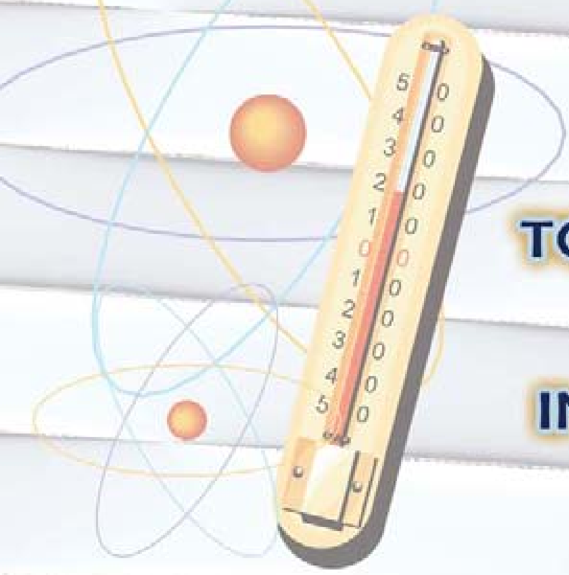

Cool Roof Coatings to Reduce Energy Demand and Temperature in an Urban Environment

By William A. Kirn, RRC

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Background

The Energy Coordinating Agency (ECA) is a Philadelphia-based, private, non-profit corporation dedicated to ensuring that low- and moderate-income people have access to safe, affordable, and reliable sources of energy and water. In the mid 1990s, ECA began exploring ways to assist its clients with issues relating to summertime cooling.

While some homeowners had air conditioners, the cost of electricity relative to their income sometimes prevented their operation. Many of ECA's clients are seniors who have a higher risk of heat-related health problems due to poor general health status, social isolation, physical limitations, and safety concerns that detract from their ability to manage high temperatures.

Above: Photo 1: Application of elastomeric acrylic roof coatings to residential roofs.

Early Experiments:

Research published by Rohm and Haas, National Coatings Corporation, Oak Ridge, Lawrence Berkeley National Laboratories, and others[1-18] has shown that some cooling and reduction in air conditioning load and electricity required to condition buildings could be realized by coating low-slope roofs white to reflect the infrared portion of solar radiation. The studies also showed energy and life-cycle benefits for reflective roof coatings. Almost all of ECA's clients live

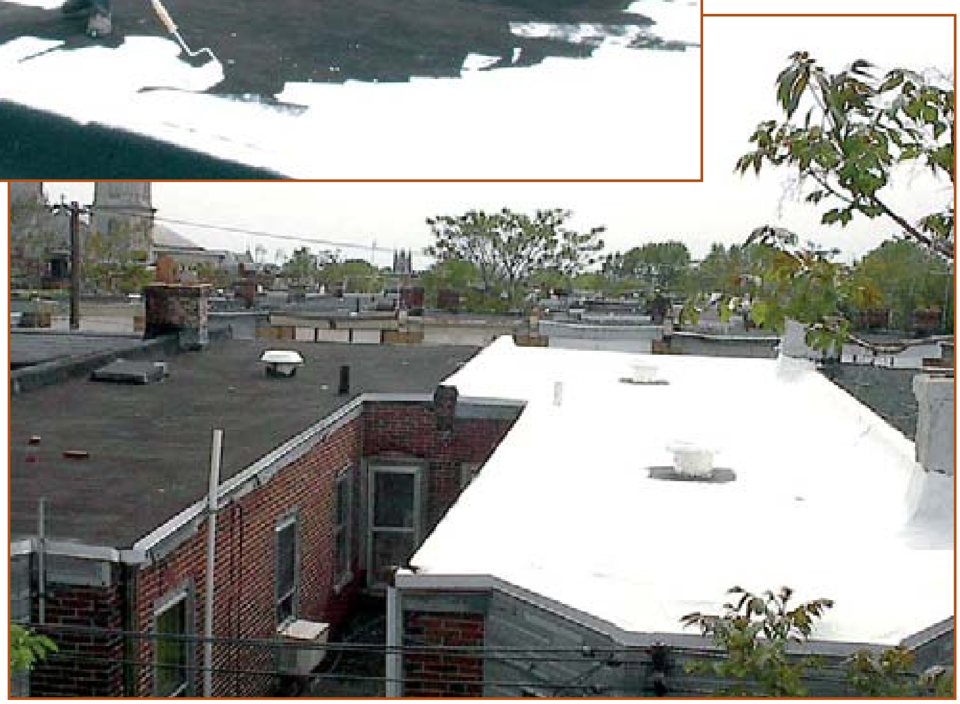

Photo 2: Comparison of coated and uncoated roofs.

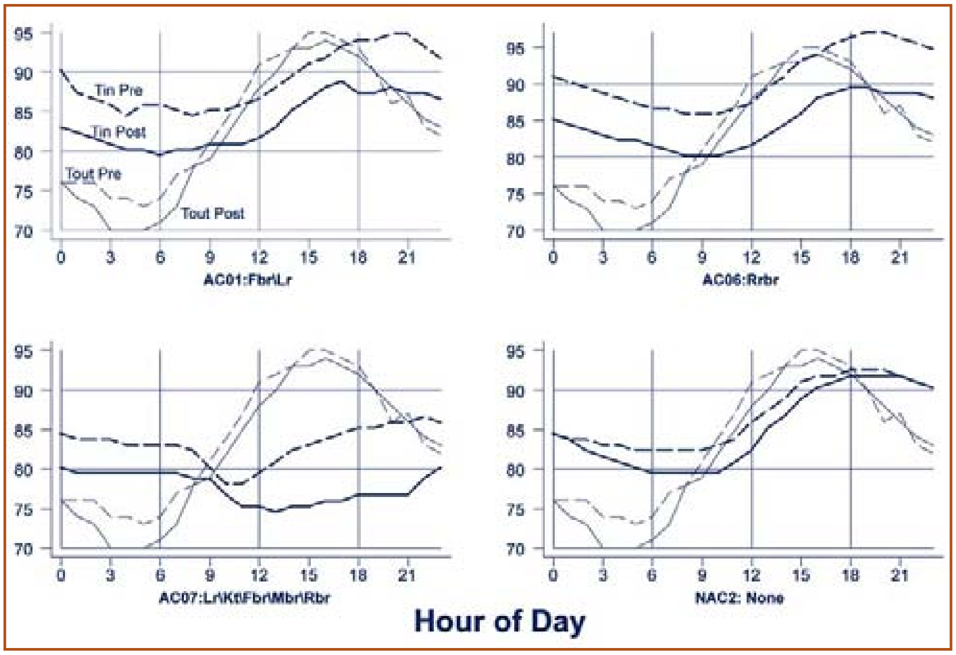

Figure 1. Matched day overlapped comparison of temperatures for four houses.

in densely populated, urban, two-story row homes with low-slope asphalt built-up or modified bitumen roofs.

"Cool Homes" Program

ECA began a pilot program coating several row homes (townhouse-type construction) in Philadelphia. The construction consisted of brick and block walls with plank roof deck and low-slope asphalt BUR or modified bitumen roofs. Each home was equipped with recording thermometers placed strategically in the structure. Some uncoated "control" homes were also monitored to determine the effects of reflective coating. Since it would be preferred to reduce the temperatures in these homes using little or no electro-mechanical cooling, electricity demand was also monitored. The homes had blown-in insulation in the cavity between the roof deck and second-floor ceilings. The R-values ranged from 8 to 12. The reflective roof coating used in the project had solar reflectance of 0.83 and thermal emittance of 0.89 as measured by the Cool Roof Rating Council methodology.

The Cool Home pilot collected temperature and humidity with data loggers at 35 houses. Six of these houses were logged in the summer of 2001 and treated before the summer of 2002. Six more houses were designated for the comparison group and did not receive coating during the summer, leaving 23 houses with potential for short-term pre- and post-analysis. Three of these houses did not have any data from the second floor bedroom wall, and one of the remaining houses did not receive any major coatings during the summer, leaving 19 houses for the pre- and post-analysis. All but two of these 19 houses have air conditioners.

Temperature Time Series Profiles

There were few days with similar outdoor temperatures between the pre- and post-coating periods, but July 2nd and July 16th were fairly similar with peak temperatures in the mid 90s and clear skies. Both also had similarly warm days preceding them (reducing the potential impact of thermal mass effects).

Figure 1 shows the temperature data for four houses where the data for each of these two days is overlapped. The dashed lines show the July 2nd data (representing the "pre-coating" condition), and the solid lines show the July 16th data (post coating). The bold lines show the 2nd floor bedroom indoor air temperatures while the lighter lines show the outdoor temperatures. (Note: In all cases, "indoor air temperatures" refers to the temperature measured at chest height.) "T in Pre" is interior (chest-height) temperature prior to coating, "T in Post" is interior (chest-height) temperature after coating, "T out Pre" is exterior temperature prior to coating, and "T out Post" is exterior temperature after coating.

House NAC2 had no coatings between the two days and the temperature profiles of both days look similar with nearly identical peaks, although the pre-coating day is a little warmer. Houses AC01 and AC06 show noticeably larger differences in second-floor temperatures between the two days, indicating the impact of coating. The difference between the days is clear throughout the 24-hour cycle. House AC07 shows obvious air conditioning, but also cooler indoor temperatures after coating. It is not clear how much of this change may be due to the coatings or different air conditioning settings.

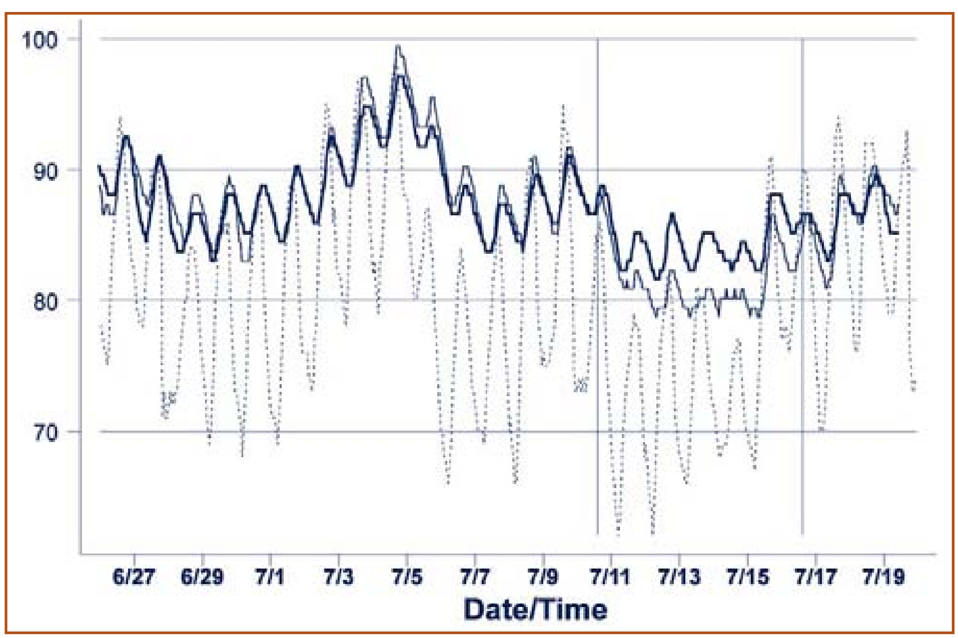

Figure 2. Second-floor temperatures of houses AC06 and AC08 with one-week gap between coating application to houses AC06 and AC08.

A simplified presentation of the data can be shown as follows. The similarity of houses AC06 and AC08 and the fact that AC06 was treated on July 10th while AC08 was treated July 16th, allow for another graphical assessment of the coatings' impact. *Figure 2* shows the second-floor temperatures for both of these houses, along with the outdoor temperatures (dotted line) from late June through July 19th. House AC08 is the bolder line.

Figure 2 also shows that AC06 was a little hotter than AC08 until coating (first vertical line); then, it was much cooler until AC08 was treated (second vertical line). Once they were both treated, the original pattern re-emerged (although both are cooler than before). This figure shows a clear impact from the reflective roof coating. Although the outdoor temperatures were cooler during the week of interest, potentially skewing results, the similarity in temperature patterns before and after both were treated provides convincing evidence of a noticeable coating impact.

Ceiling Temperatures

Figures 3 and *4* show the same relationship between daily maximum temperatures, except the indoor temperature is for the second-floor bedroom ceiling. As expected, the impact of coatings is more pronounced on these graphs, since the coatings directly affect heat gain through the ceiling and therefore only indirectly affect air temperatures.

By focusing on the ceiling temperatures, the impact on air-conditioned houses appears almost as clearly as among houses without bedroom air conditioning. This finding is significant because it implies that the impact of coatings may appear as indoor temperature reductions in houses without air conditioning in the bedrooms, but it could appear as either temperature reductions or cooling load reductions in the air-conditioned houses.

An alternative approach to this analysis is to plot the difference between the ceiling and air temperature in the second floor bedroom over time. *Figure 5* shows this for house AC06 with a vertical line showing when the roof was coated.

The figure shows a clear and immediate impact from the roof coating, confirming prior conclusions that heat gain through the roof was essentially eliminated by the coatings.

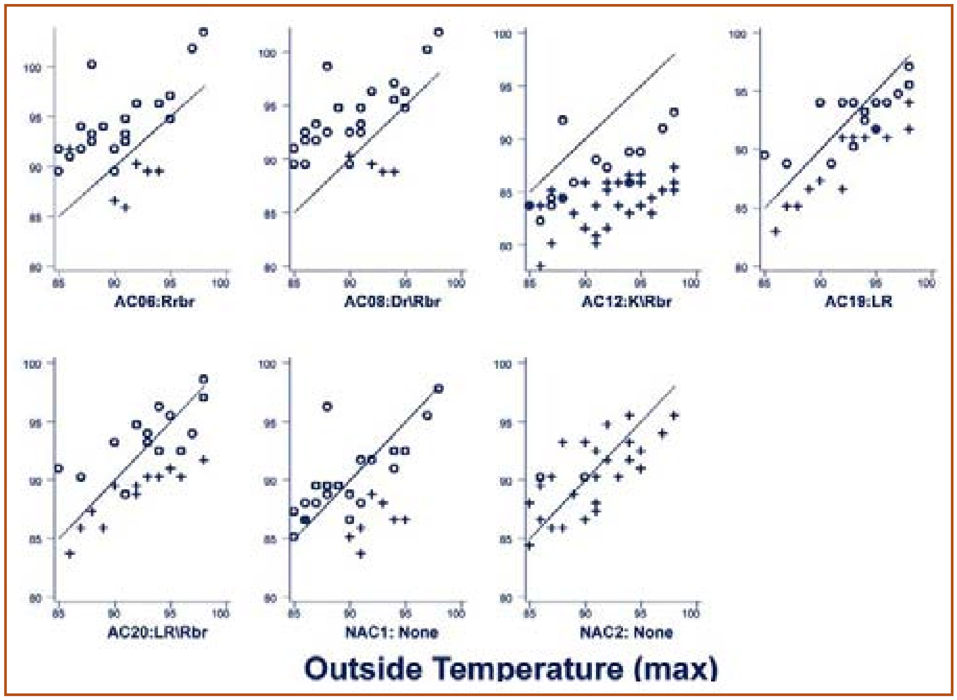

Figure 3. Maximum daily ceiling and outdoor temperatures: houses without air conditioning in bedroom.

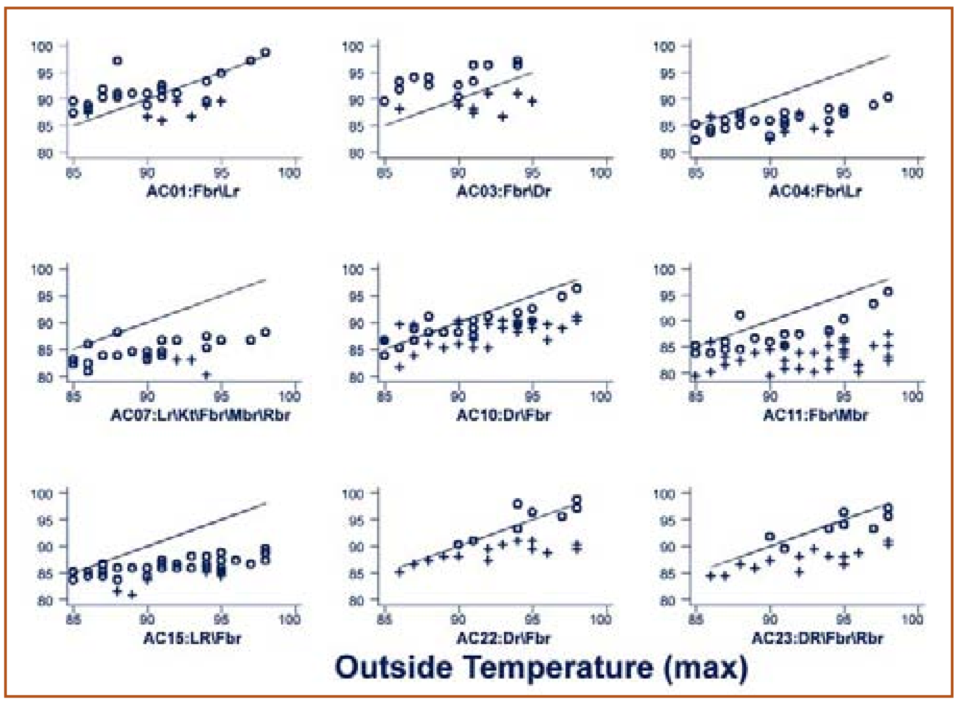

Figure 4. Maximum daily ceiling and outdoor temperatures: houses with air conditioning in bedroom.

First Floor Temperatures

We also examined the impact of cool home coatings on first floor temperatures. Most houses had air conditioners on the first floor that could obviously obscure any potential impacts. One house – site NAC1 — had no air conditioning on either floor and also had data from before and after the roof coating. *Figure 6* shows the temperature profile for NAC1.

The figure shows that the second floor was much hotter than the first floor during hot days before the coating (July 8) and then the two floors were quite similar after the roof coating. This finding is consistent with a substantial reduction in second-floor specific heat gain. When first-floor temperature data were similar to what was present-

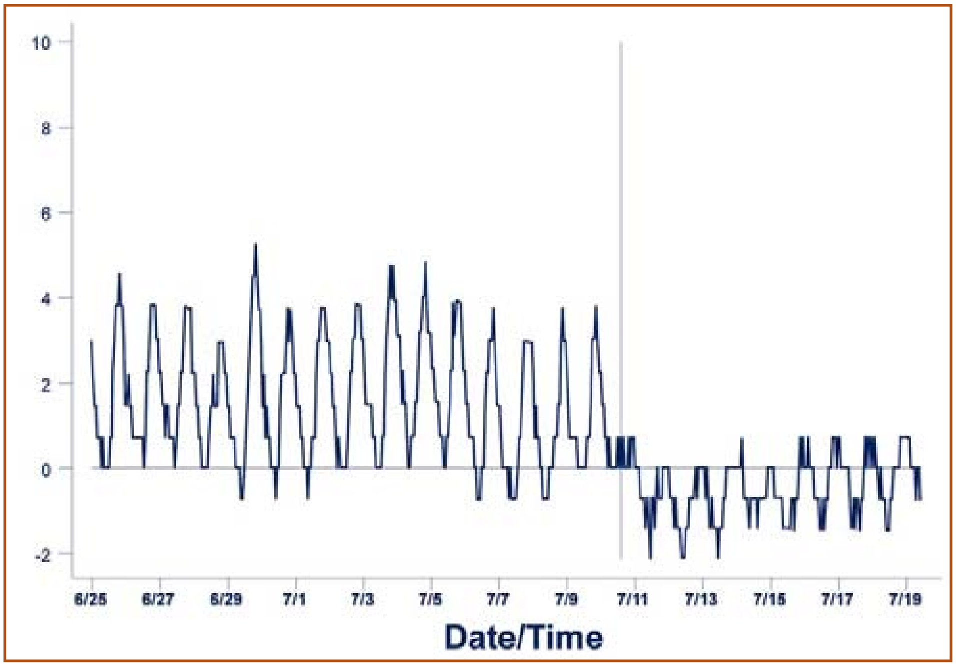

Figure 5. Temperature difference between ceiling and air: House AC06.

ed in *Table 1*, we found no significant change in maximum temperatures. On average, the first floor was one half degree warmer after coating. The data for house NAC1 shows a one-degree increase. The reason the first floor now appears cooler than the second floor is that the largest source of solar heat gain is no longer the roof, but the walls and windows.

Ceiling temperature maximum values dropped from being about equal to outside temperature maximums to being nearly 5˚F cooler than outdoor temperature maximums. On a 95˚F day, the surface temperature drop from about 95˚F to about 90˚F represents a dramatic reduction in heat gain to the room as well as a dramatic improvement in mean radiant temperature conditions for comfort. The reduced ceiling temperature led to a reduction in room air temperature about half as large. The combined changes in air and radiant temperatures can be expected to more than double an occupant's ability to cool off by losing heat to his or her surroundings.

Gas Usage Analysis and Wintertime Heating "Penalty"

We were able to collect monthly gas usage data from Philadelphia Gas Works (the natural gas utility supplier) records for 66 participants. We analyzed the data in several ways to estimate what, if any, impact the white roof coating may have had on the insulation savings or household energy usage. We used a pooled time series cross-sectional regression approach to model the impacts of the multiple program interventions.

This analysis found that the insulation saved approximately 100-120 therms of gas per year on average and that white roof coating had no statistically discernible effect on these savings. The "best" estimate of the roof coating effect was a 13 therm/year increase in gas usage, but this value had an uncertainty of +-250%. These results are consistent with expectations since the heat loss through an insulated attic should be quite small and, therefore, changes in the temperature of the roof should have little, if any, effect on overall heating usage.

Cooling Load Modeling

We performed building simulation modeling of the expected impacts of the roof coating using a proprietary model that incorporated solar gain, attic ventilation, and conduction between the attic and the outside and between the attic and the house. This modeling estimated that typical summer day attic temperatures should drop from 106˚F to 89˚F if a black roof were coated white. The model indicated that overall building cooling loads (if the building were fully air conditioned) should drop by 22% from the coating alone (from 14.9 MMBtu/year to 11.7 MMBtu/year), yielding 472 kWh/year savings.

Essentially, white roof coating will almost entirely eliminate heat gain through the attic. The advantages of the white roof coating include immediate roof integrity improvements, as well as a cooler roof surface that should provide a longer lasting roof. The white roof coating also keeps the attic space much cooler, which will provide performance benefits if the insulation quality is imperfect. The primary advantage for roof insulation is that it provides substantial winter heating savings. As noted in the

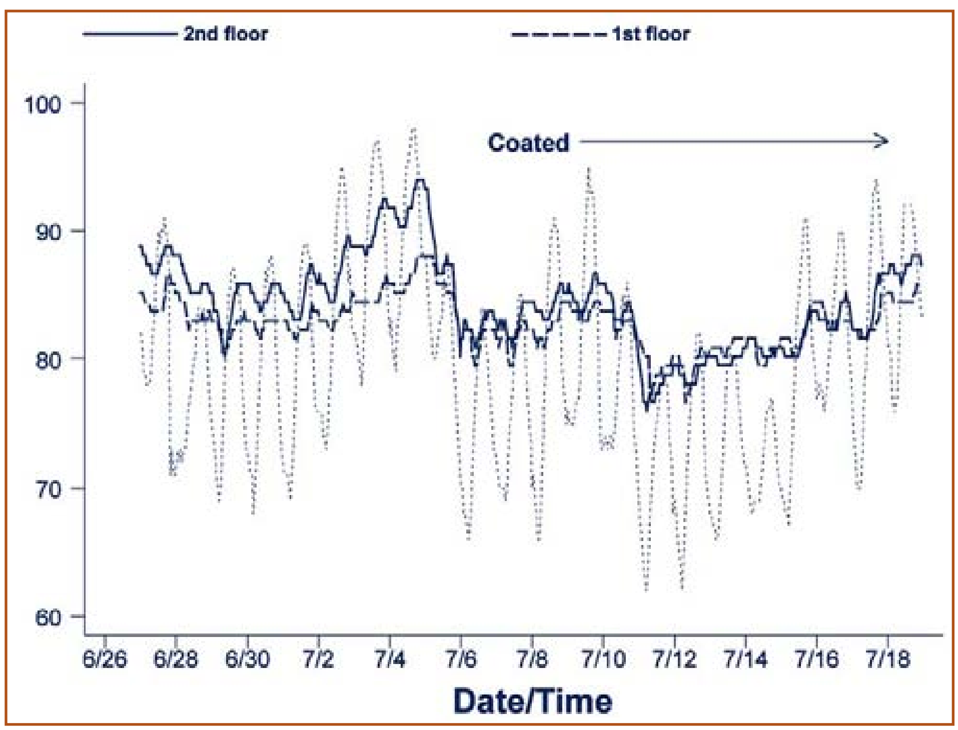

Figure 6. First and second floor temperatures for house NAC1 (no air conditioning).

section above, roof coating alone, without insulation, may increase winter heating loads as it reduces the heat benefits of roof solar gain. The coating approach provides summer performance benefits while acting as the first echelon of roof weatherproofing and protecting the insulation from potential problems due to roof leaks.

"Cool Block" Program

Introduction

Based on the encouraging results of the preliminary experiments where only individual houses in a block were coated, it was theorized that coating an entire block could reduce the cooling load on all the houses. Since these homes shared common walls, the heat load reduction in one house could positively affect the heat load in the adjoining homes. Moreover, if the entire block was coated, it was theorized that this could create an urban "thermal oasis" which would have lower ambient air temperatures compared to a block with conventional black roofs. If so, this could provide direction for solving, or at least mitigating, the "urban heat island effect" where urban areas retain significant heat during summer nights.

Experimentation and Results

Temperature recording data loggers were placed strategically in the 6200 block of Catherine Street. This is a densely populated section of southwest Philadelphia. This was the "cool block" where all the homes were coated with a white elastomeric acrylic coating. A "control" block – 6200 Webster Street – was identified as having nearly identical radiative properties. Both blocks had virtually no tree cover and were bound by asphalt-covered street paving. Thus, the only difference was the reflective coating on 6200 Catherine.

			Change in "T in" and "T out" between pre and pos (positive = cooler)					
			Maximum Temperature		Average Temperature		Minimum Temperature	
A/C in bedroom	Job	Exposure: shade	Ceiling	Air	Ceiling	Air	Ceiling	Air
No A/C	AC06	W: total	6.3	2.7	4.2	2.3	2.6	1.7
No A/C	AC08	W: total	6.4	2.6	3.5	1.6	0.3	0
No A/C	AC12	S: total	3.8	2.3	2.0	1.1	2.5	2.1
No A/C	AC19	N: some	2.7	1.0	2.4	1.3	4.1	2.7
No A/C	AC20	S: no	4.2	1.8	2.6	1.1	2.2	1.3
No A/C	AC21	N: total		2.9		1.5		0.5
No A/C	NAC1	N: no	4.9	2.0	2.4	0.7	1.7	0.6
A/C	AC01	S: no	3.3	1.0	2.4	0.4	2.1	1.3
A/C	AC03	E: some	7.2	4.3	4.5	3.1	0.6	-1.0
A/C	AC10	N: some	3.0	1.0	0.7	-0.4	0	-0.7
A/C	AC16	E: no		2.0		1.5		1.7
A/C	AC17	W: total		0.7		-1.0		-1.2
A/C	AC22	W: some	5.3	1.0	2.9	0.4	3.1	1.8
A/C	AC04	S: total	1.6	0.1	1.7	1.1	2.0	1.3
A/C	AC07	E: total	3.7	2.0	2.3	1.4	-0.3	-1.0
A/C	AC11	E: no	6.6	3.6	5.7	4.3	5.1	2.8
A/C	AC15	S: total	0.5	-1.1	1.4	0.6	3.1	3.8
A/C	AC23	S: no	5.1	2.5	3.0	0.6	1.8	-0.1
Average Impacts:								
Houses w/out A/C in bdrm.			4.7	2.2	2.9	1.4	2.2	1.3
Houses with A/C in bedroom			4.0	1.6	2.7	1.1	1.9	0.8
Overall			4.3	1.8	2.8	1.2	2.1	1.0

Table 1. Change in indoor/outdoor temperature differences after coating.

Figure 7 shows the impact of the white roof coating on ambient air temperature. The data was collected over a one-year period and is organized as mean temperature difference between the white "cool block" and the black "control block." The X axis is air temperature intervals in 5-degree increments. It is noteworthy that when the air temperature is between 95 and 100 degrees, there is almost a 1-degree difference in ambient air temperature. This difference in air temperatures varies, depending on the ambient air temperature. The reason for the variability is not fully understood but is probably related to a number of confounding factors such as wind speed, rainfall, rain and dew evaporation, cloud cover, snow, and fog. The summary effects of these coatings have been to create an urban "cool oasis" in the midst of the heat island. This work will be followed closely to get additional data inputs to further refine the model.

Photo 3: "Cool block": 6200 Catherine Street.

Conclusions

These results are encouraging as having demonstrated the use of cool roof coatings as a method for reducing not only interior air temperatures and air conditioning costs, but also in mitigating the urban heat island effect. Key conclusions are that reflective roof coatings can reduce roof and ceiling temperatures. When coated white, the roof is no longer the single largest contributor to the heat gain, but has been supplanted by the walls and windows as the leading sources. The need for large numbers of data input is necessary to identify trends in actual buildings to eliminate or account for other residential lifestyle factors that may mask or confound some data.

This research has demonstrated the value of energy savings, with resulting reduction in smog and pollution, reducing the urban heat island effect, improving social conditions in densely populated urban areas, and improving health and living conditions for at-risk, vulnerable urban residents.

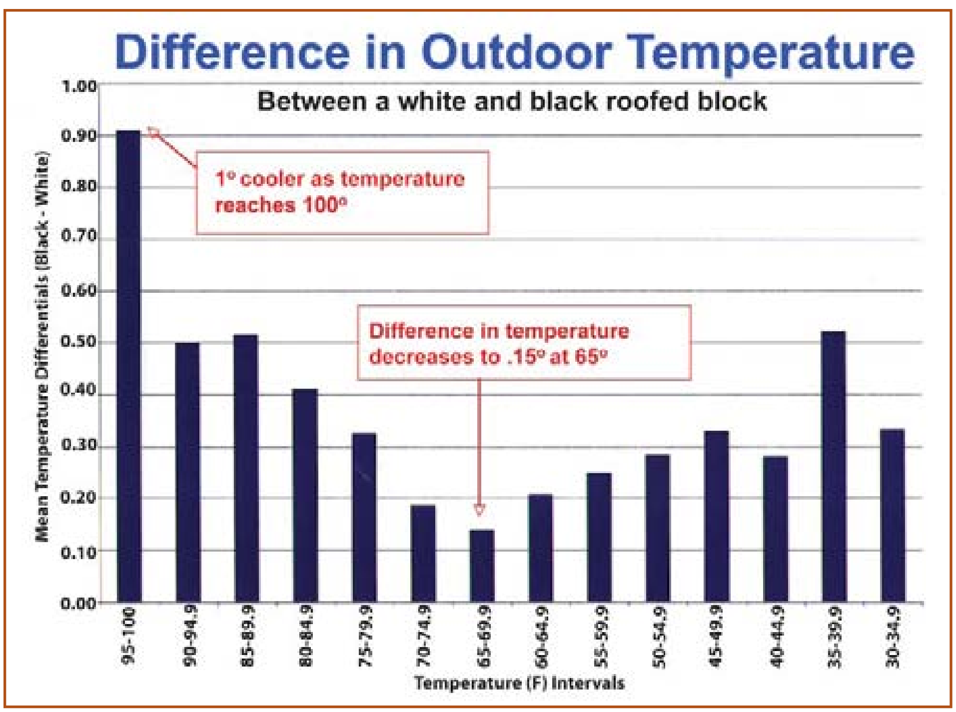

Figure 7. Exterior temperature differences between white- and black-roofed houses.

Next Steps

Now that estimated temperature impacts of the coatings have been defined, further evaluations will examine how these temperature changes affect occupant health and safety, as well as cooling loads (in houses with air conditioners). The former task can be assessed using existing models of heat stress and examining how these temperature changes should affect the ability of people to lose heat to their surroundings. The latter task can be estimated using engineering models of heat transfer from the ceiling to the air and, to the extent that sufficient data are available, by analysis.

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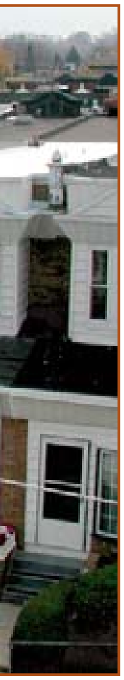

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Photo 4: Overview of several residential roofs.

Photo 5: Data logger located at a residence.

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Photo 6: Installing data loggers for "cool block" comparison.

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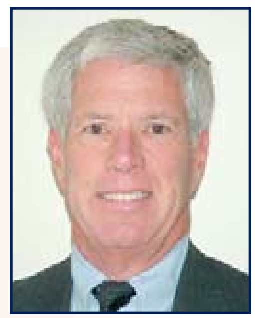

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