Radiation Control Coatings on Rough-Surfaced Roofs at a Federal Facility: Two Summers of Monitoring Plus Roof and Whole Building Modeling

Thomas W. Petrie, Ph.D.
Member ASHRAE

Phillip W. Childs

Jeffrey E. Christian
Member ASHRAE

ABSTRACT

This paper discusses the effect of radiation control coatings on rough-surfaced, low-slope roofs at a federal facility in the Panhandle of Florida. Two gravel-topped, moderately well-insulated, low solar reflectance built-up roofs (BURs) were spray coated with a white, latex-based product with ceramic beads. One roof was significantly shaded and its building had high internal loads. The other had a thermally massive deck but its building had little internal load. Samples of the coated roofs were brought periodically to the laboratory to measure the solar reflectance as the coatings weathered. Relative to the uncoated BUR, the fresh coating increased the solar reflectance from 0.09 to about 0.53, which is at least 0.2 lower than has been observed for similar fresh white coatings on smooth, low-sloped surfaces. In the course of the project, from July 1996 through October 1997, the reflectance for the shaded BUR decreased to 0.42 while the other decreased to 0.50. On smooth, low-slope surfaces after several years of weathering, values as low as 0.50 to 0.55 have been observed.

Over the project duration, average decreases in the sunlit temperatures of the coated vs. the uncoated surfaces show slight weathering effects. They also show that the shading enhanced the measured effect of the coating on the shaded roof because the coated instrumented area on it was preferentially shaded near noon on sunny days. For August through October 1996, the average sunlit surface temperature decreases were 13% on the shaded roof and 12% on the heavyweight roof. The averages for the same two months in 1997 were 12% and 11%, respectively.

Whole building models were constructed for DOE-2.1E and adjusted until predictions agreed well with measurements of total electrical power for each all-electric building. For the building with the shaded roof and high internal loads, the effect of the shading on annual energy use for cooling was about the same as that of the fresh coating, but the coating decreased annual cooling energy needs only by 0.8% (0.054 kWh/ft^2 or 0.58 kWh/m^2). In the other building, the DOE-2 model predicted a 7.4% (0.27 kWh/ft^2 or 2.9 kWh/m^2) decrease in annual cooling energy use due to the fresh coating. This building had an unconditioned plenum under all of its roof. Additional DOE-2.1E modeling to study the effect of the roof construction and presence of the plenum showed more and more annual cooling energy use as the effective amount of insulation in the uncoated roof decreased. Percentage cooling energy savings with the fresh coating increased to 43% for the final case with no plenum and an uninsulated metal roof. This case also showed that estimates of cooling energy savings over the lifetime of a coating should be done with weathered coating solar reflectances, or estimates of savings can be as much as 50% too optimistic.

INTRODUCTION

A project to do a test bed demonstration of radiation control coatings on federal buildings was begun in December 1995 with support of the New Technology Demonstration Program (NTDP) of the Federal Energy Management Program. Data include whole building electricity use as well as roof temperatures and heat fluxes for two buildings at a federal facility in the Florida Panhandle. Coating was done in early July 1996. Data acquisition and monthly summarization continued through October 1997.

This project has documented the thermal performance of existing rough-surfaced built-up roofs (BURs) that were covered by a white latex-based coating with ceramic beads. In earlier reports on the project (Petrie et al. 1998; Petrie and Childs 1997), we discussed relevant literature, project goals and monitoring protocols, installation of instruments, installation of coatings, and results through the first summer after

Thomas W. Petrie is a research engineer, **Phillip W. Childs** is a staff engineer, and **Jeffrey E. Christian** is director of the Buildings Technology Center, Oak Ridge National Laboratory, Oak Ridge, Tenn.

coating. The solar reflectance of the coatings applied to the built-up roofs was reported for the fresh coatings and after 17 and 33 weeks of weathering. These reflectances were compared to values from uncoated membranes and various coatings on smooth membranes. Although the reflectances for the coated BURs were significantly greater than for uncoated membranes, they were about 20% lower than observed for white coatings on smooth surfaces. A solar ray likely undergoes more reflections—with small absorption each time—on coated rough surfaces than on smooth surfaces. The reflectances of the coated rough surfaces, like those of smooth surfaces, showed degradation with time. Surface contamination is likely to cause degradation because nonreflecting particles adhere easily to rough surfaces.

Since the previous reports, the literature relevant to this project has been supplemented by more field measurements (Parker et al. 1998a) and more work under the auspices of the Heat Island Project directed toward generalizing the experience with coated roofs and other high albedo surfaces (Parker et al. 1998b; Akbari et al. 1998; Konopacki et al. 1997; Gartland et al. 1996). Not only are there now more scientific data for coated roofs in the open literature, but more support for use of coatings has been generated in the form of calculations about the impact of high albedo roofs. As an example, results from whole-building annual energy use predictions with the public domain program DOE-2.1E (LBL 1981, 1993) are included in the June 1997 draft for public comment on revisions to *ANSI/ASHRAE/IES Standard 90.1-1989* (ASHRAE 1989). Reflective roofs with initial solar reflectance exceeding 0.70 and infrared emittances exceeding 0.80 are considered eligible for credit. Modeled reflectance was 0.55, to account for aging effects. The proposed credit is up to 23% reduction in the roof insulation R-value for a reflective roof in cooling-dominated climates.

This paper updates and completes the presentation of data for this NTDP project. Measurements show the history of coated and uncoated outside-surface temperatures and solar reflectances of the roof surfaces from July 1996, when the roofs were coated, through October 1997. Roof models based on one-dimensional transient conduction through the roofs are used to compare the heat fluxes through the roof deck for coated and uncoated roof surfaces. DOE-2.1E whole building annual energy use predictions specific to the buildings and their operating schedules show the effect of the coatings and other building features for the climatic conditions of the Florida Panhandle. More details are available in Petrie and Childs (1998).

OVERVIEW OF PROJECT

The two buildings at the federal facility in the Florida Panhandle, which are the focus of this paper, had low-slope roofs over 2 in. (5.1 cm) thick, aged polyisocyanurate insulation, a common foam insulation for low-slope roofs. A layer of gravel was embedded in the top coat of asphalt to complete the four-ply BURs. One building, a convenience store, was significantly shaded by live oak trees to the south. The part of its roof in which instruments were installed, the roof for a storeroom at the east end of the store, was built over a metal deck directly exposed to the storeroom interior. The storeroom roof area was about one-fourth of the total for the convenience store. The rest of the building had a BUR over a wood deck with a plenum and drop ceiling below the roof. The roof of the other building, a veterinary clinic, had a heavyweight concrete deck and lightweight concrete over it, in addition to the insulation and the BUR. A plenum and drop ceiling extended under the entire roof.

Figure 1 shows cross sections of the two roofs and placement of heat flux transducers in the middle of the polyisocyanurate insulation in them. Three thermocouples were vertically aligned with each heat flux transducer, comprising a set of instruments for monitoring thermal performance. One thermocouple was attached to the underside of the deck, another was placed on the outside surface, and the third junction was about 3 in. (7.6 cm) above the surface in the outside air. There were two sets of instruments on each roof, one in an area coated in July 1996 and the other, about 2 ft by 2 ft (0.61 m by 0.61 m), left uncoated throughout the project. The uncoated areas were masked during coating by pieces of BUR like that on the roofs. These coated loose pieces were weathered along with the rest of the coated areas on each roof. Samples were cut from these pieces periodically to take to a laboratory for

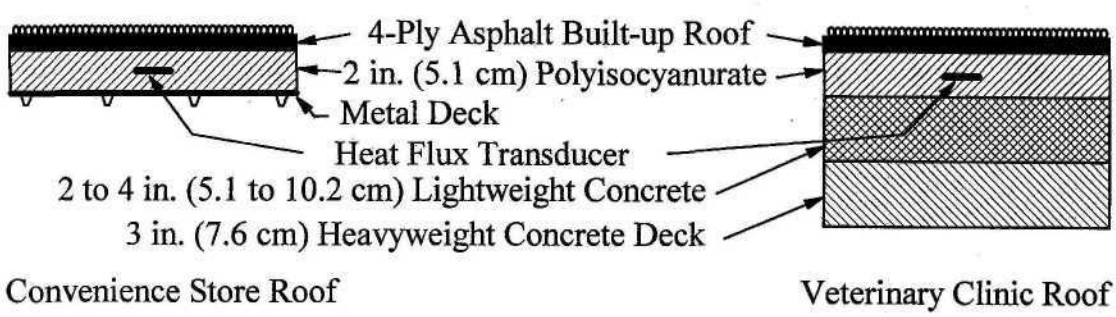

Figure 1 *Cross sections of built-up roofs on a convenience store and a veterinary clinic at the federal facility in Florida used for the project.*

measurement of solar reflectances and then stored for a historical record of weathering.

To provide comparisons to the data from the weathered BUR samples and the instrumentation at the two locations on each BUR, solar reflectances and some outside-surface temperatures are also given for two other locations and various coatings. The first additional location, on the roof of a fast food restaurant at the federal facility, had 2 ft by 2 ft (0.61 m by 0.61 m) areas where an acrylic elastomeric coating and the ceramic coating used on the BURs were tested side by side. About 3 in. (7.6 cm) of polyisocyanurate insulation and a plywood deck under a smooth single-ply membrane composed the restaurant roof. The second additional location was an outdoor test facility at a national laboratory in east Tennessee. The same coatings as used at the federal facility in Florida and two other ceramic coatings were tested during the time frame of the Florida project. Only reflectance data from fresh and weathered samples at this location are included in this paper.

The temperatures and heat fluxes from the six instrumented areas at the federal facility, as well as the total electricity use from pulse-initiating kilowatt-hour meters in the two buildings with BURs, were stored in data loggers in each building as hourly averages of one-minute scans until retrieval by modem link at one-week to one-month intervals. The samples of freshly coated membranes were retrieved during a trip in July 1996 by personnel from the national laboratory to rendezvous with personnel from the ceramic coating manufacturer to clean up the roofs, apply the coating, and check that monitoring technology was functioning after the coating was applied. The samples of weathered coatings were retrieved during trips to the federal facility in November 1996, March 1997, and November 1997, by personnel from the national laboratory. During the last trip, the data loggers were disconnected and all instrumentation leads cut off and removed. The heat flux transducers were left embedded in the roofs and the coatings were left intact. What was left of the coated loose pieces of BUR was left on the coated roofs.

MEASUREMENTS OF REFLECTANCES AND OUTSIDE-SURFACE TEMPERATURES

This project focuses on the effect of white coatings on the thermal performance of rough-surfaced built-up roofs. Solar reflectances and outside-surface temperatures show measurable evidence of this effect. Solar reflectance, or albedo, is the fraction of incoming solar irradiation that is reflected away from a surface. Since roof membranes, coated or uncoated, are not transparent to solar radiation, what is not reflected is absorbed. If the roof deck is kept at approximately constant temperature and thermal conductivities of roof components remain approximately constant, absorbed solar radiation raises the surface temperature. Under these conditions, the lower the reflectance, the more the absorption of solar irradiation and the higher the surface temperature.

Table 1 shows the history of the solar reflectance of various coated and uncoated low-slope roof membranes. Fresh and weathered values for a variety of white coatings on both smooth and rough surfaces are included. The coatings are either acrylic elastomeric coatings (RH3, RH2, RH1) or latex-based coatings with ceramic beads added (SHP, VC, TC2, SOL, TC1, INS). The data in this table include updated values from a similar table given earlier (Petrie et al. 1998) as well as values measured since the earlier data were measured by Yarbrough (1997). In the middle of this project, we purchased our own solar spectrum reflectometer from the same manufacturer as Yarbrough's. To ensure there was no error from switching reflectometers, we redid the previous measurements and updated Table 1 with them before doing the rest of the measurements with our instrument.

Figure 2 is a graph of some of the data in Table 1 for perspective on the solar reflectances of samples SHP and VC from the coated BURs. The solar reflectances of these fresh white coatings on smooth surfaces vary from 0.77 to 0.85. The fresh values on smooth surfaces are more than 0.20 higher than the fresh values on the rough BURs. However, Table 1 shows that the fresh values of 0.53 to 0.54 on the rough BURs are 0.45 higher than the reflectances of the uncoated

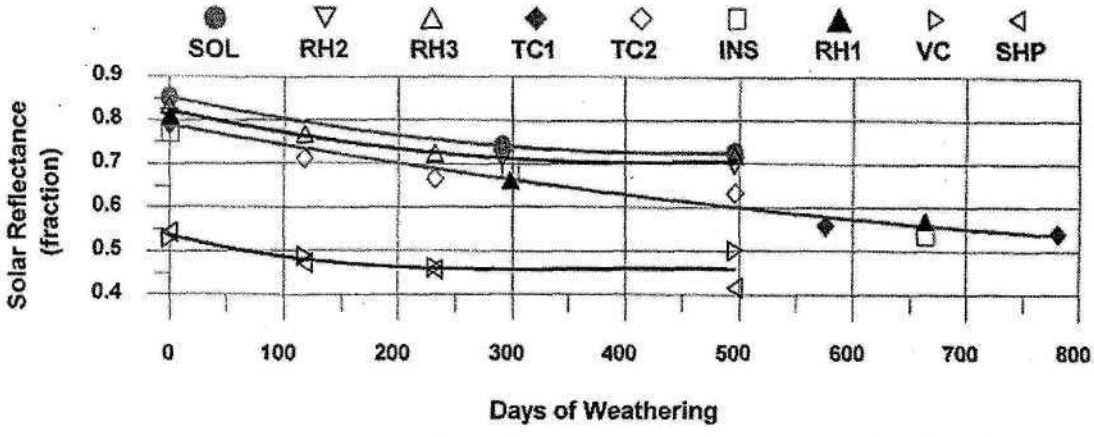

Figure 2 *History of the solar reflectances of various white coatings on smooth and rough surfaces (see Table 1 for details about coatings).*

TABLE 1
Solar Reflectances of Coated and Uncoated Membranes

Location*	Sample	Coated/Uncoated	Substrate†	Fresh $\rho \pm \sigma$ ‡	Weathered ρ (if available)
Convenience Store	SHP	Coated	Rough Surface	0.543±0.045	0.472 (after 118 days) 0.457 (after 232 days) 0.416 (after 496 days)
Veterinary Clinic	VC	Coated	Rough Surface	0.530±0.055	0.488 (after 118 days) 0.462 (after 232 days) 0.501 (after 496 days)
Store, Clinic	UNC3	Uncoated	Rough BUR Surface		0.079±0.017 (after ??)
Restaurant	RH3	Coated	Smooth EPDM	0.834±0.006	0.768 (after 118 days) 0.723 (after 232 days) 0.719 (after 496 days)
Restaurant	TC2	Coated	Smooth EPDM	0.800±0.011	0.712 (after 118 days) 0.665 (after 232 days) 0.632 (after 496 days)
BTC	RH2	Coated	Smooth APP	0.806±0.008	0.711 (after 291 days) 0.696 (after 496 days)
BTC	SOL	Coated	Smooth APP	0.853±0.005	0.741 (after 291 days) 0.725 (after 496 days)
BTC	TC1	Coated	Smooth APP	0.790±0.005	0.558 (after 576 days) 0.540 (after 781 days)
BTC	UNC2	Uncoated	Smooth APP	0.074±0.002	0.057 (after 108 days)
BTC	INS	Coated	Smooth EPDM	0.773±0.006	0.689 (after 298 days) 0.539 (after 664 days)
BTC	RH1	Coated	Smooth EPDM	0.809±0.002	0.662 (after 298 days) 0.569 (after 664 days)
BTC	UNC1	Uncoated	Black EPDM	0.068±0.001	0.072 (after 496 days)

* Convenience store, veterinary clinic, and restaurant at federal facility in Panhandle of Florida; BTC designates outdoor test facility at U.S. national laboratory in East Tennessee.
† BUR = built-up roof; EPDM = ethylene propylene diene monomer single-ply membrane; APP = atactic polypropylene polymer single-ply membrane.
‡ ρ = solar reflectance; σ = standard deviation of measurements.

membranes. The reflectances of the white-coated membranes show various rates of decrease with time, but all seem to have reached a stable weathered value by the end of two years (730 days). A smooth curve is shown through the data for SOL, another for RH2 and RH3, a third for TC1, TC2, INS, and RH1, and a fourth for VC and SHP, to aid in estimating a fully weathered value of solar reflectances for these coatings. From the reflectances displayed in Figure 2 by the coatings on smooth surfaces (all except VC and SHP), Akbari et al.'s (1998) weathered value of 0.55 is accurate for coatings TC1, INS, and RH1, and possibly TC2. It is conservative for coatings RH3, RH2, and SOL. On the rough BURs, the weathered value is less than 0.55 with large scatter.

No uncoated BUR for reflectance samples was kept on the roofs at the federal facility. The sample yielding the UNC3 data in Table 1 was a piece cut off before the remainder was coated along with the roofs. Its history was unknown. Evidence in Table 1 for samples UNC1 and UNC2 shows that the reflectances of uncoated membranes do not appear to

change significantly with time as the uncoated surfaces are exposed to climatic conditions.

Table 2 presents values of monthly average sunlit uncoated and coated surface temperatures for the veterinary clinic with the heavyweight concrete-decked roof and for the part of the convenience store with the shaded metal-decked roof. Monthly average sunlit data are generated to provide a measure of performance that emphasizes differences in thermal performance due to solar irradiation. The averages include variations during sunny daytime hours but not during nighttime and rainy daytime hours.

In the absence of evidence from measurements of solar irradiation at the test locations, "sunlit" is defined in terms of a simple criterion that was applied to each pair of hourly coated and uncoated temperatures during a month. If solar irradiation of the roofs caused an uncoated temperature to be more than 7.5°F (4.2°C) warmer than its corresponding coated temperature, the pair was included in the sunlit average taken at the end of the month. Air temperatures above the coated and uncoated areas were averaged at the same times that the surface temperatures met the sunlit criterion. They are included in Table 2 to provide a measure of how comparable climatic conditions were from month to month.

The conclusion from Table 1 is that the reflectances of samples SHP and VC decrease over the duration of the project but remain much greater than the low reflectance of the uncoated BUR. Thus, the behavior in Table 2 of the average sunlit surface temperatures for the coated and uncoated areas on the veterinary clinic roof is reasonable. The average outside-air and uncoated surface temperatures are about the same in August and September 1997 compared to August and September 1996. Data for July 1996 are not available for the veterinary clinic because they were lost from storage in the veterinary clinic's data logger during an electrical storm in late July 1996. The average coated temperatures in August and September 1997 are higher and the percent decreases lower than during the same months in 1996, which is consistent with lower solar reflectance in 1997 than in 1996. The October 1997 coated temperature is not higher than in October 1996, but the percent decrease is consistent with the comparisons in the hotter months of August and September. From November through April, no data are given because of the few pairs of temperatures that met the sunlit criterion.

For the convenience store roof, comparisons for three summer months in 1996 and 1997 are available in Table 2. The coated surface temperatures and the percentage decreases show respective increases and decreases that are expected as white-coated roofs weather. Moreover, the values of the percentage decreases are somewhat higher and the coated surface temperatures are somewhat lower than the respective monthly averages for the veterinary clinic. This is consistent with preferential shading of the coated area at midday on sunny summer days at the convenience store. The uncoated area was preferentially shaded in mid-afternoon when the sun was lower.

To illustrate this preferential shading, Figure 3 shows hourly temperatures for two similar days in 1996 just before and after the convenience store roof was coated. Outside-air

TABLE 2

Monthly Average Sunlit Temperatures on the Veterinary Clinic and the Convenience Store Roofs*

	Heavyweight Roof on Veterinary Clinic				Shaded Roof on Convenience Store			
Month	Toutside air (°F)	TOSunc (°F)	TOSctd (°F)	(unc-ctd)/unc (%)	Toutside air (°F)	TOSunc (°F)	TOSctd (°F)	(unc-ctd)/unc (%)
JUL 96	NA	NA	NA	—	90.8	113.0	95.1	15.8
AUG 96	88.0	115.7	101.7	12.1	88.2	106.9	91.5	14.4
SEP 96	86.5	112.4	98.9	12.0	86.4	98.4	86.9	11.7
OCT 96	74.2	93.2	81.2	12.9	74.8	82.5	72.2	12.5
MAR 97	72.2	92.9	82.2	11.5	73.2	84.8	74.9	11.7
APR 97	72.7	97.8	85.5	12.6	74.7	99.1	83.7	15.5
MAY 97	79.6	109.1	96.6	11.5	82.1	109.2	93.5	14.4
JUN 97	86.0	117.7	105.8	10.1	87.8	121.0	104.7	13.5
JUL 97	90.5	121.6	109.9	9.6	93.0	124.3	110.1	11.4
AUG 97	89.5	118.3	106.6	9.9	93.5	120.6	104.4	13.4
SEP 97	87.4	112.7	100.7	10.6	87.8	98.5	88.6	10.1
OCT 97	74.6	91.0	80.4	11.6	75.2	85.2	74.8	12.2

* Sunlit criterion: Outside uncoated surface temperature, TOSunc - Outside coated surface temperature, TOSctd > 7.5°F.

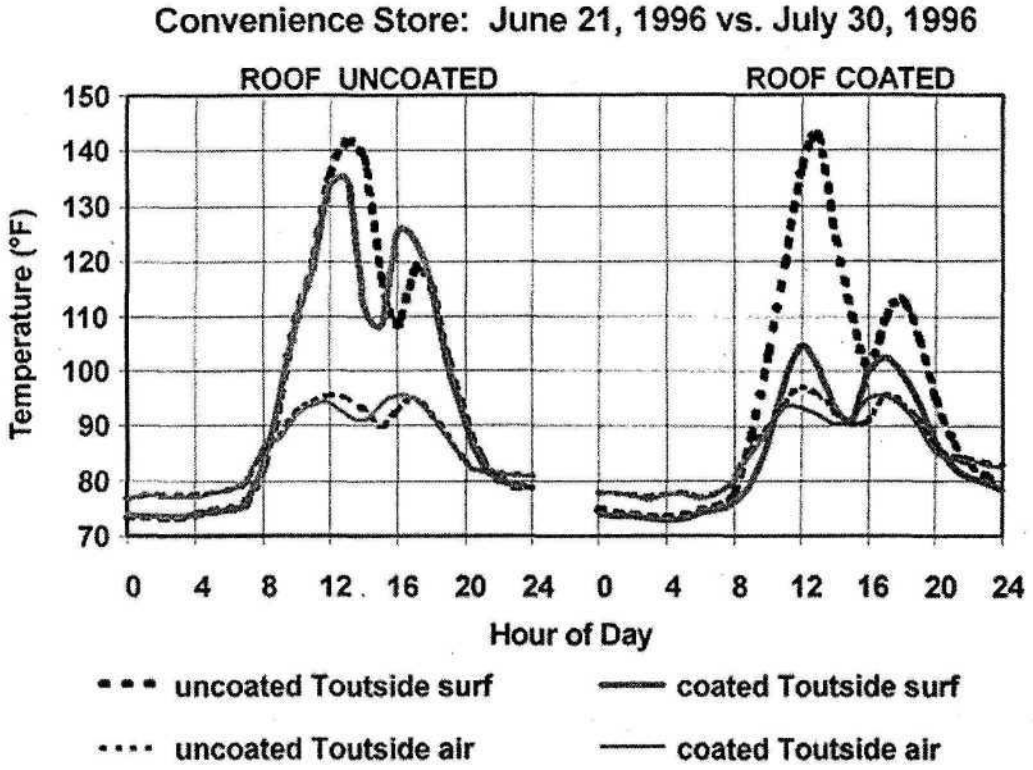

Figure 3 *Hourly outside-air and outside-surface temperatures for the coated and uncoated locations on the convenience store roof for similar sunny days just before and after the roof was coated.*

temperatures for the coated location (lower solid curve) and uncoated location (lower dashed curve) and the uncoated surface temperatures (upper dashed curves) are affected by the shading but have similar profiles before and after the roof was coated. As the upper solid curves show, there is clearly a beneficial decrease in the surface temperatures from the roof uncoated to the roof coated situation.

In Table 2 for August, September, and October 1996 and September and October 1997, the uncoated surface temperatures on the convenience store roof show the effect of shading. They are lower than the corresponding temperatures for the veterinary clinic despite essentially equal outside-air temperatures. The uncoated surface temperatures and outside-air temperatures from April 1997 through August 1997 are slightly higher for the convenience store than for the veterinary clinic and the coated surface temperatures are generally lower, but by less for these months than other months. The shading of the convenience store roof is due to live oak trees. Differences in shading patterns from year to year are possible. The summary from Table 2 of average decreases in outside surface temperatures of the sunlit coated vs. uncoated surfaces for the summer months of 1996 and 1997 is as follows:

	8/96	9/96	10/96	Avg.'96	8/97	9/97	10/97	Avg.'97
Shaded roof	14.4%	11.7%	12.5%	12.9%	13.4%	10.1%	12.2%	11.9%
Heavy roof	12.1%	12.0%	12.9%	12.3%	9.9%	10.6%	11.6%	10.7%

Table 3 shows monthly average sunlit temperatures on the roof of the fast food restaurant where there was no low-reflectance surface. Based on behavior observed when the veterinary clinic showed sunny days at the federal facility, the restaurant sunlit criterion requires a 2.5°F (1.4°C) difference between the temperatures for the TC2 and RH3 coated surfaces. Throughout the project, air temperatures on the roof of the fast food restaurant were slightly higher than on the veterinary clinic. The restaurant roof was surrounded by a parapet that sheltered its roof somewhat from wind effects. Also, temperatures from a different part of the day were used. The sunlit criterion for the restaurant tended to be satisfied earlier in the morning of sunny days and ceased being satisfied earlier in the evening compared to the veterinary clinic's criterion.

The surface temperatures for the TC2 and RH3 coated surfaces are consistent with the behavior of the solar reflectances. Figure 2 showed that the solar reflectance of coating TC2 started out slightly lower than the reflectance of coating RH3 and decreased more in the 500 days of the project. Both coatings were brushed on the smooth fast food restaurant roof itself and a piece of smooth EPDM substrate laid down over

TABLE 3
Monthly Average Sunlit Temperatures of Coatings RH3 and TC2 on the Roof of the Fast Food Restaurant*

Month	Coated Areas on Roof of Fast Food Restaurant			
	Toutside air (°F)	Ttc2 (°F)	Trh3 (°F)	(tc2-rh3)/tc2 (%)
JUL 96	92.9	98.3	93.8	4.6
AUG 96	90.5	95.4	90.2	5.5
SEP 96	88.6	93.4	87.7	6.1
OCT 96	79.7	84.0	77.8	7.4
MAR 97	75.4	83.9	76.2	9.2
APR 97	75.5	84.7	76.6	9.6
MAY 97	81.6	93.2	84.2	9.7
JUN 97	87.1	101.1	92.3	8.7
JUL 97	92.1	106.8	97.9	8.3
AUG 97	93.5	107.8	98.9	8.3
SEP 97	93.2	107.9	99.1	8.2
OCT 97	84.2	96.3	88.6	8.0

* Sunlit criterion: Outside-surface temperature of TC2, Ttc2 - Outside-surface temperature of RH3, Trh3 > 2.5°F.

this roof for the pieces from which samples were cut off for reflectance measurements. The ceramic-filled TC2 brushed on much thicker and yielded a rougher surface than the acrylic elastomeric RH3. Greater roughness is likely to increase the rate of weathering and reflectance degradation. The percent differences between the temperatures of RH3 and TC2 increase in July, August, and September 1997 relative to the same months in 1996. The temperatures of both coated surfaces are somewhat lower than those of the coated surfaces on the veterinary clinic in summer 1996. By summer 1997, this is only true for coating RH3. The advantage of the smooth-surfaced substrate has disappeared for coating TC2, apparently because it had a rougher surface than coating RH3.

HEAT FLUXES THROUGH THE BUILT-UP ROOFS

The test protocol for this project included measurement of roof heat fluxes. Heat fluxes through the roof deck can be a direct indicator of the effect of a coating on the energy performance of a building because they are the direct effect of the roof on the interior of the building. For the veterinary clinic and three-fourths of the convenience store roofs, however, the heat fluxes through the deck entered an unconditioned plenum space above a drop ceiling. These plenum spaces contained insulated supply ducts and the return paths for the conditioned air distribution to the spaces under the plenums. For these areas, the conditioned interior felt the roof heat fluxes more indirectly than the exposed metal deck of the storeroom in the convenience store.

No measurements were made of the effect of the coatings on the air temperatures in the plenums or, consequently, on the temperatures of the distribution air in the ducts. In the convenience store, the instrumented areas were chosen in the heavily shaded part of its roof away from the part with a plenum. No attention was paid to the plenum. In the veterinary clinic, the insulation and heavy concrete deck of the roof mitigated the effect of the coating on the plenum temperature. To illustrate, the averages of all hourly temperatures on the outside and inside surfaces at the instrumented areas of the veterinary clinic were as follows for June and August 1996, the months immediately before and after the roof was coated:

	Uncoated TOS	Coated TOS	Uncoated TIS	Coated TIS
June 1996	93.9°F (34.4°C)	94.5°F (34.7°C)	81.7°F (27.6°C)	81.1°F (27.3°C)
August 1996	91.3°F (32.9°C)	85.2°F (29.6°C)	81.8°F (27.7°C)	80.6°F (27.0°C)

In June 1996, both areas were uncoated. The outside surface temperatures (TOS) of the uncoated and to-be-coated areas are identical within the ±0.9°F (±0.5°C) uncertainty of the measurements with thermocouples. In August 1996, the outside surface temperature for the coated area decreases over 9°F (5°C) due to the coating and milder weather compared to less than 3°F (2°C) decrease for the uncoated area due to milder weather. The average inside surface temperatures (TIS) remain the same in June and August for the uncoated area. These inside temperatures are on the ceiling of an unconditioned air-handler room with a window open to the outside. The maximum surface temperatures here during June and August 1996 were 88.5°F (31.4°C) and 85.3°F (29.6°C), respectively, showing a slight effect of milder weather in August. The average inside surface temperatures are also constant for the coated area. The maxima of 85.9°F (29.9°C) in June and 82.7°F (28.2°C) in August again show the effect of milder weather in August. The coated inside surface temperatures are on the ceiling of the unconditioned and unventilated plenum where the supply ducts are for the veterinary clinic. This is taken as evidence that the coating did not significantly affect the ducts in this plenum. A significant effect is possible. In a Florida commercial building with the plenum above an insulated ceiling and below a shingled, plywood-decked roof, Parker et al. (1998a) measured a decrease of nearly 23% in annual maximum plenum temperature and over 8% in average plenum temperatures after covering the roof with a white coating.

To ensure accuracy of measured heat fluxes, the heat flux transducers were calibrated in aged polyisocyanurate insula-

tion and embedded in the middle of the insulation, not on the decks, in all three roofs at the federal facility. Deck heat fluxes were predicted as described next. Only results for the built-up roofs are included here. Heat fluxes for coatings RH3 and TC2 on the restaurant roof were smaller than for the built-up roofs due to thicker insulation in the restaurant roof. A sunlit criterion was difficult to implement since there were no large differences between heat fluxes for the RH3 and TC2 coated areas.

Despite the careful calibration and installation of the heat flux transducers in all roofs, the one in the uncoated location at the veterinary clinic failed early in the project. Data from the first few weeks of reliable operation were used to verify the accuracy of the computer program STAR (Wilkes 1989). It uses the one-dimensional transient heat conduction equation with components and their properties for the roof of the veterinary clinic (see Figure 1) and boundary conditions from inside-surface and outside-surface temperatures measured at the veterinary clinic. See Petrie et al. (1998) for details. In the thermally massive unshaded roof of the veterinary clinic, STAR was able to follow the diurnal transient behavior very well. The remaining measured heat flux through the coated area was considered sufficient to provide an ongoing measure of STAR's accuracy.

Figure 4 shows typical behavior of measured and predicted heat fluxes in the roof of the convenience store at the uncoated location (dashed curves) and coated location (solid curves) for two sunny days about a year apart. Measured and predicted heat fluxes are shown in the middle of the insulation. The predicted heat fluxes for the deck are also shown. The shading of the roof of the convenience store induced irregular transient behavior in the measured heat fluxes, in addition to the expected diurnal behavior. One-hour averages captured these behaviors well. Figure 3 showed the same irregular behavior imposed on diurnal variations for the outside-surface temperatures just before and after the roof was coated.

Figure 4 shows that STAR was not able to mirror the measured heat flux behavior given only the hourly surface temperatures as boundary conditions. The solid curves for the coated location show that the predictions for the middle of the insulation compare well, except for a delay, to the measured insulation heat fluxes up to the noontime peak. The predictions do not fall off fast enough to follow the dip at 2 p.m., overshoot the 4 p.m. peak, and are significantly above the measurements in late afternoon and evening. The predictions for the coated heat flux through the metal deck generally follow the predictions for the coated insulation heat flux, wiggling above and below them. This is reasonable for the lightweight roof on the convenience store. Note that the increase in measured heat flux for the coated area after a year of weathering is duplicated by the predictions. The dashed curves for the uncoated heat fluxes show the same inability of the predictions to mirror the measured heat fluxes. The situation is exacerbated by the more severe peaks and valleys of the uncoated heat fluxes. However, there are again small differences between the predicted insulation and deck heat fluxes, much smaller than between the measured and predicted insulation heat fluxes, with the deck fluxes wiggling above and below the predicted insulation fluxes.

Figure 5 shows the same comparisons of heat fluxes for the veterinary clinic as Figure 4 did for the convenience store, except that measured heat fluxes were not available for the

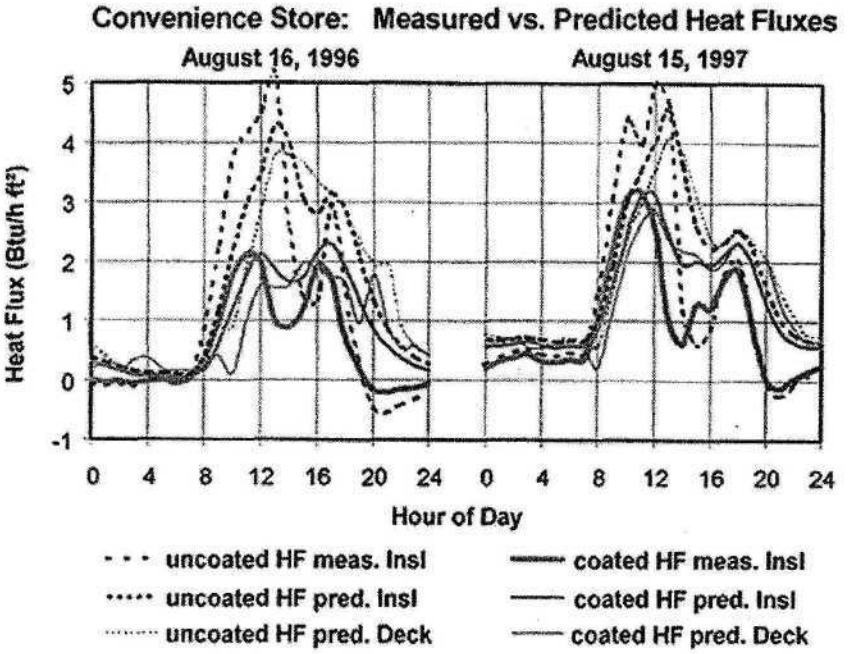

Figure 4 *Hourly measured and predicted heat fluxes for the coated and uncoated locations on the convenience store roof for similar sunny days one year apart.*

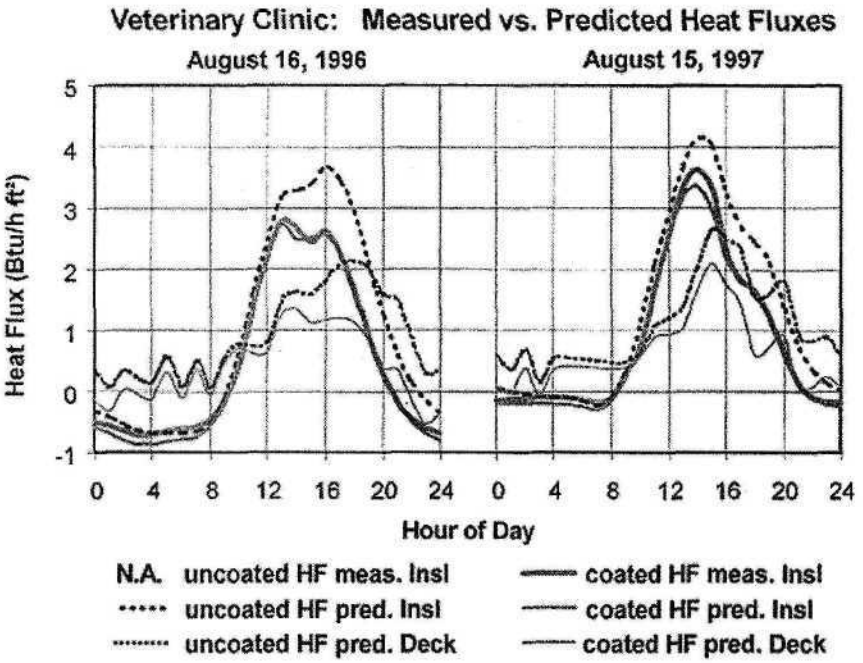

Figure 5 *Hourly measured and predicted heat fluxes for the coated and uncoated locations on the veterinary clinic roof for similar sunny days one year apart.*

uncoated area due to the failure of the heat flux transducer there early in the project. The agreement between the measured and predicted heat fluxes in the middle of the polyisocyanurate insulation under the coated area is excellent on these hot sunny days, and both capture the effect of the weathering of the coating. Weathering effects do not seem as severe as on the roof of the convenience store, which the measurements of solar reflectance at 500 days for the samples VC and SHP in Figure 2 corroborate. The differences between the predicted coated and uncoated heat fluxes are not as large as on the convenience store either, which is due to the enhanced effect of the shading on the coated area on the convenience store, preferentially shading it near noon when solar irradiation peaks. The predicted heat fluxes through the heavyweight concrete deck of the veterinary clinic are delayed and diminished relative to those through the insulation. The deck heat flux through the uncoated area is positive (into the building) all 24 hours of these sunny hot days. The fresh coating allowed a few hours per day of negative heat fluxes (out of the building), but after a year, the weathered coating has lost this advantage or the climatic conditions are slightly more severe.

To generalize the lessons from Figures 4 and 5, Table 4 presents average sunlit roof values for heat fluxes in the same manner as Table 2 did for outside-surface temperatures. Sunlit heat fluxes are included in the monthly averages in Table 4 for times when the coated heat flux was positive and the uncoated heat flux exceeded it by 0.5 Btu/h·ft^2 (1.6 W/m^2). This sunlit criterion is more complicated than for surface temperatures, but was necessary because heat fluxes routinely became negative at night and still occasionally satisfied the difference. Requiring positive heat fluxes excluded nighttime heat fluxes. The sunlit criteria generally yielded entries for pairs of heat fluxes beginning slightly later in the day than pairs of surface temperatures and continuing later into the early evening.

For the convenience store, the measured heat fluxes and, therefore, their averages, are more accurate. However, the average predicted heat fluxes yield useful information. They show that the percent decreases in heat fluxes predicted through the insulation and the deck due to the coating are the same within 0% to +2% for the summer months of June, July, August, and September. Hence, for the convenience store on average, the percent decrease in heat fluxes through the deck can be characterized by the behavior of the measured heat fluxes through the insulation. These heat fluxes are proportional to differences between summertime roof temperatures, so percentage decreases for them are larger than for the outside-surface temperatures. The fresh coating shows an average heat flux decrease of 55% in heat fluxes in July, August, and September 1996 compared to an average 14% outside-surface temperature decrease for the same months in Table 2. The average heat flux decrease falls off to 44% in July, August, and September 1997 compared to 12% for outside-surface temperatures.

For the heavyweight concrete-decked roof on the veterinary clinic, the accuracy of the predictions is acceptable for comparisons of the effect of the coating on heat fluxes. This is fortunate because the heat fluxes of direct interest for the effect of the roof on the building interior are those through the deck. They are significantly different from the insulation heat fluxes and yield larger percent decreases for the effect of the coating. For August and September 1996, using the deck predictions, the average percent decrease is 51% compared to an average 12% decrease for outside-surface temperatures in August and September 1996 from Table 2. The average heat

TABLE 4

Monthly Average Sunlit Heat Fluxes for the Veterinary Clinic and the Convenience Store Roofs*

Month	Heavyweight Roof on Veterinary Clinic						Shaded Roof on Convenience Store								
	Pred. Insl HFunc (B/h·ft²)	Pred. Insl HFctd (B/h·ft²)	(unc-ctd) / unc (%)	Pred. Deck HFunc (B/h·ft²)	Pred. Deck HFctd (B/h·ft²)	(unc-ctd) / unc (%)	Meas. Insl HFunc (B/h·ft²)	Meas. Insl HFctd (B/h·ft²)	(unc-ctd) / unc (%)	Pred. Insl HFunc (B/h·ft²)	Pred. Insl HFctd (B/h·ft²)	(unc-ctd) / unc (%)	Pred. Deck HFunc (B/h·ft²)	Pred. Deck HFctd (B/h·ft²)	(unc-ctd) / unc (%)
JUL 96	NA	NA	----	NA	NA	—	3.23	1.41	56.3	2.97	1.70	42.8	2.82	1.61	42.9
AUG 96	2.59	1.63	37.1	1.75	0.87	50.3	2.70	1.22	54.8	2.52	1.46	42.1	2.41	1.38	42.7
SEP 96	2.59	1.65	36.3	1.67	0.81	51.5	2.14	1.01	52.8	1.99	1.20	39.7	1.96	1.16	40.8
OCT 96	2.18	1.32	39.4	1.14	0.42	63.2	1.42	0.49	65.5	1.16	0.44	62.1	1.17	0.46	60.7
MAR 97	1.96	1.23	37.2	1.10	0.44	60.0	1.45	0.65	55.2	1.25	0.59	52.8	1.17	1.49	58.1
APR 97	2.40	1.55	35.4	1.49	0.71	52.3	2.25	0.94	58.2	2.01	0.95	52.7	1.91	0.83	56.5
MAY 97	2.66	1.80	32.3	1.66	0.84	49.4	2.64	1.30	50.8	2.60	1.49	42.7	2.41	1.31	45.6
JUN 97	2.72	1.92	29.4	1.73	0.98	43.4	3.29	1.87	43.2	3.29	2.18	33.7	2.93	1.92	34.5
JUL 97	2.76	1.98	28.3	1.71	0.99	42.1	3.57	2.10	41.2	3.69	2.66	27.9	3.27	2.28	30.3
AUG 97	2.68	1.90	29.1	1.64	0.90	45.1	3.51	2.00	43.0	3.41	2.30	32.6	3.01	1.97	34.6
SEP 97	2.44	1.62	33.6	1.52	0.78	48.7	2.14	1.13	47.2	1.87	1.18	36.9	1.86	1.17	37.1
OCT 97	1.74	0.97	44.3	1.34	0.66	50.7	1.75	0.78	55.4	1.40	0.68	51.4	1.49	0.77	48.3

* Sunlit criterion: heat flux through coated roof location, HFctd > 0; heat flux through uncoated roof location, HFunc — heat flux through coated roof location, HFctd > 0.5 Btu/h·ft².

flux decrease falls off to 47% in August and September 1997 compared to 10% for outside-surface temperatures.

The summary from Table 4 of the average decreases in heat fluxes through the deck under the sunlit coated vs. uncoated surfaces (using measurements in the insulation for the shaded roof of the convenience store and predictions for the heavy roof of the veterinary clinic) is as follows:

	8/96	9/96	10/96	Avg.'96	8/97	9/97	10/97	Avg.'97
Shaded roof	55%	53%	66%	58%	43%	47%	55%	48%
Heavy roof	50%	52%	63%	55%	45%	49%	51%	48%

From the perspective of average heat fluxes through the deck during sunlit times, there is no significant difference in behavior between the lightweight roof on the convenience store, where the effect of the coating is slightly enhanced by the preferential shading, and the heavyweight roof on the veterinary clinic, where deck heat fluxes are delayed by the thermal mass and the coating did not appear to weather as much during the project. However, because the veterinary clinic and three-fourths of the convenience store had an unconditioned plenum shielding the roof from the conditioned interior, the effect of the coating on deck heat fluxes may not mirror its effect on building heating or cooling loads.

WHOLE BUILDING MODELING USING DOE-2.1E

Of particular interest in this New Technology Demonstration Program project is the effect of white coatings on the annual cooling energy demand of buildings in the federal sector. Due to the unconditioned plenums under much of the roof of the convenience store and all of the roof of the veterinary clinic, it is difficult to extrapolate to annual energy impact from the trends shown by the heat fluxes through the roofs in Table 4. Even if the effect of the coatings on the annual cooling energy demand of the buildings were obtainable from the heat fluxes in Table 4, the buildings are certainly not typical of all federal buildings and the weather during which the data were obtained is not typical of that for all federal buildings.

At best, the buildings can serve as examples of the effect of coatings. In order to maximize their worth as examples, DOE-2.1E modeling of the convenience store and the veterinary clinic was done. This section describes that effort and presents results from the models for the relative effects of the coatings and natural shading on the annual energy demand of these buildings in the climate of the Florida Panhandle. The model for the veterinary clinic for no, fresh, and weathered coatings was then modified to see the effect of the composition of the roof and the presence of the plenum on the annual energy use.

The test protocol included monitoring of total electricity demand in the all-electric convenience store and veterinary clinic. Pulse-initiating kilowatt-hour meters in each building reported total electricity demand to a pulse counter in the data loggers. Little could be done directly with these data. The high internal electrical loads in the convenience store and the consequent erratic nighttime demand prevented simple correlation of the effect of the coating to total demand (Petrie and Childs 1997). The essentially zero nighttime and weekend demand in the veterinary clinic did allow generation of monthly average electrical demands during occupied hours. In fact, a comparison between average outside-air temperatures on the roof of the veterinary clinic and average power demand was offered as tentative proof that the coating was saving electricity (Petrie et al. 1998). The averages before and after the coating was applied were computed when power demand exceeded 1.5 kW. The level of 1.5 kW was judged to mean that the HVAC system of the building was in active operation at normal occupied thermostat setpoints.

Table 5 presents the complete list of monthly average power demand and outside-air temperatures with the criterion that hourly power exceeds 1.5 kW for the veterinary clinic. Data for May and June 1996 are included to show months before the veterinary clinic roof was coated. The average outside-air temperatures are slightly different for corresponding months in Table 2 and Table 5 because the criteria are different. For example, Table 5 does not include data for any sunny weekend days when the veterinary clinic's HVAC system was not operating at normal occupied thermostat setpoints. From Table 5, by comparison of data only for June and August 1996, there is an apparent decrease of 13% in average power despite a 1.1% increase in average outside-air temperature. The likely incorrectness of assigning this as the effect of the coating is brought out by comparing data for May and June 1996 with data for May and June 1997. The opposite conclusion is reached. The same building with a slightly weathered coating on the roof uses 12% (May) and 14% (June) more average power for a 2.8% (May) and 1.6% (June) decrease in average outside-air temperature in 1997 compared to 1996. Average power does increase for August and September 1997 relative to August and September 1996, consistent with the effect of weathering on white coatings, but the increase averages 14%. This is too much to be due to the slight decrease in the reflectance observed on the veterinary clinic roof. Clearly, there are too many uncontrolled variables affecting power demand even for the simple veterinary clinic. A very noticeable effect is that June is the month of highest electricity use in the veterinary clinic despite the milder weather compared to subsequent summer months.

TABLE 5
Monthly Average Occupied Power and Outside-Air Temperatures for the Veterinary Clinic*

Month	Power (kW)	Toutside air (°F)
MAY 96	50	84.7
JUN 96	3.02	87.3
JUL 96	N.A.	N.A.
AUG 96	2.63	88.3
SEP 96	2.62	87.4
OCT 96	2.45	73.6
MAR 97	2.51	75.7
APR 97	2.30	75.6
MAY 97	2.90	82.3
JUN 97	3.44	85.9
JUL 97	3.31	89.8
AUG 97	2.84	88.8
SEP 97	3.17	88.0
OCT 97	2.79	76.7

* Occupied criterion: Power > 1.5 kW.

DOE-2.1E Modeling of Existing Buildings

DOE-2.1E models were generated for the veterinary clinic and convenience store and subjected to Typical Meteorological Year climatic data for Apalachicola, Florida, near the federal facility. A successful DOE-2 model includes good descriptions of the basic construction features of a building, its heating, ventilating, and air-conditioning system and schedules for occupancy, lighting, thermostat settings, and, especially in the case of the convenience store, internal equipment usage and the shading of the building. Details follow about the convenience store and the veterinary clinic that are relevant to the DOE-2 models.

The convenience store is a concrete block building with a built-up roof shaded by large live oak trees to the south. A sketch was drawn of the shading pattern in mid-morning of a clear, mid-August day. The shadow cast by the trees covered 27% of the roof area. A large 50% transparent rectangle was input as the shading to cast a shadow of equal area at the time of the sketch. So much of the roof is shaded that the instruments were deliberately installed in shaded areas. The original part of the building, about 3,060 ft^2 (284 m^2) in floor area, has a wood deck with nominal 2×10 ceiling joists. This part serves as the store itself and has a suspended ceiling forming an unconditioned plenum with R-11 $h \cdot ft^2 \cdot °F/Btu$ (1.9 $m^2 \cdot K/W$) batts laid on the ceiling tiles. Insulated ducts are in the plenum to distribute air heated by electric resistance strip heaters or cooled by a direct expansion evaporator coil. Air temperature is controlled by a thermostat in the store area. Refrigerant lines go to and from a compressor and condenser coil on a concrete pad outside the building. There are also several compressors and condenser coils on other external pads to serve the refrigerators and freezers in the store. No equipment is on the roof.

A stockroom, about 950 ft^2 (88 m^2) in area, was built when the building was converted to a convenience store. Its built-up roof is over a metal deck and 2 in. (5.1 cm) of polyisocyanurate insulation and was the site of the instrumented areas. The stockroom is open to the store through a door-sized archway and is separately heated and cooled by a through-the-wall air-to-air heat pump. Suspended fluorescent fixtures serve the lighting needs of both the store and stockroom. Before the convenience store roof was coated, the store was open for customers seven days a week from 10 a.m. to 10 p.m. As of August 1, 1996, at the end of the first month after coating, hours were cut back to 9 a.m. to 7 p.m. weekdays and Saturdays and 11 a.m. to 5 p.m. Sundays. The facility's energy management system adjusted the hours of HVAC system operation in response to the new schedule.

The veterinary clinic is a 1,500 ft^2 (140 m^2) concrete block building with a built-up roof over 2 in. (5.1 cm) of polysocyanurate insulation over 2 in. to 4 in. (5.1 cm to 10.2 cm) of insulating concrete with a 2 in. to 3 in. (5.1 cm to 7.6 cm) heavyweight concrete deck. It originally housed a radar facility. There are two deciduous trees at the south end of the building that shaded some of the south wall and roof of the building but not the areas that were instrumented. Rectangles, 50% transparent in summer but 100% transparent in winter, modeled this shade. A small unconditioned room at a back corner of the building houses the air handler for an air-to-air heat pump that heats and cools the building. The thermostat to control the heating and air conditioning is in a reception area at the front of the building. Air distribution is in ducts in the plenum above a suspended ceiling. Recessed fluorescent lights are in the ceiling. The building is operated as a small animal clinic from 8 a.m. to 4 p.m. weekdays and 8 a.m. to 12 noon some Saturdays and is closed most Sundays and holidays. It, too, is served by the facility's energy management system. There is very little equipment in the building—two refrigerators and miscellaneous office equipment. Regular occupancy is limited to one receptionist and one or two veterinarians and occasional walk-in visitors with pets. The kennels for occasional boarding of pets are outdoors.

To test the accuracy of the DOE-2 models of the convenience store and the veterinary clinic, hourly reports were scheduled in DOE-2 to print out the roof shading and roof temperatures as well as the total electrical load on the plants specified to separately serve each building. Reports were written hourly for a week in February, June, August, and September 1996 and June, July, August, and September 1997. The months were selected to cover the duration of the project and as ones in which continuous power measurements were available. The week in each month was selected so that the measured outdoor-air temperatures, T_{oa}, for each building approximately matched the dry-bulb temperature, T_{db}, in the TMY weather file for Apalachicola, Florida.

Figure 6 shows examples of the results after all adjustments in the models. The weeks shown are February 7-13, 1996, and July 19-25, 1997. The TMY T_{db} temperatures in general match the measured T_{oa}, but the measured power in both buildings does not exactly follow the outside-air temperature anyway. Moreover, measured power is more erratic than the predicted power despite considerable effort to match the observed power by adjustments in occupancy, lighting, and equipment as well as heating and cooling thermostat setting schedules. Note that the DOE-2 model successfully followed the change in schedule starting August 1, 1996, in the convenience store. The hours of nonsetback power demand in February 1996 are longer than in July 1997. The data loggers were kept on Eastern Standard Time year-round and scheduling was adjusted in the DOE-2 models.

Daytime peaks were modeled well for the convenience store, but the erratic nighttime demand was more difficult to follow. A summer-only equipment schedule was implemented to specify about 5 kW extra summer demand by the refrigerators and freezers operating in hot weather. The much lower power demand of the veterinary clinic, as well as its being closed on weekends, shows up clearly in both the measured and predicted power for the veterinary clinic building. The nighttime demand is often nearly zero, which was easier to model than the erratic convenience store situation.

The reflectance of the uncoated roofs on both buildings was assumed to be 0.10. The convenience store and veterinary clinic models with coated roofs were run with solar reflectances of 0.525 and 0.45, corresponding to the fresh and weathered values in Figure 2. To the scale of Figure 6, the dashed lines for the weathered value deviate little from the solid curves for the fresh value.

The base cases for each building with an appropriately shaded and freshly coated roof, assumed to have solar reflectance of 0.525, were modified to test the effect of shading and no coating as well as the effect of the weathered coating. The results are in Table 6, with total annual energy use and portions for cooling and heating (including supplemental heat for the heat pumps) given in kilowatt-hours for each case. Changes in total energy use do not equal the sum of the changes in cooling and heating energy use because of small changes in other categories of use such as for ventilation fans. Percent changes due to shading, weathering, and no coating compared to the base case (shading and fresh coating) are calculated as shown in the heading above each set.

The annual energy uses for the convenience store are much larger than for the veterinary clinic because the convenience store is larger and has greater internal loads. Hence, the effect of coating the roof and even the small shade trees at the south of the veterinary clinic have a larger percent impact for this building. For both buildings, the effect of the changes in Table 6 cause a misleadingly high percent change in the heating energy needs. This is because the annual heating energy itself is small for both buildings.

The decrease of 0.075 in the solar reflectance value for the coating observed over the duration of the project has a negligible impact on the cooling energy and total energy for the convenience store. It is not very significant for the veter-

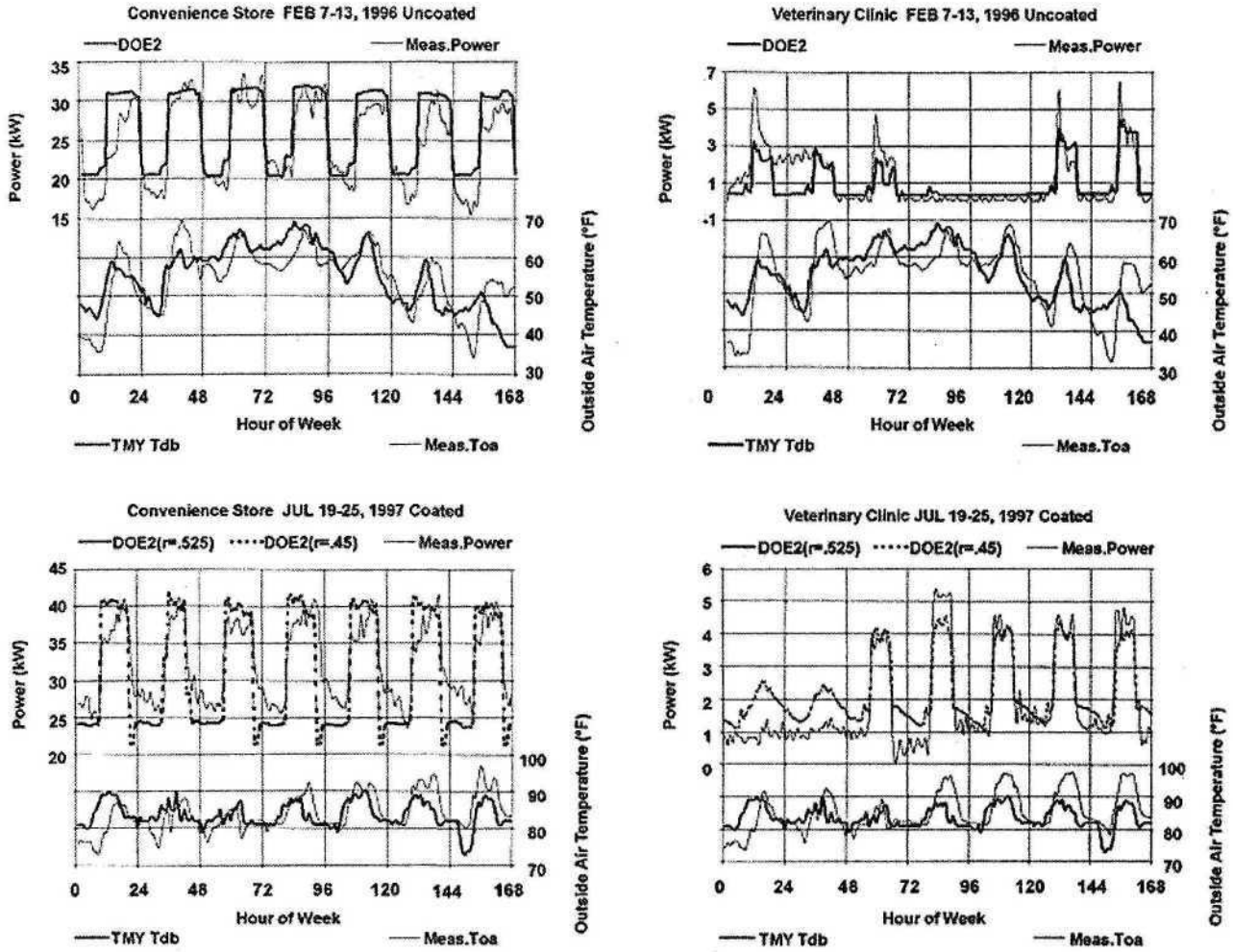

Figure 6 *Comparison between measurements and DOE2 predictions of electrical power for the convenience store and veterinary clinic for a winter and summer week during the project.*

inary clinic either. The hourly reports showed that peak roof temperatures (at 10 a.m.) in mid-August were 6°F to 7°F (3.3°C to 3.9°C) warmer with the weathered coating on both roofs. The decrease of 0.425 in roof solar reflectance from the fresh coating to no coating caused the roof temperature in the models to increase 31°F to 36°F (17°C to 20°C) at peak times without the coating. However, even this change is not very significant for the convenience store, and energy savings were likely not noticed in the effects of the change to a shorter schedule just after the convenience store roof was coated.

The savings of 7.4% (0.27 kWh/ft^2 or 2.9 kWh/m^2) in cooling energy and 3.2% (0.24 kWh/ft^2 or 2.6 kWh/m^2) in total energy use predicted for the veterinary clinic are encouraging, although not as much as the misleading 13% saving in occupied power obtained from data in Table 5 for June and August 1996. As shown above in the discussion of the heat fluxes through the built-up roofs, the average plenum temperatures before and after the veterinary clinic roof was coated did not show a significant change. The conclusion is that there was little effect of the coating on heat transfer to the duct system in the plenum for this building. DOE-2 did not model any effect. For this reason, the predictions may be conservative.

The partially transparent rectangles used in the model delivered a peak shading fraction of 0.10 for the convenience store roof and 0.00 for the veterinary clinic roof in mid-August. Relative to the base case, peak roof temperatures without shade were only 1°F (0.6°C) warmer on the convenience store and unchanged for the veterinary clinic. The predictions for the effect of shading are put into perspective by comparing them to the effect of the coating. The 1.8% effect on cooling of shading the south wall of the veterinary clinic is one-fourth the 7.4% effect of the coating. Conversely, the 0.9% effect on cooling of shading for the convenience store is about the same as the 0.8% effect of the coating. Despite the smaller percent savings, shading is a more important cooling energy saving measure for the convenience store than for the veterinary clinic.

DOE-2.1E Modeling of Modified Veterinary Clinic Building

Table 6 shows the promise of significant cooling energy and total energy savings with a fresh coating on the veterinary clinic roof compared to the uncoated roof. This is despite the thermally massive roof, which delays some roof load until after the clinic is unoccupied and in energy-conserving thermostat setup. It also is despite the unconditioned plenum between the drop ceiling and the roof deck, which shields the conditioned space from direct interaction with the roof but may affect the temperature of conditioned air distributed in ducts in the plenum.

To explore the sensitivity to the thermally massive roof and the plenum of potential energy savings with radiation control coatings, modifications were made to the base case model for the veterinary clinic building. First, the metal-decked built-up roof with 2 in. (5.1 cm) of polyisocyanurate insulation from the instrumented part of the convenience store roof was substituted for the existing veterinary clinic roof. This replaced the massive heavyweight concrete and lightweight concrete above it by a metal deck. Second, with the less thermally massive metal deck in place, the plenum was removed from the model so the interior conditioned space was exposed directly to the roof deck. Third, with the plenum removed, a smooth metal roof was used on the veterinary clinic. DOE-2.1E required that the construction of this roof be modeled simply as a U-factor (inverse of R-value), including the effect of inside convection but allowing outside convection to be modeled by DOE-2.1E in response to conditions in the weather file. Three R-values were used for the smooth metal roof. An R-value of 15.4 h·ft^2·°F/Btu (2.7 m^2·K/W) was estimated for inside convection in downward heat flow from a nonreflecting surface in series with a thin metal layer and 2.0 in. (5.1 cm) of polyisocyanurate foam insulation over 0.5 in. (1.3 cm) thick plywood (ASHRAE 1997). With 1.0 in. (2.5 cm) of foam insulation, the R-value was 8.4 h·ft^2·°F/Btu (1.5 m^2·K/W). With no foam insulation, the R-value was 1.4 h·ft^2·°F/Btu (0.25 m^2·K/W). The solar reflectances of the smooth metal roof surface

TABLE 6
Comparisons of DOE-2 Predictions for the Effects of Fresh and Weathered Coatings and Shading on Annual Energy Use in the Veterinary Clinic and the Convenience Store

Category	Veterinary Clinic Annual Energy Use (kWh)	Percent Change	Convenience Store Annual Energy Use (kWh)	Percent Change
Base Case: Shading and Fresh Coating (fc: ρ = 0.525)				
Total	10,739	—	213,925	—
Cooling	5,037	—	27,900	—
Heating	1,006	—	1,199	—
Shading (sh) and Weathered Coating (wc: ρ = 0.45) vs. Base				
		(wc-fc)/fc		**(wc-fc)/fc**
Total	10,806	+0.6%	213,959	+0.01%
Cooling	5,111	+1.5%	27,943	+0.15%
Heating	996	−1.0%	1,188	−0.9%
No shade (ns) but Fresh Coating (fc: ρ = 0.525) vs. Base				
		(ns-sh)/ns		**(ns-sh)/ns**
Total	10,815	+0.7%	214,105	+0.08%
Cooling	5,130	+1.8%	28,162	+0.9%
Heating	986	−2.0%	1,112	-7.3%
Shading and No Coating (nc: ρ = 0.10) vs. Base				
		(nc-fc)/nc		**(nc-fc)/nc**
Total	11,095	+3.2%	214,095	+0.08%
Cooling	5,439	+7.4%	28,116	+0.8%
Heating	949	−6.0%	1,128	−5.9%

TABLE 7
Comparisons of DOE-2 Predictions for the Effects of Fresh and Weathered Coatings on Annual Energy Use for Modifications of the Veterinary Clinic Building

Base Case (from Table 6)

	Fresh $\rho_{fc} = 0.525$	Weathered $\rho_{wc} = 0.45$		Uncoated $\rho_{nc} = 0.1$		
	Energy (kWh)	Energy (kWh)	% Change (wc-fc)/wc	Energy (kWh)	Percent Change (nc-fc)/nc	Percent Change (nc-wc)/nc
Total	10,739	10,806	+0.6%	11,095	+3.2%	+2.6%
Cooling	5,037	5,111	+1.5%	5,439	+7.4%	+6.0%
Heating	1,006	996	-1.0%	949	-6.0%	-5.0%

Replace thermally massive decked roof with convenience store metal-decked BUR

	Fresh $\rho_{fc} = 0.525$	Weathered $\rho_{wc} = 0.45$		Uncoated $\rho_{nc} = 0.1$		
	Energy (kWh)	Energy (kWh)	% Change (wc-fc)/wc	Energy (kWh)	Percent Change (nc-fc)/nc	Percent Change (nc-wc)/nc
Total	10,753	10,820	+0.6%	11,123	+3.3%	+2.7%
Cooling	5,054	5,133	+1.5%	5,485	+7.9%	+6.4%
Heating	1,002	988	-1.4%	937	-6.9%	-5.4%

Convenience store metal-decked BUR and no plenum

	Fresh $\rho_{fc} = 0.525$	Weathered $\rho_{wc} = 0.45$		Uncoated $\rho_{nc} = 0.1$		
	Energy (kWh)	Energy (kWh)	% Change (wc-fc)/wc	Energy (kWh)	Percent Change (nc-fc)/nc	Percent Change (nc-wc)/nc
Total	11,004	11,098	+0.8%	11,496	+4.3%	+3.5%
Cooling	5,248	5,357	+2.0%	5,826	+9.9%	+8.1%
Heating	1,020	1,000	-2.0%	910	-12.1%	-9.9%

Smooth metal roof with 2 in. foam insulation (R = 15.4 h·ft²·°F/Btu) and no plenum

	Fresh $\rho_{fc} = 0.75$	Weathered $\rho_{wc} = 0.525$		Uncoated $\rho_{nc} = 0.2$		
	Energy (kWh)	Energy (kWh)	% Change (wc-fc)/wc	Energy (kWh)	Percent Change (nc-fc)/nc	Percent Change (nc-wc)/nc
Total	10,731	10,987	+2.3%	11,345	+5.4%	+3.2%
Cooling	4,945	5,252	+5.8%	5,681	+13.0%	+7.6%
Heating	1,064	1,001	-6.3%	913	-16.5%	-9.6%

Smooth metal roof with 1 in. foam insulation (R = 8.4 h·ft²·°F/Btu) and no plenum

	Fresh $\rho_{fc} = 0.75$	Weathered $\rho_{wc} = 0.525$		Uncoated $\rho_{nc} = 0.2$		
	Energy (kWh)	Energy (kWh)	% Change (wc-fc)/wc	Energy (kWh)	Percent Change (nc-fc)/nc	Percent Change (nc-wc)/nc
Total	10,912	11,376	+4.1%	12,021	+9.2%	+5.4%
Cooling	4,995	5,548	+10.0%	6,284	+20.5%	+11.7%
Heating	1,185	1,074	-10.3%	950	-24.7%	-13.1%

Smooth metal roof with no foam insulation (R = 1.4 h·ft²·°F/Btu) and no plenum

	Fresh $\rho_{fc} = 0.75$	Weathered $\rho_{wc} = 0.525$		Uncoated $\rho_{nc} = 0.2$		
	Energy (kWh)	Energy (kWh)	% Change (wc-fc)/wc	Energy (kWh)	Percent Change (nc-fc)/nc	Percent Change (nc-wc)/nc
Total	12,861	14,596	+11.9%	16,662	+22.8%	+12.4%
Cooling	5,792	7,829	+26.0%	10,116	+42.7%	+22.6%
Heating	2,249	1,900	-18.4%	1,599	-40.7%	-18.8%

were adjusted for each R-value to correspond to our experience with freshly coated smooth surfaces ($\rho_{fc} = 0.75$ from Figure 2), a weathered value on smooth surfaces ($\rho_{wc} = 0.525$) to coincide with the fresh value on a rough surface and with a handbook value ($\rho_{nc} = 0.20$) for the solar reflectance of uncoated but oxidized steel (Sparrow and Cess 1970).

Table 7 presents the DOE-2 predictions of annual energy use of the modified veterinary clinic building. Data for the base case are repeated from Table 6 in the first set of total, cooling, and heating energy uses. Due to the climate of the Florida Panhandle, heating energy is small but is included for completeness. All features of the base case were retained in the modifications except for the changes listed in the heading for each and explained above. The thermally massive roof does not have much impact in the DOE-2 model, judging from the fact that the energy uses and percent changes due to the coating hardly change at all when a lighter weight but equally insulated roof is used. For example, the cooling energy savings due to a fresh coating only increase 0.5% relative to the base case, from 7.4% to 7.9%. Since the insulation level equivalent to 2 in. (5.1 cm) of polyisocyanurate was held constant with and without the thermally massive roof and DOE-2.1E was able to calculate custom weighting factors for both roofs, the effect of the thermal mass should be estimated accurately.

The absence of a plenum makes a little more difference in energy savings, for example, another 2% cooling savings from 7.9% to 9.9% due to the coating. The effect of the 2 in. (5.1 cm) of polyisocyanurate seems to prevent greater savings when the coating is applied. There was no input method in DOE-2.1E to model the duct system in the plenums of both the store part of the convenience store and the veterinary clinic. Hence, the effect of the plenum on building energy use is likely underestimated by DOE-2.1E. Parker et al. (1998b) modified DOE-2.1E source code to reflect the significant effect their measurements showed of reflective roof coatings on conditions for ducts in plenums. We did not measure duct conditions.

The smooth roof cases show more significant energy savings. For a smooth roof, when the amount of insulation is decreased from 2 in. (5.1 cm) to 1 in. (2.5 cm) to no polyisocyanurate insulation, the coating saves significant amounts of energy. For example, cooling energy savings are 13%, 21%, and 43%, respectively, for fresh coatings over the three levels of insulation. The difference in solar reflectances between the freshly coated and uncoated smooth roofs are slightly greater than for the BURs in Table 7. For the smooth roofs, the freshly coated solar reflectance is 0.75 relative to an uncoated value of 0.20. For the rough BURs, the freshly coated solar reflectance is 0.525 relative to an uncoated value of 0.10. Hence, the smooth roof with 2 in. (5.1 cm) of insulation but without a plenum slightly outperforms the rough BUR with 2 in. (5.1 cm) of insulation but without a plenum. The difference for the smooth roofs may be optimistic. The uncoated reflectance for the metal roof corresponds to heavily oxidized steel. An uncoated galvanized roof, even if it is very dull, has handbook reflectance values that equal those of fresh white coatings (Sparrow and Cess 1970).

The estimates of energy use with the uncoated roofs also are compared to those with the weathered coating in Table 7. Over the range of solar reflectances in the table, the total energy use and the cooling energy vary approximately linearly with solar reflectances. For example, for the metal roofs, the reflectance assumed for the weathered coating yields 60% of the improvement that the fresh coating yields. The total and cooling percent savings relative to the uncoated roofs for the cases with 2 in. and 1 in. (5.1 cm and 2.5 cm) of insulation with the weathered coating are 57% to 59% of the percent savings with the fresh coating. For the uninsulated cases, the dependence on reflectance is less linear and the percent savings with the weathered coating are 53% to 54% of the percent savings with the fresh coating. As Figure 2 showed, our experience with white coatings has been that they attain their fully weathered values in less than two years of service. For projected coating lifetimes of about ten years, the coating is weathered over 80% of the time it is on the roof. These metal roof cases in Table 7 show that weathered values of solar reflectance should be used to avoid overly optimistic estimates of energy savings for economic decisions based on performance over the lifetime of the coating. As mentioned in the introduction, this was the approach taken in establishing the credit for reflective roofs against additional insulation in the proposed revision of *ANSI/ASHRAE/IES Standard 90.1* (Akbari et al. 1998).

SUMMARY AND CONCLUSIONS

Support of the federal New Technology Demonstration Program (NTDP) allowed us to learn the effect of radiation control coatings on low-slope roofs at a federal facility in the Panhandle of Florida. Two existing rough-surfaced, moderately well insulated, low solar reflectance, built-up roofs (BURs) were spray coated with a white, latex-based product with ceramic beads. Samples of the coated roofs were brought periodically to the laboratory to measure the solar reflectance as the coatings weathered. Relative to the uncoated BUR, the fresh coating increased the solar reflectance from 0.09 to about 0.53. This freshly coated solar reflectance is at least 0.2 lower than we have observed for similar fresh latex- or acrylic-based white coatings on smooth, low-slope surfaces, including the ceramic coating used on the BURs. In the course of the project, the reflectance for one BUR decreased to 0.42 while the other decreased to 0.50. In other tests, white coatings on smooth, low-slope surfaces that have weathered several years show solar reflectances as low as 0.50 to 0.55.

Beginning several months before the BURs were coated in July 1996 and ending in October 1997, we monitored the power demand of the all-electric buildings that the roofs covered and the temperatures and heat fluxes for two instrumented areas on each roof. The data were analyzed for monthly average sunlit performance. The BUR whose reflectance decreased to 0.42 was shaded significantly, including

the instrumented areas, by trees to the south of its building. We measured about 27% shading of the roof in mid-August in mid-morning. The other had a heavyweight concrete deck with some shading away from the instruments.

Average decreases in the sunlit temperatures of the coated vs. the uncoated surfaces for August, September, and October of 1996 and 1997 show the effects of weathering for comparable climatic conditions. They also show that shading enhanced the measurement of the coating effect on the significantly shaded roof. The coated instrumented area there was preferentially shaded near noon.

	8/96	9/96	10/96	Avg.'96	8/97	9/97	10/97	Avg.'97
Shaded roof	14.4%	11.7%	12.5%	12.9%	13.4%	10.1%	12.2%	11.9%
Heavy roof	12.1%	12.0%	12.9%	12.3%	9.9%	10.6%	11.6%	10.7%

The data from before the roofs were coated on through two summers with the roofs coated allow models to be calibrated for the roofs and for the whole buildings with fresh and weathered coatings and without the coatings. Calibrated models allow us to generalize the performance of the coatings to address the effect of varying R-value and other roof features, climatic conditions, and solar reflectance, including the effect of weathering. Generalizations are useful to federal building managers seeking to adopt a new technology demonstrated by the NTDP.

Deck heat fluxes are the direct contribution of the roof to the building interior. To obtain heat fluxes through the bottom of the roof decks, results from a one-dimensional transient heat conduction program, using measured inside-surface and outside-surface temperatures as boundary conditions, were compared to heat fluxes measured in the middle of the 2 in. (5.1 cm) thick polyisocyanurate insulation on each roof. At summer conditions, trends for percentage decreases in average heat fluxes through the bottom of each deck for the coated vs. the uncoated surfaces are similar to those for sunlit surface temperatures. Values are larger because the heat fluxes are the result of temperature differences.

	8/96	9/96	10/96	Avg.'96	8/97	9/97	10/97	Avg.'97
Shaded roof	55%	53%	66%	58%	43%	47%	55%	48%
Heavy roof	50%	52%	63%	55%	45%	49%	51%	48%

Unconditioned plenums under much of the roofs, with insulated ducts for distribution of conditioned air to the spaces under the plenums, complicated the relation between decreases in deck heat fluxes and decreases in building cooling load. Our failure to observe significant decreases in total power demand after the roofs were coated suggests that the deck heat flux decreases were much larger than cooling load decreases for these buildings.

Although the white coatings on the rough-surfaced BURs did not increase their solar reflectances as much as white coatings on smooth surfaces, the increase was significant. With weathered coatings, relative to uncoated BURs, temperatures of the roof surfaces and heat fluxes through the roof decks were decreased by more than 10% and 45%, respectively, during times the roofs were sunlit. Fresh coatings performed slightly better with temperature decreases over 12% and deck heat flux decreases over 55%. For more insight into the effect of the coatings on building energy use, whole building models for DOE-2.1E were constructed with the architectural details and operational features of each building. They were subjected to Typical Meteorological Year (TMY) climatic data for Apalachicola, Florida, near the federal facility. Verification of model accuracy was achieved by comparing measured and predicted building power for eight weeks throughout the project when air temperatures measured above the roofs approximately matched the TMY dry-bulb temperatures.

Large vertical 50% transparent rectangles south of the building with the shaded roof were sized to produce the roof shading observed in mid-August. This building had very high internal loads. The effect of shading and the coating on annual energy use showed that the shading and the coating were equally effective in decreasing cooling and total load, but neither did much. The heating percentage increases are larger in magnitude because of the small amount of heat required by the building in the Florida Panhandle.

Shaded Roof	Total	Cooling	Heating
% change (unshaded-shaded)/unshaded for coated roof	+0.08%	+0.9%	−7.8%
% change (uncoated-coated)/uncoated for shaded roof	+0.08%	+0.8%	−6.3%

The building with the thermally massive decked roof had small internal loads. For it, the coating noticeably decreased annual total and cooling energy use. The small heating load again exaggerated the heating penalty.

Heavy Roof	Total	Cooling	Heating
% change (uncoated-coated)/uncoated roof	+3.2%	+7.4%	−6.0%

Within the limits of DOE-2.1E for handling thermally massive components and plenums with ducts, additional modeling was done with the thermally massive roofed building to study the effect of the roof composition and plenum, holding all other features in the model constant. Without modifications of this small building, the fresh coating saved 7.4% (0.27 kWh/ft^{2}or 2.9 kWh/m^2) of the annual cooling energy. This is larger than the 0.8% (0.054 kWh/ft^2 or 0.58 kWh/m^2) savings in cooling energy for the larger convenience store with the shaded roof. In the first modification to the small building, the thermally massive roof deck was replaced by a lightweight deck. Then the plenum was removed. Finally, without a plenum, a smooth metal roof with three levels of insulation was postulated. These modifications showed progressively more and more annual cooling energy use as the effective amount of insulation in the uncoated roof decreased. Savings with the fresh coating increased to 43% (1.6 kWh/ft^2 or 17 kWh/m^2) in the final case with an uninsulated metal roof and no plenum. This case also showed that estimates of energy savings over the lifetime of a coating should be done with weathered coating solar reflectances, or, for this building, estimates of savings due to improved thermal performance were about 50% too optimistic.

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Tyndall AFB and the Burger King Corporation made three buildings available and provided communication lines with which to do remote monitoring. Gulf Power Company, the electric utility serving Tyndall AFB, installed pulse-initiating kilowatt-hour meters for two of the buildings.

Other national laboratories were involved in this project. Pacific Northwest National Laboratory did an economic analysis based on information in ThermShield's technology submittal to the New Technology Demonstration Program of FEMP and provided input to an interlaboratory council. The council—which had representation from Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—decided to choose the ThermShield coating technology and approved funding of the work plan submitted by the Buildings Technology Center at the Oak Ridge National Laboratory. Lawrence Livermore National Laboratory provided most of the coating applied at Tyndall AFB from a supply purchased from ThermShield for evaluation of its effectiveness in various applications.

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