_2O (249 Pa) for 150 kcfm,
  - Fan efficiency: 50%
  - Infiltration: 0

Parameters

- Electric Rates
  - June through September
    - $0.031/kWh
    - $6.61/kW
  - October through May
    - $0.031/kWh
    - $9.26/kW
- Natural Gas Rate
  - $0.481/therm



Influencing (Varied) Parameters



- Roof Orientation
  - South sloped roofs typically receive higher radiation intensity and less snow coverage than flat.
  - Since the building was a big box retailer, we chose a flat roof with the front facing south.
- ***This parameter did not vary in the study***

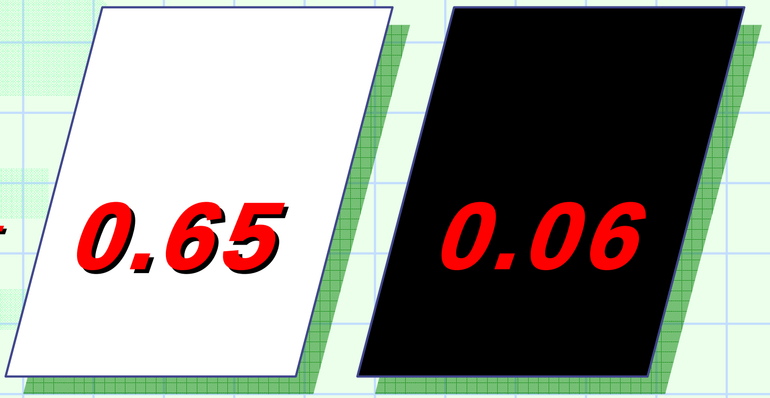
Influencing (Varied) Parameters

- Sunshine/Snow cover
  - Increased Sunshine = Increased heat load
  - Summer
    - Reflective roof reduces effects of sunshine and saves A/C energy.
  - Winter
    - Reflective roof reduces effects of sunshine and increases heating load.
    - Less hours of sunshine in winter
    - Snow cover negates the effect of the roof since all roofs become white.

- *8,760 simulation including sun, wind and cloud*
- *With snow cover vs. no snow cover*

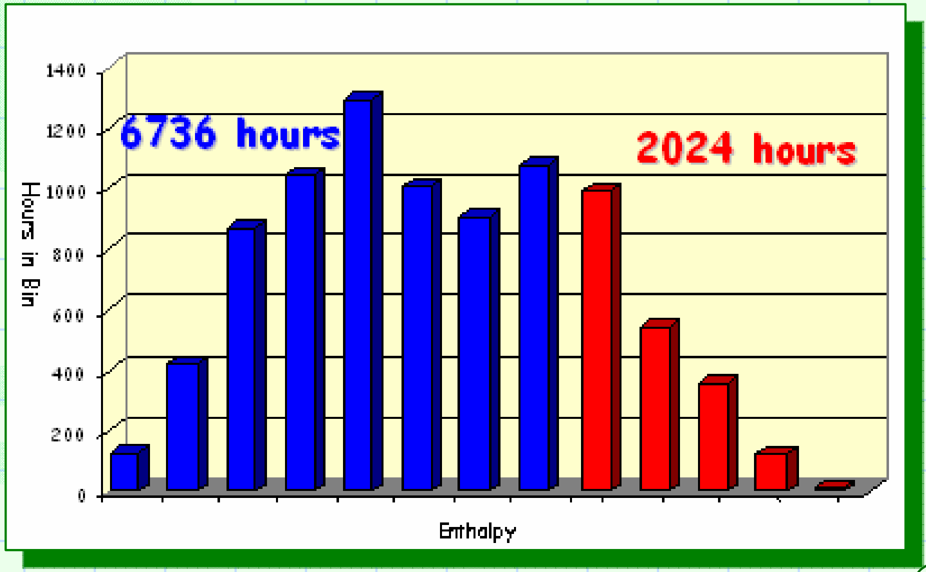
Influencing (Varied) Parameters

- Roof Construction and Insulation
  - “R-24” is sheet metal roof with an EPDM membrane insulation material with R-value = 24 hr-ft^2-F/Btu plus variable heat transfer coefficient
  - Average R-value = 3.28 + insulation R-value
- *Roof insulation levels*
  - *Insulation levels of R0, R4, R8, R16, R24*
  - R0 indicates no insulation.
- *Roof surface reflectance*
  - *Black = 0.06 vs. White = 0.65*
  - 0.65 is Energy Star minimum
  - 0.80 is common installation value



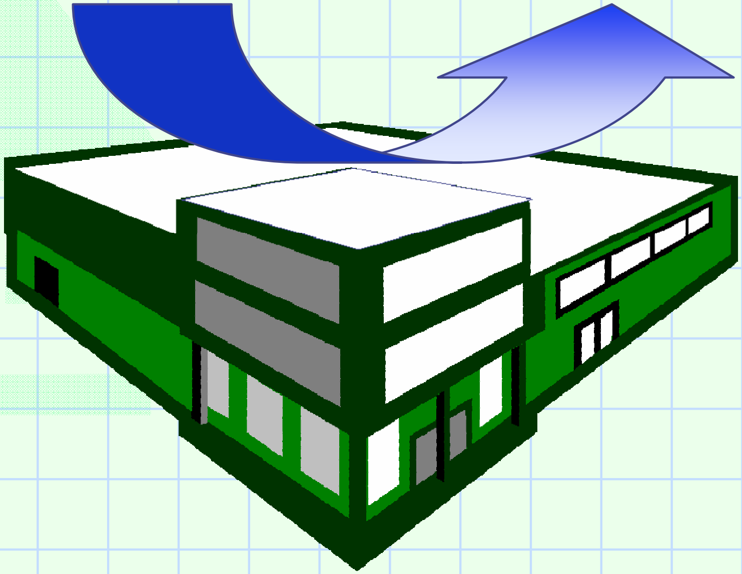
Influencing (Varied) Parameters

- Internal Gains & Heat Load
  - During cooling season, reduced roof surface temperature results in lower cooling load.
    - Reduces payback of white roof
  - Cooling season extended by:
    - Warmer climate
    - Higher internal loads
- *Economizer vs. No economizer*



Heat Transfer Coefficients

- Outside convective heat transfer coefficient (h_w) based on wind speed.
  - Free convection coefficient = 5 W/m^2-K
    - Used at low wind speed
  - $h_w = \max[5, 2.5 + 1.9v]$
    - v = wind speed [m/s]
- h_w is recalculated every hour of the simulation



Heat Transfer Coefficients

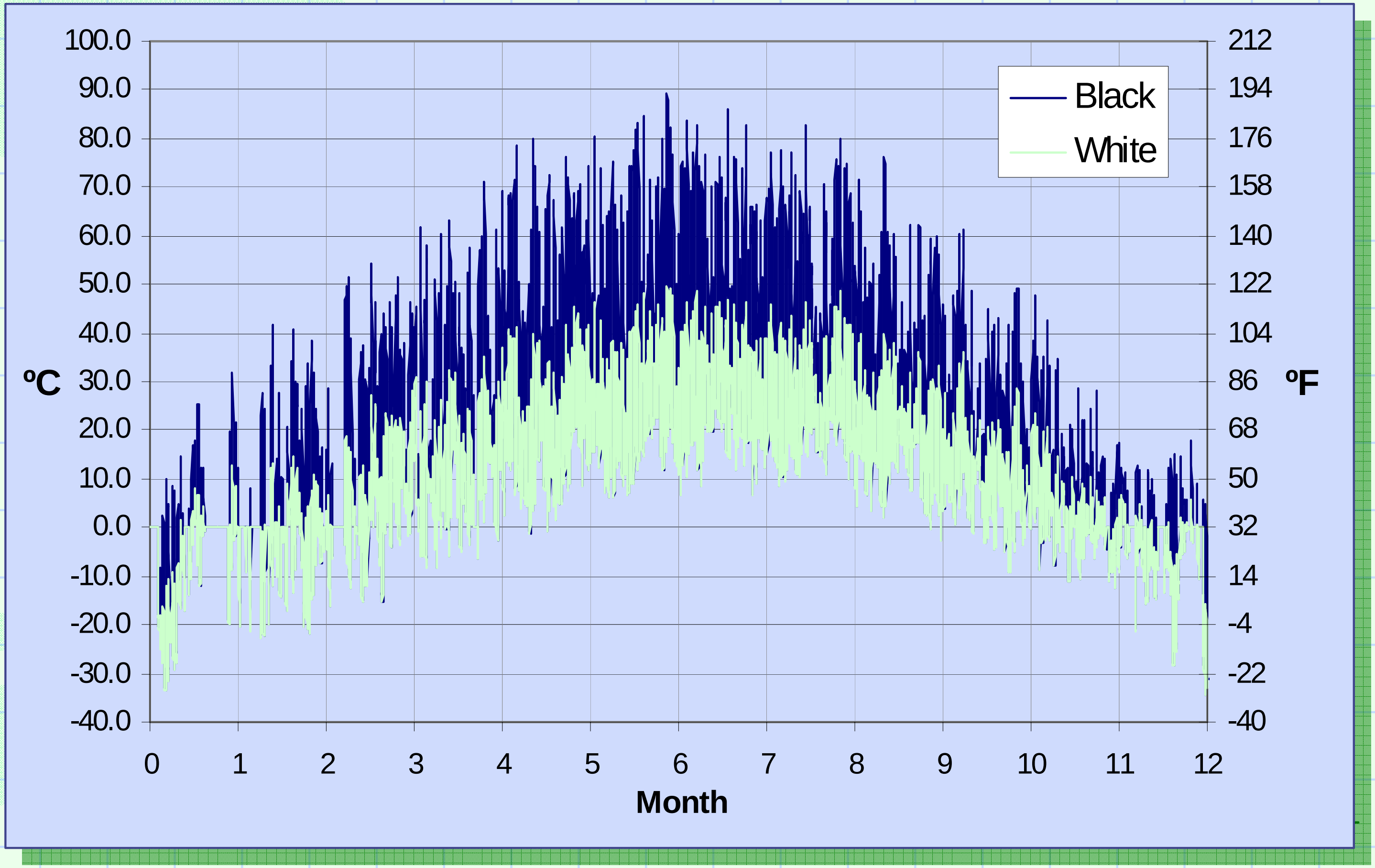
- Inside convective heat transfer coefficient h_{in} based on air change per hour (ACH) and ΔT between inside of roof and room.
  - For *cooling* season (warm roof):
    - $h_{in} = 0.49\ ACH^{0.8} + 0.525\ (T_{roof} - T_{room})^{0.2446}$
  - For *heating* season (cool roof):
    - $h_{in} = 0.49\ ACH^{0.8} + 4 - 0.0017\ T_{roof} + 0.0032\ T_{roof}^{2} - 0.0005\ T_{roof}^{3}$
- h_{in} is also recalculated every hour of the simulation.

Heat Transfer Coefficients

- Radiative heat transfer also taken into account using empirical formula from Berdahl and Martin [1984]

Simulated Roof Surface Temperature

R8 insulation



Roof Temperatures

R-value of Roof Insulation		R4	R8	R16	R24
Black, Max.	°F	192	192	195	195
White, Max.	°F	122	122	123	122
Black, Ave.	°F	61	61	62	67
White, Ave.	°F	50	50	51	56

Snow Cover

- Simulated snow cover on roof
  - Start with snow height data from TMY2
  - Calculate hourly melting rate due to heat flux through the roof
  - Sets roof surface temp to 32°F and high heat transfer coefficient if snow present
  - Negligible heat transfer through snow
    - Snow melts from bottom up

Summary of the Annual Cooling Simulation Results

R-value of roof insulation		R-0	R-4	R-8	R-16	R-24
Building Cooling Load [Btu/ft²]						
	Black	25,701	25,663	26,194	26,646	27,586
	White	19,037	21,483	23,134	24,703	26,084
	Difference	6,665	4,181	3,060	1,943	1,502
Cooling Consumption [kWh/1,000 ft²]						
	Black	2,545	2,541	2,593	2,638	2,731
	White	1,885	2,127	2,291	2,446	2,583
	Difference	660	414	303	192	149
Peak Cooling Power [kW/1,000 ft²]						
	Black	3.06	2.71	2.64	2.44	2.42
	White	2.49	2.42	2.43	2.35	2.35
	Difference	0.57	0.29	0.21	0.09	0.06
		19%	11%	8%	4%	3%
Cooling Cost [$/1,000 ft²]						
	Black	79	79	80	82	85
	White	58	66	71	76	80
	Difference	20	13	9	6	5
		26%	16%	12%	7%	5%
Annual Compressor Demand [$/1,000 ft²]						
	Cost Difference	$33.52	$17.55	$11.87	$5.82	$4.28

Summary of the Annual Heating Simulation Results

R-value of roof insulation		R-0	R-4	R-8	R-16	R-24
Building Heating Load [Btu/ft^2]						
	Black	24,818	15,589	11,872	9,071	7,645
	White	27,690	17,052	12,665	9,420	7,855
	Difference	-2,871	-1,463	-793	-349	-210
Gas Consumption [Therm/1000ft^2]						
	Black	310	195	148	113	96
	White	346	213	158	118	98
	Difference	-35.9	-18.3	-9.9	-4.4	-2.6
Peak Gas Consumption [Therm/h-1000ft^2]						
		0.31	0.27	0.24	0.21	0.18
Heating Cost [$/1000ft^2]						
	Black	149	94	71	55	46
	White	166	103	76	57	47
	Difference	-17.3	-8.80	-4.77	-2.10	-1.26
		-12%	-9%	-7%	-4%	-3%

Summary of Simulation Results

R-value of roof insulation		R0	R4	R8	R16	R24
Overall R-value of roof		R3.50	R7.82	R11.82	R19.82	R27.82
Heating Savings	Load, Btu/ft^2	-2,871	-1,463	-793	-349	-210
	\$/1,000ft^2	-\$17.30	-\$8.80	-\$4.77	-\$2.10	-\$1.26
Cooling Savings	Load, Btu/ft^2	6,665	4,181	3,060	1,943	1,502
	\$/1,000ft^2	\$53.98	\$30.39	\$21.26	\$11.78	\$8.89
Total Savings	Load, Btu/ft^2	3,793	2,718	2,266	1,594	1,293
	\$/1,000ft^2	\$36.71	\$21.59	\$16.49	\$9.68	\$7.63

Summary of the heating and cooling savings per year for a white roof compared to a black roof. White roof values subtracted from the black roof values. Economizer is used and roof is covered with snow at appropriate times.

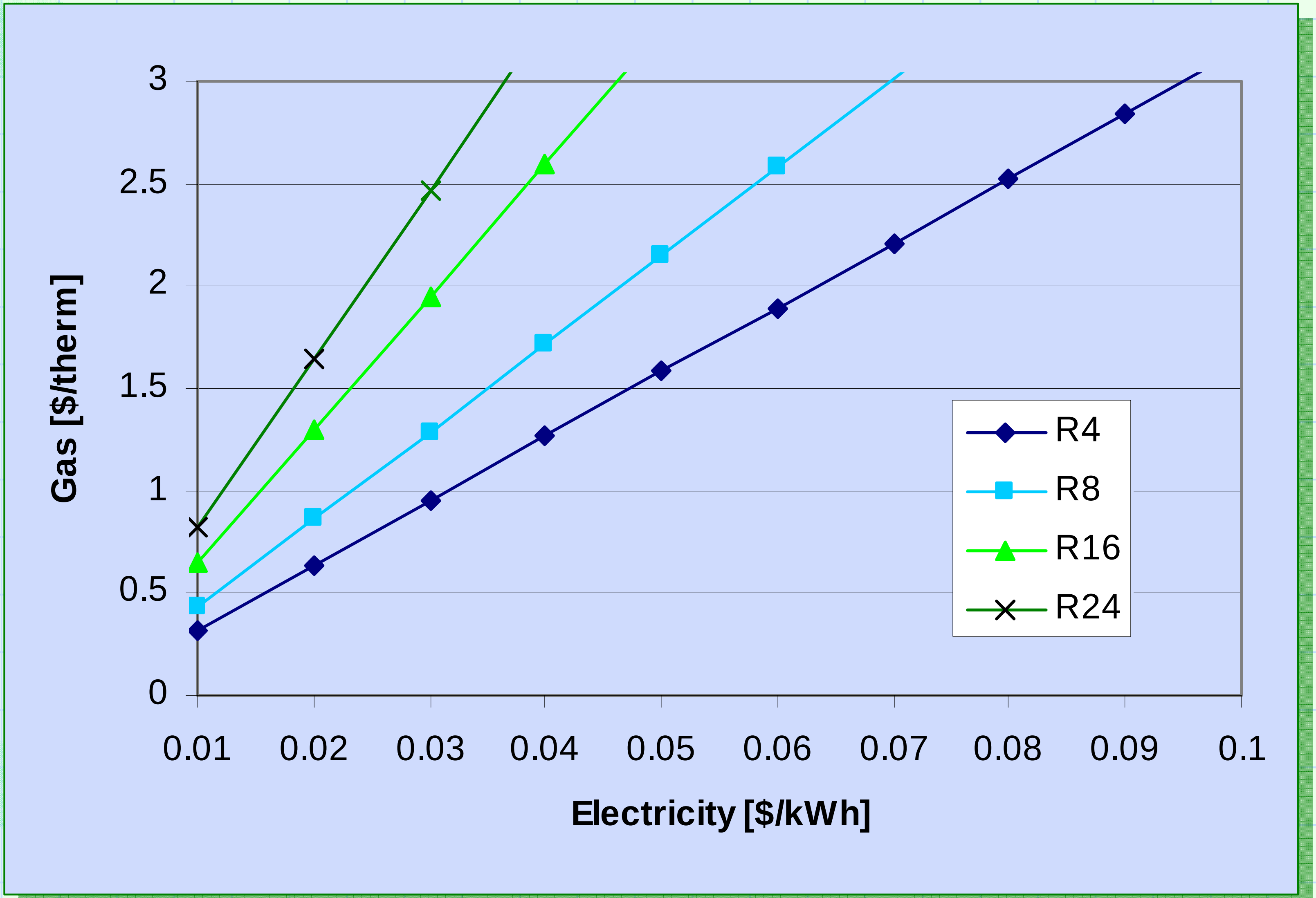
Influence of Snow

- High insulation increases negating effect of snow
- Even without snow, energy cost savings are 22% lower for R4 and 26% for R24

	R4	R24
Hours of Snowcover	615	1,511
Building Heating Loads [Btu/ft^2]		
Black, with snow	15,588	7,578
Black, without snow	16,054	8,115
Difference	2.9%	6.6%
White, with snow	17,052	7,798
White, without snow	17,859	8,610
Difference	4.5%	9.4%
Building Cooling Loads [Btu/ft^2]		
Black, with snow	33,988	38,974
Black, without snow	34,011	38,994
Difference	0.1%	0.1%
White, with snow	28,149	36,690
White, without snow	28,151	36,660
Difference	0.0%	-0.1%

Influence of Energy Prices

Break-Even Energy Costs



Influence of Increased Insulation

Savings for Incremental Increases in Roof Insulation.

Roof is a black roof, with snow cover and economizer in use.

Incremental insulation increase		R4 to R8	R8 to R16	R16 to R24	R4 to R24
Heating Savings	Load, Btu/ft^2	3,717	2,801	1,426	7,944
	$/1000ft^2	$22.35	$16.84	$8.57	$47.76
Cooling Savings	Load, Btu/ft^2	-531	-452	-940	-1,923
	$/1000ft^2	-$1.63	-$1.39	-$2.89	-$5.90
Total Savings	Load, Btu/ft^2	3,187	2,348	486	6,021
	$/1000ft^2	$20.72	$15.45	$5.69	$41.86

Summary of Simulation Results:

R-value of roof insulation		R0	R4	R8	R16	R24
Total Savings for Installing White Roof	Load, Btu/ft^2	3,793	2,718	2,266	1,594	1,293
	$/1,000ft^2	$36.71	$21.59	$16.49	$9.68	$7.63

Influence of Economizer

Savings for Installing White Roof without an Economizer.

With snow cover but NO economizer in use.

Roof insulation		R4	R8	R16	R24
Heating Savings	Btu/ft^2	-1,464	-803	-353	-220
	$\$/1000ft^2$	-\$8.80	-\$4.83	-\$2.12	-\$1.32
Cooling Savings	Btu/ft^2	5,839	4,363	2,889	2,283
	$\$/1000ft^2$	\$36.13	\$26.91	\$15.08	\$11.36
Total Savings	Btu/ft^2	4,375	3,560	2,537	2,064
	$\$/1000ft^2$	\$27.33	\$22.08	\$12.95	\$10.04

Summary of Simulation Results: Just the Total

R-value of roof insulation		R0	R4	R8	R16	R24
Total Savings for Installing White Roof	Load, Btu/ft^2	3,793	2,718	2,266	1,594	1,293
	$\$/1,000ft^2$	\$36.71	\$21.59	\$16.49	\$9.68	\$7.63

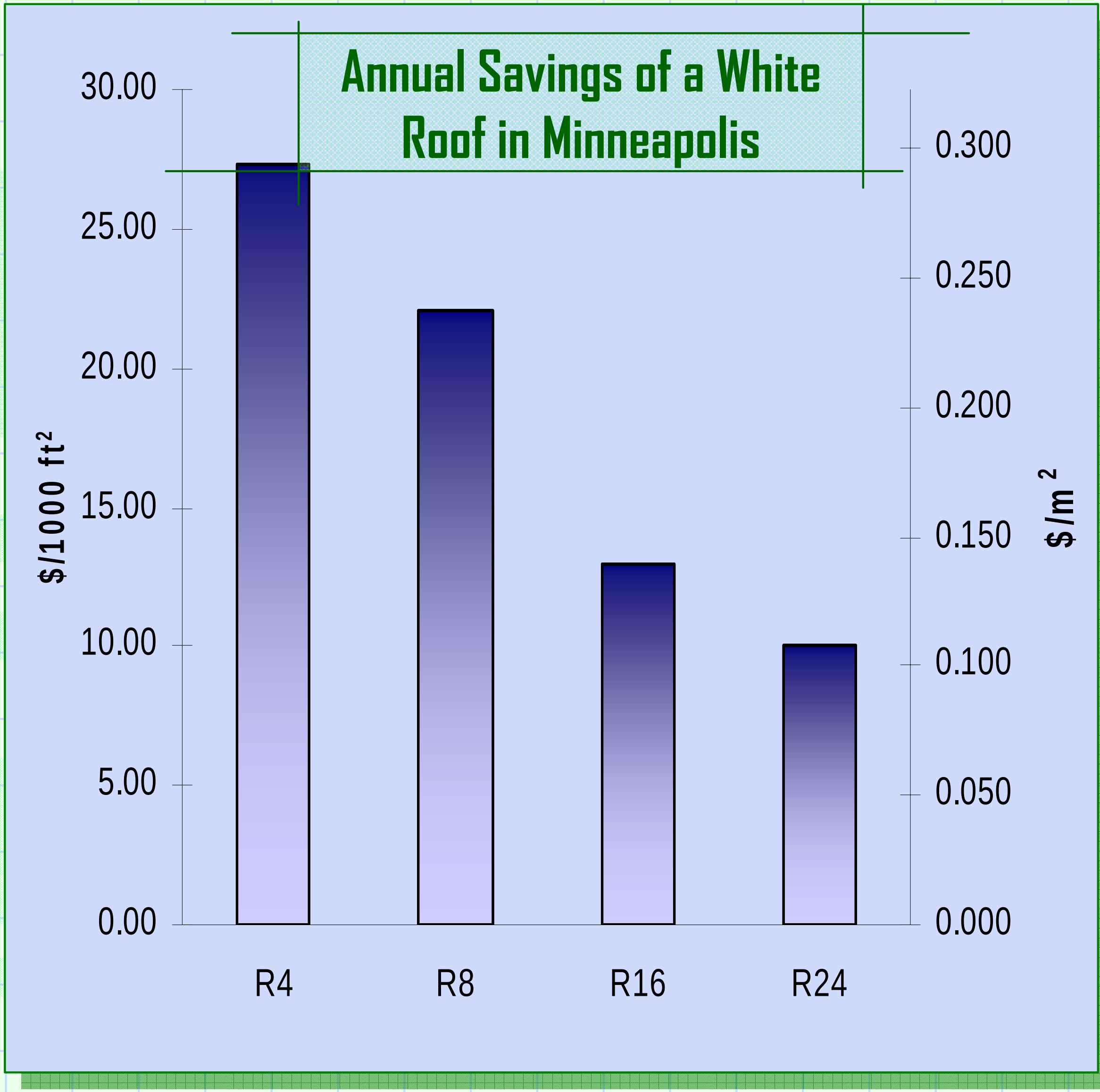
Denver, CO

Savings Summary for Installing White Roof In Denver, CO

Roof insulation			R4	R24
Heating Energy	Black	therm/1000 ft²	88	24
	White	therm/1000 ft²	102	25
	Difference	%	-15.2%	-4.3%
	Difference	therm/1000 ft²	-13.4	-1.0
Cooling Energy	Black	kWh/1000 ft²	3539	4162
	White	kWh/ft²	2736	3854
	Difference	%	22.7%	7.4%
	Difference	kWh/1000 ft²	803	307
Energy Cost	Difference	$/1000 ft²	18.42	9.04
Demand Cost	Difference	$/1000 ft²	29.32	7.05
Total costs	Difference	$/1000 ft²	47.74	16.09

Summary

- Installation of high albedo (white) roofs saves energy and money in northern U.S. climates.



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Questions or Comments??

Daniel Dettmers

HVAC&R Center & Industrial Refrigeration Consortium

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