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Radiation Control Coatings Installed on Federal Buildings at Tyndall Air Force Base

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Abstract

The U.S. Department of Energy's (DOE's) Federal Energy Management Program (FEMP) supported this effort to reduce energy use and associated expenses in the federal sector. The effort was a project under the New Technology Demonstration Program (NTDP) to install, operate, monitor, evaluate and make known the results of the demonstration of radiation control coatings manufactured by Thermshield International, Ltd. and installed on federal buildings at Tyndall Air Force Base. The Buildings Technology Center (BTC) at Oak Ridge National Laboratory (ORNL) gathered, analyzed and reported on the data. Two entire roofs at Tyndall AFB and parts of several others at Tyndall AFB and at the BTC were coated.

A monitoring plan was implemented and included pre-coating monitoring at Tyndall AFB. Results from the pre-coating monitoring and from immediately after coating showed a significant reduction in roof surface temperatures and heat fluxes through the roof insulation during sunlit times. The buildings at Tyndall AFB and all the coatings were monitored through two summers after coatings were applied to see effects of weathering on thermal performance. The monitoring equipment was then removed but the coatings remained in place. Solar reflectance is an important performance parameter for coatings. The solar reflectances of the coatings decreased from initial levels of 0.8 down to about 0.7 on smooth surfaces over the 500 days of monitoring. On the rough surfaces of the two entire roofs, the reflectances decreased from 0.55 initially down to about 0.45 at the end of 500 days.

The roofs were insulated with two inches (5.1 cm) of foam insulation. The buildings under the roofs had varying features of construction and operation. Generalizations were sought from roof and whole-building models calibrated to the monitored roofs and buildings at Tyndall AFB. The roof models addressed the effects of roof composition and coating on heat fluxes throughout the roof. They generally showed significant heat flux reductions through the roof decks under the coated roofs compared to the uncoated roofs. The whole-building models showed the effect of the coatings on annual energy use of the buildings, both for cooling and total energy use, as a function of roof composition (especially insulation level), coating (uncoated, fresh coating and weathered coating) and other specific features (for examples, shading by trees and presence of a plenum under the roof). According to the models, on the roof of one building at Tyndall AFB (with few internal loads and little external shading of the roof by trees), the fresh coating saved 7.4% of annual cooling energy and 3.2% of total energy.

Modifications of this building were made in the models and showed progressively more and more energy use as the amount of insulation in the uncoated roof was decreased. In the final case with an uninsulated smooth metal roof and no plenum, annual cooling energy savings with the fresh coating increased to 43%. This case also showed that estimates of energy savings over the lifetime of the coatings should be done with weathered coating solar reflectances; otherwise estimates would be too optimistic (for this case, savings estimates were about 50% higher with fresh coatings compared to weathered coatings). Simple payback times using weathered coating reflectances exceeded the projected coating life of 10 to 15 years except on the uninsulated metal roof. These simple payback times did not address other possible benefits of coatings, such as extending the life of the roof membranes they cover.

Objectives

The technical objectives of this CRADA comprise technology deployment and energy conservation efforts with the radiation control coatings industry and the utility sector. The results of this collaboration include a high-level data reporting, analysis and management system to support the deployment efforts. The technical objectives include successfully install, commission, operate, maintain and document the performance of radiation control coatings on roofs at Tyndall AFB and the Buildings Technology Center at the Oak Ridge National Laboratory; determine the life cycle savings that can be achieved by using radiation control coatings on entire roofs at Tyndall AFB, based on documented installed cost and operating/maintenance costs with and without the coatings; determine if any specific improvements are required in the coatings before they can be successfully deployed in the federal sector; determine the most effective way to facilitate the widespread and rapid deployment of radiation control coatings in the federal sector; and clearly define any barriers to deployment.

Benefits to the Mission of the Funding DOE Office

The mission of the Federal Energy Management Program, which sponsored this project, is to reduce energy use and associated expenses in the federal sector. Federal buildings are located in various climates and are constructed and operated in many ways. The roofs of many of these buildings in cooling dominated climates are potential candidates for application of radiation control coatings. This project collected detailed data on the performance of radiation control coatings in less than ideal circumstances for maximizing the energy savings from the coatings: rough-surfaced roofs with moderate levels of insulation. It has also provided evidence on the performance of the coatings over time sufficient for their solar reflectances to decrease due to weathering effects. The models of the buildings whose roofs were coated under these conditions reflect the effects of the conditions on energy savings. Generalizations of the models to buildings with smooth and rough roof surfaces and various levels of roof insulation show the range of economic benefits from energy savings. Radiation control coatings are not for every roof. This project provides data and procedures to help federal building managers decide if their roof is a viable candidate for a coating.

Technical Discussion

Introduction

A cooperative research and development agreement (CRADA) was formed between Lockheed Martin Energy Research Corporation and Thermshield International, Ltd., in order to install, operate, monitor, evaluate, and report the results of a demonstration of radiation control coatings installed on federal buildings at Tyndall Air Force Base (AFB). Through a submittal to the New Technology Demonstration Program (NTDP) of the Federal Energy Management Program (FEMP) and a favorable economic analysis based on the submittal, Thermshield was selected as the manufacturer of the product to be applied to two entire roofs at Tyndall AFB in Florida. The Buildings Technology Center (BTC) at the Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee, was assigned the lead role for carrying out the demonstration and reporting the results. Lawrence Livermore National Laboratory provided most of the radiation control coatings from a supply purchased from Thermshield.

The CRADA allowed 2 years to monitor the pre-coating performance of roofs at Tyndall AFB and then the performance of the roofs with radiation control coatings as they weathered. For several years, the BTC has been monitoring small areas of roofs covered with various white radiation control coatings. This experience shows that there is a significant decrease in the thermal performance of white radiation control coatings due to weathering during the first 2 years after application. In this study, the Tyndall AFB roofs were coated less than 4 months into the 2-year period of performance of the CRADA. Therefore, the roofs were monitored during most of the critical first summer after coating and all of the equally critical second summer.

This report describes the effects of radiation control coatings installed on the federal buildings at Tyndall AFB and on an outdoor test facility at ORNL. Measurements at Tyndall AFB show the history of outside-surface temperatures for coated and uncoated roof surfaces and solar reflectances of roof surfaces from July 1996 (when the roofs were coated) through October 1997. They are supplemented by solar reflectances for test roof surfaces at the BTC. Roof models based on one-dimensional transient conduction through the Tyndall AFB roofs are used to compare the heat fluxes through the roof decks 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. The DOE2 models were validated by comparisons to whole-building electricity use monitored for the buildings at Tyndall AFB.

Overview of Project

The two buildings selected for monitoring at Tyndall AFB — a convenience store and a veterinary clinic — had low-slope roofs over 2 in. (5.1 cm) thick and 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 built-up roofs (BURs). The convenience store roof is significantly shaded by live oak (encina) trees to the south. The part of this 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 second building, a veterinary clinic, had a heavyweight concrete deck and lightweight concrete over it, in addition to the insulation and the BUR.

Figure 1 shows cross sections of the two roofs and the placement in them of heat flux transducers in the middle of the polyisocyanurate insulation. Three thermocouples, vertically aligned with each heat flux transducer, constituted 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 in an area about 2 ft by 2 ft (0.61 m by 0.61 m) that was 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 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 for two other locations and various coatings are also given in this report. The first additional location, on the roof of a fast-food restaurant at Tyndall AFB, had 2-ft by 2-ft areas where an acrylic elastomeric coating and the ceramic coating used on the BURs were tested side by side. The restaurant roof consisted of about 3 in.

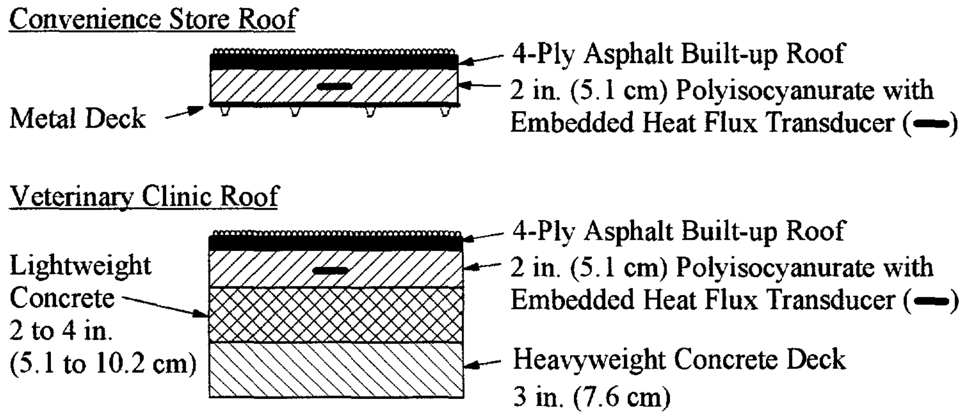

Fig. 1. Cross sections of built-up roofs on the convenience store and the veterinary clinic at Tyndall Air Force Base in Florida.

(7.6 cm) of polyisocyanurate insulation and a plywood deck under a smooth single-ply membrane. The second additional location was an outdoor test facility at ORNL, in East Tennessee. The same coatings used at Tyndall AFB in Florida and two other ceramic coatings were tested at ORNL during the time frame of the Florida project. Only reflectance data from fresh and weathered samples at this location are included.

The temperatures and heat fluxes from the six instrumented areas at Tyndall AFB, 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 1-min scans until these data were retrieved by modem link at one-week to one-month intervals. Personnel from ORNL retrieved the freshly coated membrane samples during a trip to Tyndall AFB in July 1996 to rendezvous with personnel from Thermshield, the ceramic coating manufacturer, to clean up the roofs, apply the coating, and check that the monitoring technology was functioning after the coating was applied. The samples of weathered coatings were retrieved by ORNL personnel during trips to Tyndall AFB in November 1996, March 1997, and November 1997. 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.

We originally planned to continue monitoring at Tyndall AFB for two more summers beyond the period of performance of the CRADA before decommissioning the technology monitoring system. With the coatings in place and the monitoring system functioning, it would have been convenient to get additional data on the effect of weathering beyond the period of performance of this CRADA. However, during the second summer of monitoring we learned that the convenience store was scheduled for extensive renovation within a year. The evidence from two summers showed that a fully weathered value of solar reflectance had been reached on the rough-surfaced roofs at Tyndall AFB. The decision was made to end all monitoring in November 1997.

Measurements of Reflectances and Outside-Surface Temperatures

This project's unique focus was to document the effect of white coatings on the thermal performance of rough-surfaced BURs. 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 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 (SHP, VC, TC2, SOL, TC1, INS). Figure 2 is a graph of some of the data in Table 1 to provide a perspective on the solar reflectances of the samples SHP and VC from the coated rough-surfaced BURs on the convenience store and the veterinary clinic. The solar reflectances of the 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, as Table 1 shows, the fresh values of 0.53 to 0.54 on the rough BURs are 0.45 higher than the reflectances of the uncoated 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). The ceramic coatings on the rough surfaces appear to be fully weathered before 300 days. Smooth curves are shown through the data for SOL; for RH2 and RH3; for TC1, TC2, INS, and RH1; and for VC and SHP, respectively, to aid in estimating a fully weathered value of solar reflectance.

Akbari and associates (1998) used annual energy use models to prepare support material for the June 1997 draft for public comment of revisions to ASHRAE/IES Standard 90.1-1989 (ASHRAE 1989). This draft proposes insulation credits for reflective roofs. Reflective roofs with an 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 a 23% reduction in roof insulation R-value for a reflective roof in cooling-dominated climates. The reflectances displayed in Fig. 2 for the coatings on smooth surfaces (all except VC and SHP) indicate that the proposed weathered value is accurate for coatings TC1, INS, RH1, and possibly TC2. It is conservative for coatings RH3, RH2, and SOL. On the rough BURs, the weathered value is definitely less than 0.55, with large scatter.

No uncoated BUR for reflectance samples was kept on the roofs at Tyndall AFB. 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; hence, the indication in the table that no information was available for fresh $\rho \pm \sigma$ and the question marks for the age when the weathered ρ was measured. 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 1. Solar reflectances of coated and uncoated membranes

Location[a]	Sample	Coated/ Uncoated	Substrate[b]	Fresh ρ ± σ [c]	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	NA	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)

[a] Convenience store, veterinary clinic, and restaurant at Tyndall AFB in Panhandle of Florida; BTC designates outdoor test facility at the Oak Ridge National Laboratory in East Tennessee.

[b] BUR = built-up roof; EPDM = ethylene propylene diene monomer single-ply membrane; APP = atactic polypropylene polymer single-ply membrane.

[c] ρ = solar reflectance; σ = standard deviation of measurements.

Table 2 presents values of monthly average sunlit uncoated and coated surface temperatures for the part of the convenience store with the shaded metal-decked roof and for the veterinary clinic roof (the heavyweight concrete-decked roof). Of primary interest in this project is the benefit of white coatings due to their high solar reflectances compared to uncoated black surfaces. By averaging data during times that the coated and uncoated surfaces are sunlit, the benefit is emphasized and quantified while other climatic conditions, such as wind speed and direction and air temperature, are undergoing normal variations. Nighttime and rainy daytime data are not included in the averages.

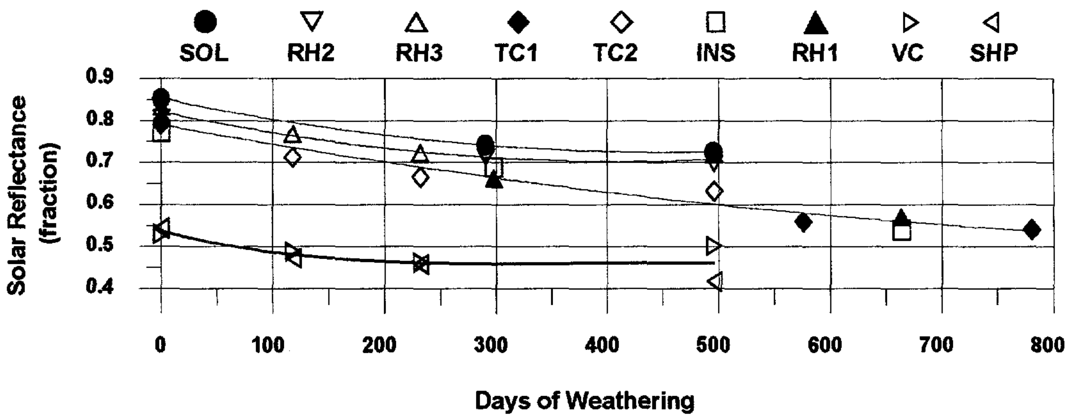

Fig. 2. History of the solar reflectances of various white coatings on smooth and rough surfaces. Samples RH1, 2, and 3 were acrylic elastomeric coatings; the remainder were latex-based with ceramic beads. All the coatings except VC and SHP were on smooth surfaces. See Table 1 for details.

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 a temperature on an uncoated roof to be more than 7.5°F (4.2°C) warmer than the corresponding temperature on a coated roof, the pair of temperatures was included in the sunlit averages 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 the comparability of climatic conditions from month to month.

The data in Table 1 indicate that the reflectances of samples SHP and VC decrease over the duration of the project but remain much greater than those of the uncoated BURs. Thus, the behavior of the average sunlit surface temperatures for the coated and uncoated areas on the veterinary clinic roof that is indicated by the data in Table 2 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 late in the month. The average coated temperatures in August and September 1997 are higher and the percentage decreases lower than during the same months in 1996, a result that is consistent with lower solar reflectance in 1997 than in 1996. The coated temperature for October 1997 is not higher than that in October 1996, but the percentage decrease is consistent with the comparisons in the hotter months of August and September. No data are given for November through April because too few pairs of temperatures met the sunlit criterion.

For the convenience store roof, Table 2 shows comparisons for three summer months in 1996 and 1997. As is expected as white coated roofs weather, the coated surface temperatures in 1997 increase relative to 1996, while the benefits in 1997 decrease relative to 1996. Moreover, the coated surface temperatures are somewhat lower and the benefits are somewhat higher than the respective monthly averages for the veterinary clinic. This is consistent with preferential shading of the coated area at midday

Table 2. Monthly average sunlit temperatures on the convenience store and veterinary clinic roofs[a]

	Shaded roof on convenience store [b]				Heavyweight roof on veterinary clinic [b]			
Month	TOA (°F)	TOS_{UnC} (°F)	TOS_C (°F)	Benefit[c] (%)	TOA (°F)	TOS_{UnC} (°F)	TOS_C (°F)	Benefit[c] (%)
JUL 96	90.8	113.0	95.1	15.8	NA	NA	NA	—
AUG 96	88.2	106.9	91.5	14.4	88.0	115.7	101.7	12.1
SEP 96	86.4	98.4	86.9	11.7	86.5	112.4	98.9	12.0
OCT 96	74.8	82.5	72.2	12.5	74.2	93.2	81.2	12.9
MAR 97	73.2	84.8	74.9	11.7	72.2	92.9	82.2	11.5
APR 97	74.7	99.1	83.7	15.5	72.7	97.8	85.5	12.6
MAY 97	82.1	109.2	93.5	14.4	79.6	109.1	96.6	11.5
JUN 97	87.8	121.0	104.7	13.5	86.0	117.7	105.8	10.1
JUL 97	93.0	124.3	110.1	11.4	90.5	121.6	109.9	9.6
AUG 97	93.5	120.6	104.4	13.4	89.5	118.3	106.6	9.9
SEP 97	87.8	98.5	88.6	10.1	87.4	112.7	100.7	10.6
OCT 97	75.2	85.2	74.8	12.2	74.6	91.0	80.4	11.6

[a] The sunlit criterion for obtaining averages was based on conditions where the temperature of the outside uncoated surface, TOS_{UnC}, exceeded the temperature of the outside coated surface, TOS_C, by more than 7.5°F ($TOS_{UnC} - TOS_C > 7.5°$ F).

[b] Abbreviations: TOA = temperature of outside air; TOS_{UnC} = temperature of outside surface, uncoated; TOS_C = temperature of outside surface, coated.

[c] The percentage benefit of lower surface temperature is computed by $[(TOS_{UnC} - TOS_C)/TOS_{UnC}] \times 100$.

on sunny summer days at the convenience store. The uncoated area was preferentially shaded in mid-afternoon, when solar irradiation was lower.

This preferential shading is illustrated by Fig. 3, which shows hourly temperatures for two similar days in 1996 just before and just after the convenience store roof was coated. Outside-air 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 as a result of coating the roof. The effects of shading on uncoated surface temperatures are apparent in the data for the convenience store roof for August, September, and October 1996 and September and October 1997 (Table 2). These temperatures 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 for 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.

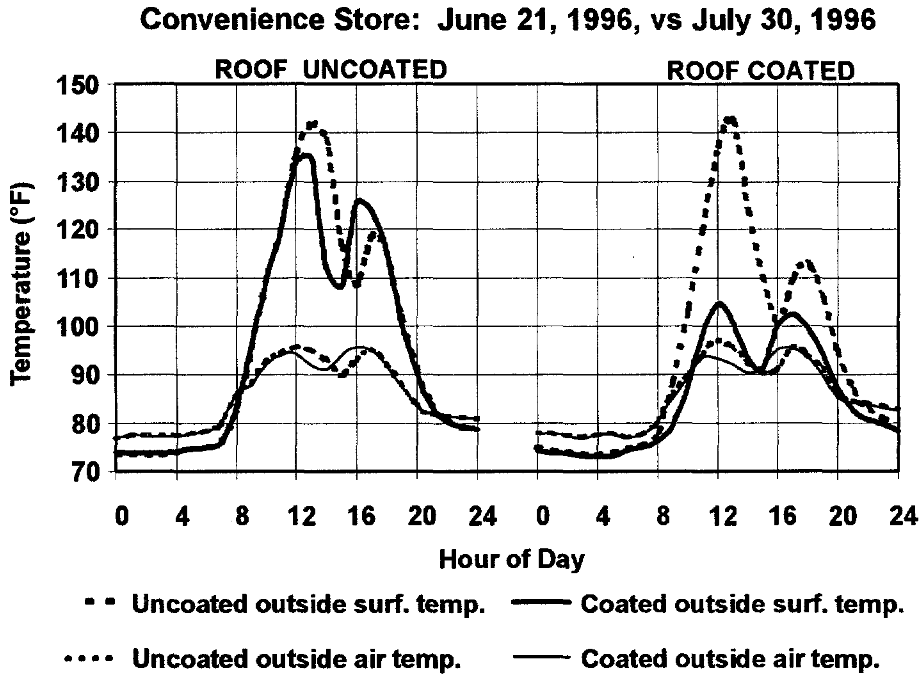

Fig. 3. Hourly outside-air and outside-surface temperatures for the coated and uncoated locations on the convenience store roof for similar sunny days just before and just after the roof was coated.

Table 3 shows monthly average sunlit temperatures on the roof of the fast food restaurant, where there was no low-reflectance surface. Based on observations when data for the veterinary clinic showed sunny days at Tyndall AFB, the sunlit criterion for the restaurant requires a 2.5°F (1.4°C) difference between the coated surface temperatures for samples TC2 and RH3. Throughout the project, air temperatures on the roof of the fast food restaurant were slightly higher than those on the veterinary clinic. The restaurant roof was surrounded by a parapet which 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 shows 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 brush-applied to the smooth fast food restaurant roof itself and to the smooth EPDM substrate used on this roof for the pieces from which samples were cut for reflectance measurements. The ceramic-filled TC2 brushed on much thicker and yielded a rougher surface than the acrylic elastomeric RH3. The differences between the temperatures of RH3 and TC2 increased in July, August, and September 1997 relative to the same months in 1996. In the summer of 1996 the temperatures of both coated surfaces were somewhat lower than those of the coated surfaces on the veterinary clinic. By the summer of 1997 this was true only for coating RH3. The advantage of the smooth-surfaced substrate had disappeared for coating TC2, apparently because it had a rougher surface that encouraged faster weathering than did coating RH3.

Table 3. Monthly average sunlit temperatures of coatings RH3 and TC2 on the roof of the fast food restaurant [a]

Month	TOA (°F)	TOS_{TC2} (°F)	TOS_{RH3} (°F)	Difference[b] (%)
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

[a] The sunlit criterion for obtaining averages was based on conditions where the temperature of the outside surface for sample TC2 (TOS_{TC2}) exceeded the temperature of the outside surface of RH3 (TOS_{RH3}) by more than 2.5°F ($TOS_{TC2} - TOS_{RH3} > 2.5$°F).

Abbreviations: TOA = temperature of outside air; TOS_{TC2} = temperature of outside surface for sample TC2; TOS_{RH3} = temperature of outside surface for sample RH3.

[b] The percentage difference between the temperatures of the two coated surfaces is computed by $[(TOS_{TC2} - TOS_{RH3})/TOS_{TC2}] \times 100$.

Heat Fluxes through Built-Up Roofs

The test protocol for this project included measurement of roof heat fluxes. Heat fluxes through the roof deck can be a good 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 roof and three-quarters of the convenience store roof, however, the heat fluxes through the deck entered an unconditioned plenum space above a drop ceiling. Thus, for these areas, the effect of the roof heat flux on the conditioned interior was more indirect than it was for the exposed metal deck of the storeroom in the convenience store. Moreover, roof heat fluxes are sensitive to the composition of the roof, especially the level of insulation.

To ensure accurate measurement of heat fluxes, the heat flux transducers were calibrated in aged polyisocyanurate insulation and embedded in the middle of the insulation, not on the decks, in all three roofs at Tyndall AFB (Fig. 1). Deck heat fluxes were predicted as described below. Only the results for the BURs are included. Heat fluxes for coatings RH3 and TC2 on the restaurant roof were smaller than for the BURs because of thicker insulation in the restaurant roof. A sunlit criterion was difficult to implement, since there were no large differences between heat fluxes as there were for the coated and uncoated areas of the BURs.

Despite the careful calibration and installation of the heat flux transducers in all roofs, the transducer 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). This program uses the one-dimensional transient heat conduction equation with components and their properties for the roof of the veterinary clinic and boundary conditions from inside-surface and outside-surface temperatures measured at the veterinary clinic. 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 the 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. The plots show measured and predicted heat fluxes for the middle of the insulation (the location of the heat flux transducers), as well as predicted heat fluxes for the deck. The shading of the convenience store roof 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.

STAR was not able to mirror such irregular 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., they overshoot the 4 P.M. peak, and they remain above the measurements the rest of the time. 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

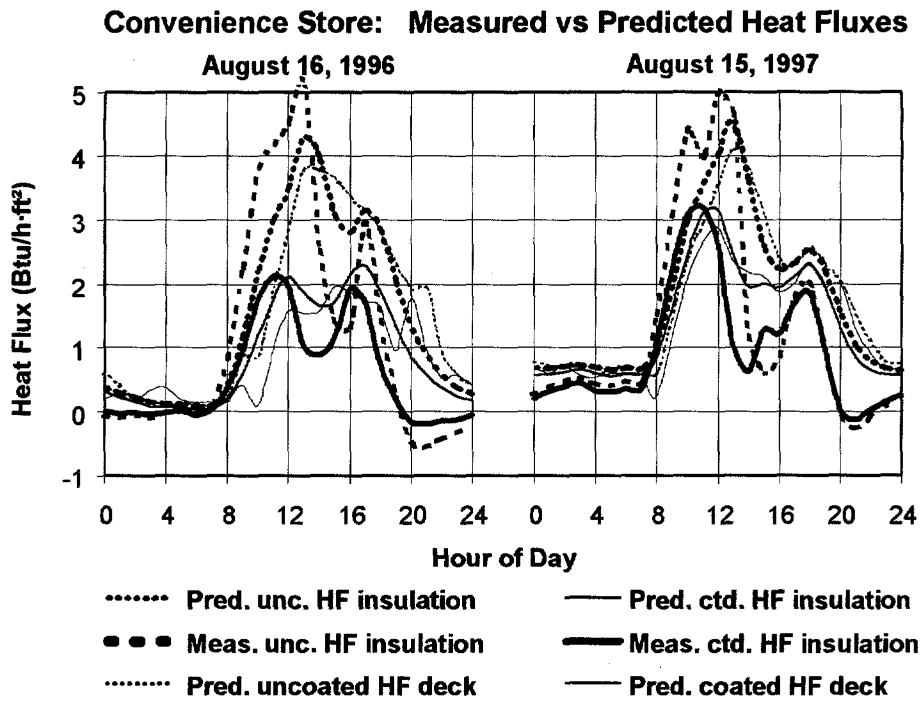

Fig. 4. Hourly measured and predicted heat fluxes for the coated and uncoated locations on the convenience store roof for similar sunny days one year apart.

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, except that measured heat fluxes were not available for the uncoated area because of 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 weathering of the coating. Weathering effects do not seem as severe as on the roof of the convenience store, and this is corroborated by the measurements of solar reflectance at 500 days for the samples VC and SHP shown in Fig. 2. The differences between the predicted coated and uncoated heat fluxes are not as large as for the convenience store either. The discrepancy in the case of the convenience store was due to the enhanced effect of the shading on the coated area of the roof, with preferential shading 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 a year later, the weathered coating has lost this advantage or the climatic conditions are slightly more severe.

To generalize the lessons from Figs. 4 and 5, Tables 4 and 5 present average sunlit roof values for heat fluxes in the same manner as Table 2 did for outside-surface temperatures. Sunlit heat fluxes are

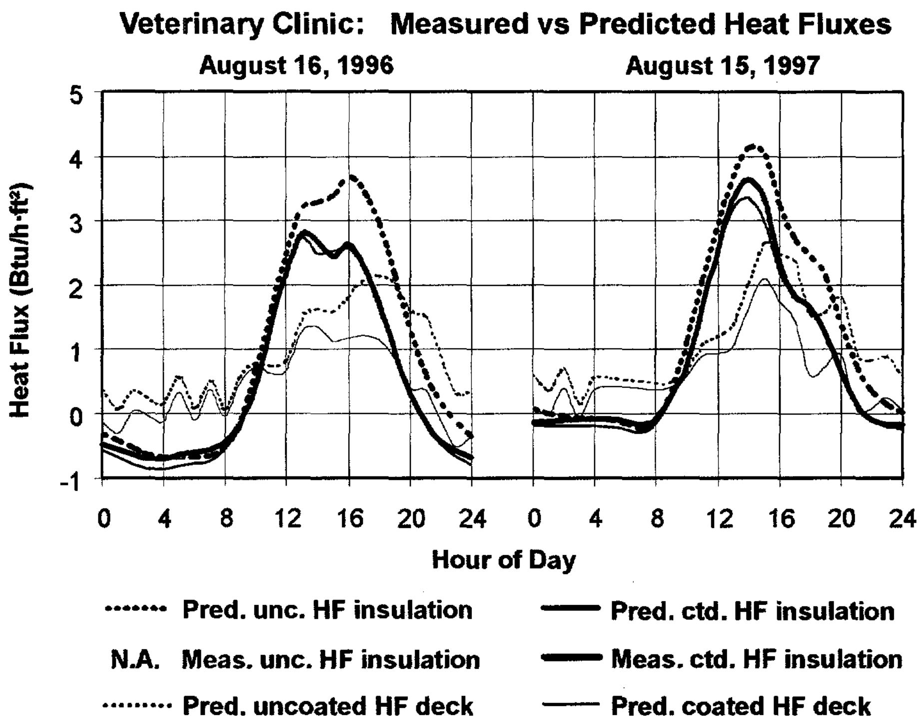

Fig. 5. Hourly measured and predicted heat fluxes for the coated and uncoated locations on the veterinary clinic roof for similar sunny days one year apart.

included in the monthly averages in these tables 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 percentage 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 through September. Hence, for the convenience store on average, the percentage 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 roof temperatures inside the roof during summertime; therefore, percentage decreases for them are larger than for the outside-surface temperatures. The fresh coating shows an average heat flux decrease of 55% in July, August, and September 1996 (Table 4), compared to an average 14% outside-surface temperature decrease for the same months (Table 2). The average heat flux decrease falls off to 44% in July, August, and September 1997, compared to 12% for outside-surface temperatures.

Table 4. Monthly average sunlit heat fluxes for the convenience store roof [a]

Month	Meas. HF_{UnC} insl.	Meas. HF_C insl.	Benefit [b] (%)	Pred. HF_{UnC} insl.	Pred. HF_C insl.	Benefit [b] (%)	Pred. HF_{UnC} deck	Pred. HF_C deck	Benefit [b] (%)
JUL 96	3.23	1.41	56.3	2.97	1.70	42.8	2.82	1.61	42.9
AUG 96	2.70	1.22	54.8	2.52	1.46	42.1	2.41	1.38	42.7
SEP 96	2.14	1.01	52.8	1.99	1.20	39.7	1.96	1.16	40.8
OCT 96	1.42	0.49	65.5	1.16	0.44	62.1	1.17	0.46	60.7
MAR 97	1.45	0.65	55.2	1.25	0.59	52.8	1.17	1.49	58.1
APR 97	2.25	0.94	58.2	2.01	0.95	52.7	1.91	0.83	56.5
MAY 97	2.64	1.30	50.8	2.60	1.49	42.7	2.41	1.31	45.6
JUN 97	3.29	1.87	43.2	3.29	2.18	33.7	2.93	1.92	34.5
JUL 97	3.57	2.10	41.2	3.69	2.66	27.9	3.27	2.28	30.3
AUG 97	3.51	2.00	43.0	3.41	2.30	32.6	3.01	1.97	34.6
SEP 97	2.14	1.13	47.2	1.87	1.18	36.9	1.86	1.17	37.1
OCT 97	1.75	0.78	55.4	1.40	0.68	51.4	1.49	0.77	48.3

[a] The sunlit criterion for obtaining heat flux was based on the coated heat flux being positive ($HF_C > 0$) and on the heat flux through the uncoated roof location exceeding the heat flux through the coated roof location by 0.5 Btu/h·ft² ($HF_{UnC} - HF_C > 0.5$ Btu/h·ft²).

Predicted and measured heat fluxes are in units of Btu/h·ft².

Abbreviations: HF = heat flux; UnC = uncoated; C = coated; NA = not available.

[b] The respective percentage benefits of lower surface temperature on the heat fluxes through the insulation and through the deck are computed by $[(HF_{UnC} - HF_C)/HF_{UnC}] \times 100$.

In the case of 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 in regard to the effect of the roof on the building interior are the heat fluxes through the deck. These are significantly different from heat fluxes through the insulation and yield larger percentage decreases for the effect of the coating. Using the deck predictions, the average decrease in heat flux for August and September 1996 is 51% (Table 5), compared to an average 12% decrease in outside-surface temperatures in August and September 1996 (Table 2). The average heat flux decrease falls off to 47% in August and September 1997, compared to 10% for outside-surface temperatures.

From the perspective of average heat fluxes through the deck during sunlit periods, 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 cannot be interpreted as its direct effect on building heating or cooling loads.

Table 5. Monthly average sunlit heat fluxes for the heavyweight roof on the veterinary clinic[a]

Month	Pred. HF_{UnC} insl.	Pred. HF_C insl.	Benefit[b] (%)	Pred. HF_{UnC} deck	Pred. HF_C deck	Benefit[b] (%)
JUL 96	NA	NA	—	NA	NA	—
AUG 96	2.59	1.63	37.1	1.75	0.87	50.3
SEP 96	2.59	1.65	36.3	1.67	0.81	51.5
OCT 96	2.18	1.32	39.4	1.14	0.42	63.2
MAR 97	1.96	1.23	37.2	1.10	0.44	60.0
APR 97	2.40	1.55	35.4	1.49	0.71	52.3
MAY 97	2.66	1.80	32.3	1.66	0.84	49.4
JUN 97	2.72	1.92	29.4	1.73	0.98	43.4
JUL 97	2.76	1.98	28.3	1.71	0.99	42.1
AUG 97	2.68	1.90	29.1	1.64	0.90	45.1
SEP 97	2.44	1.62	33.6	1.52	0.78	48.7
OCT 97	1.74	0.97	44.3	1.34	0.66	50.7

[a] The sunlit criterion for obtaining heat flux was based on the coated heat flux being positive ($HF_C > 0$) and on the heat flux through the uncoated roof location exceeding the heat flux through the coated roof location by 0.5 Btu/h·ft² ($HF_{UnC} - HF_C > 0.5$ Btu/h·ft²).

Predicted and measured heat fluxes are in units of Btu/h·ft².

Abbreviations: HF = heat flux; UnC = uncoated; C = coated; NA = not available.

[b] The respective percentage benefits of lower surface temperature on the heat fluxes through the insulation and through the deck are computed by $[(HF_{UnC} - HF_C)/HF_{UnC}] \times 100$.

Whole-Building Modeling Using DOE 2.1E

Of particular interest in this NTDP project is the effect of white coatings on the annual cooling energy demand of buildings in the federal sector. The unconditioned plenums under much of the roof of the convenience store and all of the roof of the veterinary clinic make it difficult to extrapolate annual energy impact from the trends shown by the heat fluxes through the roofs in Tables 4 and 5. Even if the effect of the coatings on the annual cooling energy demand of the buildings were obtainable from the heat fluxes in these two tables, 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, we performed annual energy use modeling of the convenience store and the veterinary clinic using the public domain program DOE 2.1 Version E (LBNL 1981, 1993). 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 and its roof with no coating, fresh coating, and weathered coating was then modified to determine the effect of the type of roof and the plenum on the annual energy use. Based on the annual energy use predictions and information about the purchase and installation of the coatings, we generated simple economic payback times for the coated roofs. These simple payback times do not address other possible benefits of coatings besides energy savings, such as extending the life of the membranes they cover.

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. 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 the average power demand of the veterinary clinic building and the average outside-air temperature on its roof was offered as tentative proof that the coating was saving electricity (Petrie, Childs, and Christian 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.

Table 6 presents the complete list of monthly average power demand and outside-air temperatures for the veterinary clinic based on hourly power demands in excess of 1.5 kW. Data for May and June 1996 are included to show months before the veterinary clinic roof was coated. The average outside-air temperatures shown here are slightly different from those for corresponding months in Table 2 because the criteria are different. For example, Table 6 does not include data for any sunny weekend days when the veterinary clinic's HVAC system was not operating at normal occupied thermostat setpoints

The data in Table 6 show an apparent decrease of 13% in average power between June and August 1996, despite a 1.1% increase in average outside-air temperature. The likelihood that this is due to some cause other than the effect of the coating is brought out by comparing data for May and June 1996 (before the roof was coated) with data for May and June 1997 (after about a year of weathering for the coating). Even though in May and June of 1997 the building had the advantages of a coated roof and lower monthly average temperatures, its power demand was higher than for the same two months of 1996. With a slightly

Table 6. Monthly average occupied power and outside-air temperatures for the veterinary clinic[a]

Month	Power (kW)	Outside air temperature (°F)
MAY 96[b]	2.60	84.7
JUN 96[b]	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

weathered coating on the roof, the building used 12% (May) and 14% (June) more average power in 1997 than in 1996, despite a 2.8% (May) and 1.6% (June) decrease in average outside-air temperature in 1997.

Average power demand did increase in August and September 1997 relative to August and September 1996, an expected result as the white coatings weather; but the increase — an average of 14% — 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. For example, both in 1996 and 1997, June was the month of highest electricity use in the veterinary clinic despite milder weather as compared to subsequent summer months.

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 (TMY) climatic data for Apalachicola, Florida, near Tyndall AFB. A successful DOE 2.1E 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 a building like the convenience store, internal equipment usage and the shading of the building. Descriptions of the convenience store and the veterinary clinic follow.

The Convenience Store. The convenience store is a concrete block building with a BUR shaded by large live oak trees to the south. A sketch was drawn of the shading pattern at mid-morning of a clear mid-August day. The shadow cast by the trees covered 27.5% of the roof area. A large 50% transparent rectangle was input into the model to represent the shading and cast a shadow with an area equal to that at the time of the sketch. So much of the convenience store roof is shaded that the instruments were deliberately installed in shaded areas. The original part of the building — about 3060 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-value of 11 h·ft^2·°F/Btu (1.9 m^2·K/W) batts laid on the ceiling tiles. Insulated ducts in the plenum distribute air that is 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 BUR 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 large 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, it 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), store hours were reduced to 9 A.M. to 7 P.M. weekdays and Saturdays and 11 A.M. to 5 P.M. on Sundays. The energy management system at Tyndall AFB adjusted the hours of HVAC system operation in response to the new schedule.

The Veterinary Clinic. The veterinary clinic is a 1500-ft^2 (140-m^2) concrete block building with a BUR over 2 in. (5.1 cm) of polyisocyanurate insulation over 2 to 4 in. (5.1 to 10.2 cm) of insulating concrete with a 2- to 3- in. (5.1- 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 through 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 12:00 noon some Saturdays and is closed most Sundays and holidays. It too is served by the Tyndall AFB energy management system. There is very little electrical equipment in the building: two refrigerators and miscellaneous office equipment. Regular occupancy is limited to one receptionist and one or two veterinarians, in addition to walk-in visitors with pets. The kennels for occasional boarding of pets are outdoors.

To test the accuracy of the DOE 2.1E models of the convenience store and the veterinary clinic, hourly reports were scheduled in the models 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 of 1996 and June, July, August, and September of 1997. The months were selected when power measurements were available and to cover the duration of the project. The week in each month was selected so that the measured outdoor-air temperatures, TOA, for each building approximately matched the dry-bulb temperature, TDB, 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 dry-bulb temperatures in general match the measured outdoor-air temperatures, but the variations in measured power in both buildings still do not exactly match variations in the outside-air temperature. Moreover, measured power use is more erratic than the predicted power use despite considerable effort to match the observed power usage by adjustments in occupancy, lighting, and equipment as well as heating and cooling thermostat setting schedules. Note that the DOE 2.1E model successfully followed the change in schedule starting August 1, 1996, in the convenience store. The hours of non-setback 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 models.

Daytime peaks in power usage 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 caused by the operation of refrigerators and freezers in hot weather. The much lower power demand of the veterinary clinic as well as its being closed on weekends show up clearly in both the measured and predicted power use for the building. Because the nighttime demand is often nearly zero, it was easier to model than the erratic convenience store power demand.

The reflectance (ρ) 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 Fig. 2. To the scale of Fig. 6, the dashed lines for the weathered value deviate little from the solid curves for the fresh value.

The base cases for each building — for an appropriately shaded and freshly coated roof, with a 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 shown in Table 7, 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. Percentage 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 of values.

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, for the veterinary clinic the effects of coating the roof and even of the small shade trees at the south of the clinic have a larger percentage impact for this building. For both buildings the effect of the changes shown in Table 7 cause a misleadingly high percentage 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 veterinary clinic either. The hourly reports showed that peak roof temperatures in mid-August were 6 to 7°F (3.3 to 3.9°C) warmer with the weathered coating on both roofs than with the fresh coating. 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 to 36°F (17 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 probably not noticed in the effects of the change to a shorter schedule just after the convenience store roof was coated. The predicted savings of 7.4% in cooling energy and 3.2% in total energy use for the veterinary clinic are encouraging, although not as much as the misleading 13% saving in occupied power obtained from data in Table 6 for June and August 1996.

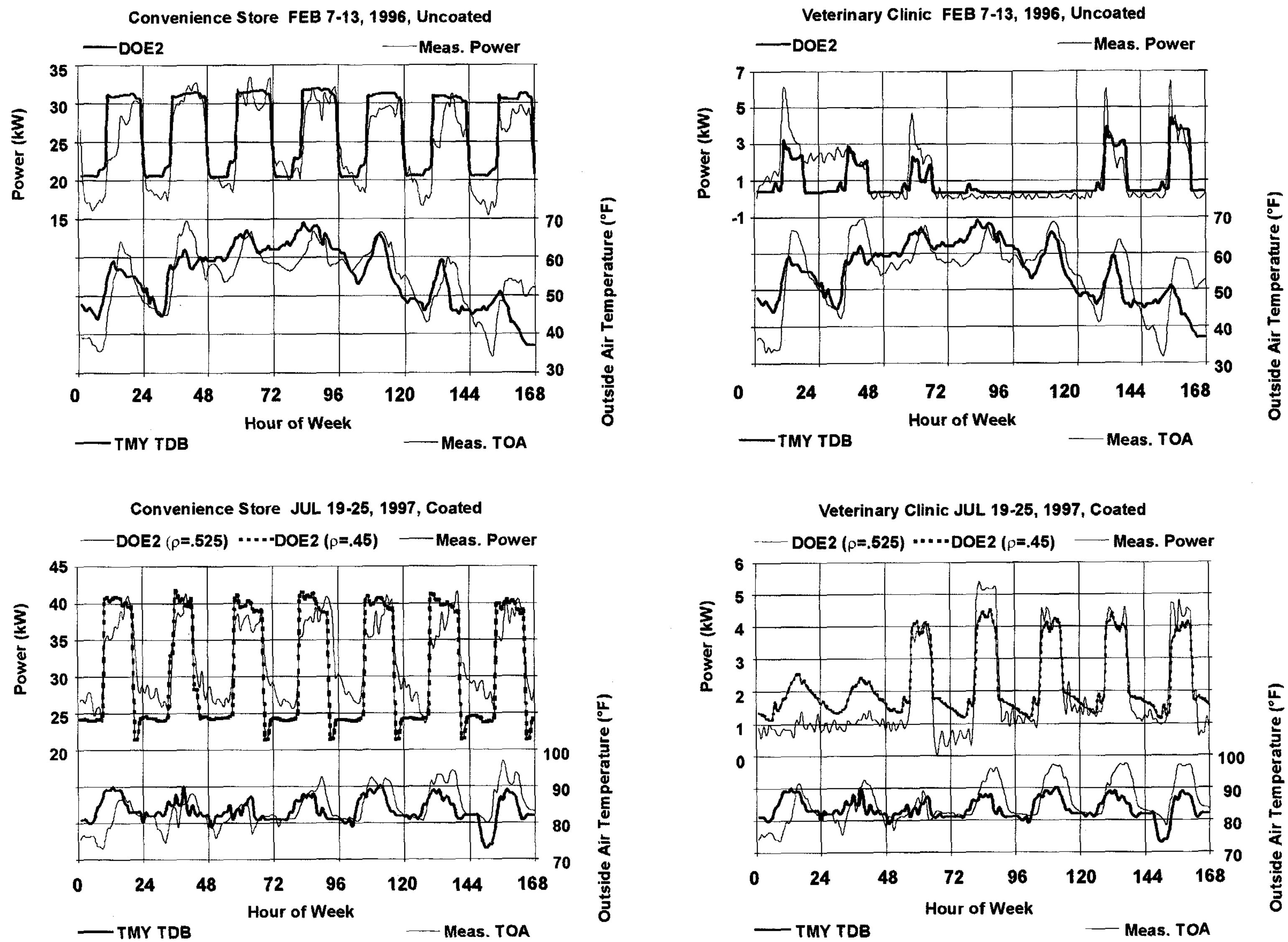

Fig. 6. Comparison between measurements and DOE 2.1E predictions of electrical power for the convenience store and the veterinary clinic for a winter and a summer week during the project.

Table 7. Comparisons of DOE 2.1E predictions for the effects of fresh and weathered coatings and shading on annual energy use in the veterinary clinic and the convenience store [a]

Category	Veterinary Clinic		Convenience Store	
	Annual energy use (kWh)	% change	Annual energy use (kWh)	% 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

[a] Abbreviations: ρ = solar reflectance; FC = fresh coating; WC = weathered coating; NC = no coating; SH = shading; NS = no shading.

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 predicted 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 percentage in 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

The data shown in Table 7 indicate significant savings in cooling energy and total energy for the veterinary clinic with a fresh coating on the roof as 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 mode. It also is despite the unconditioned plenum between the drop ceiling and the roof deck that shields the conditioned space from direct interaction with the roof.

To determine how the thermally massive roof and the plenum might impact energy savings from radiation control coatings, modifications were made to the base case model for the veterinary clinic building. For identification purposes in Table 8 and Fig. 7, the cases are labeled A through F, with the base case being case A.

In the first modification (case B), we substituted the metal-decked BUR with 2 in. (5.1 cm) of polyisocyanurate insulation from the instrumented part of the convenience store roof for the existing veterinary clinic roof in the model. This replaced the massive heavyweight concrete and the light-weight concrete above it with a metal deck. Second, with the less thermally massive metal deck in place, we removed the plenum from the model so that the interior conditioned space was exposed directly to the roof deck (case C). Third, with the plenum removed, we used a smooth metal roof on the veterinary clinic (cases D–F). The thermal mass of this roof is small. DOE 2.1E assumes that it is small and uses its U-value (the inverse of the R-value) to calculate the heat flux. For these so-called "quick" roofs, we used three R-values in cases D through F. For case D, we estimated an R-value of 15.4 $h{\cdot}ft^2{\cdot}°F/Btu$ (2.7 $m^2{\cdot}K/W$) for inside convection in downward heat flow with a nonreflecting surface in series with a thin metal layer and 2 in. (5.1 cm) of polyisocyanurate over a plywood deck 0.5 in. (1.3 cm) thick (ASHRAE 1997). We then decreased the insulation to 1 in. (2.5 cm) in case E, yielding an R-value of 8.4 $h{\cdot}ft^2{\cdot}°F/Btu$ (1.5 $m^2{\cdot}K/W$). Finally, in Case F we modeled an uninsulated metal roof with no plenum. The polyisocyanurate was removed from the insulated metal roof, yielding an R-value of 1.4 $h{\cdot}ft^2{\cdot}°F/Btu$ (0.25 $m^2{\cdot}K/W$). The solar reflectances of the roof surface were adjusted for each R-value to correspond to our experience with freshly coated smooth surfaces ($\rho_{fc} = 0.75$), 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 8 presents the DOE 2.1E predictions of annual energy use by the modified veterinary clinic building. Data for the base case (A) are repeated from Table 7 in the first set of total, cooling, and heating energy uses. Heating energy use is low in the climate of the Florida Panhandle but is included for completeness. All features of the base case were retained in the modifications (cases B–F) except for the changes listed in the heading for each and explained above. The thermally massive roof does not have much impact in the model, judging from the fact that the energy uses and percentage changes due to the coating hardly change at all when a lighter-weight but equally insulated roof is used (case B). For example, the cooling energy savings due to a fresh coating increase only 0.5% — from 7.4% to 7.9% — relative to the base case. 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 accurately modeled.

The absence of a plenum (case C) makes a little more difference in energy savings — for example, another 2% cooling savings to 9.9% due to the coating. The presence of the 2 in. (5.1 cm) of polyisocyanurate seems to prevent greater savings. There is no direct way in DOE 2.1E to model the influence of plenum temperature on the distribution air temperature. It is possible to specify a temperature change for

Table 8. Comparisons of DOE 2.1E predictions for the effects of fresh and weathered coatings on annual energy use for modifications of the veterinary clinic building[a]

A. Base Case (from Table 7)

	Fresh ρ_{FC} = 0.525	Weathered ρ_{WC} = 0.45		Uncoated ρ_{NC} = 0.1		
	Energy	Energy	% change (WC−FC)/WC	Energy	% change (NC−FC)/NC	% change (NC−WC)/NC
Total	10,739	10,806	+0.6	11,095	+3.2	+2.6
Cooling	5,037	5,111	+1.4	5,439	+7.4	+6.0
Heating	1,006	996	−1.0	949	−6.0	−5.0

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

	Fresh ρ_{FC} = 0.525	Weathered ρ_{WC} = 0.45		Uncoated ρ_{NC} = 0.1		
	Energy	Energy	% change (WC−FC)/WC	Energy	% change (NC−FC)/NC	% 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

C. Convenience store metal-decked BUR and no plenum

	Fresh ρ_{FC} = 0.525	Weathered ρ_{WC} = 0.45		Uncoated ρ_{NC} = 0.1		
	Energy	Energy	% change (WC−FC)/WC	Energy	% change (NC−FC)/NC	% 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

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

	Fresh ρ_{FC} = 0.75	Weathered ρ_{WC} = 0.525		Uncoated ρ_{NC} = 0.2		
	Energy	Energy	% change (WC−FC)/WC	Energy	% change (NC−FC)/NC	% 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

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

	Fresh ρ_{FC} = 0.75	Weathered ρ_{WC} = 0.525		Uncoated ρ_{NC} = 0.2		
	Energy	Energy	% change (WC−FC)/WC	Energy	% change (NC−FC)/NC	% 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

Table 8 (continued)

F. Smooth metal roof with no foam insulation ($R = 1.4\ h{\cdot}ft^2{\cdot}°F/Btu$) and no plenum

	Fresh $\rho_{FC} = 0.75$	Weathered $\rho_{WC} = 0.525$		Uncoated $\rho_{NC} = 0.2$		
					% change	
	Energy	Energy	% change (WC−FC)/WC	Energy	(NC−FC)/NC	(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

[a] Energy use in kilowatt-hours.

[a] Abbreviations: ρ = solar reflectance; FC = fresh coating; WC = weathered coating; NC = no coating; SH = shading; NS = no shading.

the distribution air, but we did not measure any duct conditions to justify a specification other than the default. Hence, the effect of the plenum on building energy use is probably underestimated by DOE 2.1E. Parker and associates (1998) modified DOE 2.1E source code to reflect the significant effect, shown in their measurements, of reflective roof coatings on conditions for ducts in plenums under uninsulated roofs.

The smooth roof cases (D–F) show more significant energy savings. For smooth roofs with 2 in. (5.1 cm) of polyisocyanurate insulation, 1 in. (2.5 cm) of insulation, and no insulation, the cooling energy savings for the freshly coated cases relative to the corresponding uncoated cases are 13%, 21%, and 43%, respectively. The differences in solar reflectances between the freshly coated and uncoated cases are slightly greater for the smooth roofs (cases D–F) than for the rough BURs (cases A–C). For the smooth roofs, the freshly coated solar reflectance is 0.75, as compared with an uncoated value of 0.20. For the rough BURs, the freshly coated solar reflectance is 0.525, compared with an uncoated value of 0.10. Hence, the smooth roof with 2 in. (5.1 cm) of insulation but without a plenum (case D) slightly outperforms the rough roof with 2-in. insulation and no plenum (case C). However, 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 equal to those of fresh white coatings (Sparrow and Cess 1970).

The estimates of energy use with the uncoated roofs also are compared to uses with the weathered coating (Table 8, last column). Over the range of solar reflectances shown in the table, the total energy use and the cooling energy vary approximately linearly with solar reflectances. For example, for the metal roofs in cases D–F, the reflectance assumed for the weathered coating yields 60% of the improvement that the fresh coating yields. For cases D and E (2-in. and 1-in. insulation, respectively) the total and cooling savings with a weathered coating are 57 to 59% of the savings with a fresh coating. For the uninsulated cases, the dependence on reflectance is less linear, and the energy savings with the weathered coating are 53 to 54% of the savings with the fresh coating. As was shown in Fig. 2, 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 10 years, the coating is in a weathered condition for more than 80% of the time it is on the roof. The data for metal roofs in Table 8 show that weathered values of solar reflectance should be used for economic decisions based on performance over the lifetime of the coating to avoid overly optimistic estimates of energy savings. This was the approach taken in establishing the credit for reflective roofs against additional insulation in the proposed revision of ASHRAE/IES Standard 90.1 (Akbari et al. 1998).

Economic Payback of Coated Roofs

The total annual energy use savings for the weathered coating compared to energy use with an uncoated roof for cases A through F in Table 8 were used to generate simple payback times. An additional case, C′, as described below, was included in order to compare savings for the fresh coating to an uncoated condition for the rough-surfaced BUR without a plenum. The differences between the total energy uses for the uncoated roof surface and the weathered (and one fresh) coating were multiplied by \$0.075 per KWh (the average price of electricity at Tyndall AFB during the project) and divided by 1500 ft^2 (the size of the veterinary clinic roof) to yield savings per square foot per year. Quantities per square foot can be multiplied by 10.76 to convert to the same quantities per square meter.

Experience from coating the rough-surfaced BURs at Tyndall AFB showed that coverage was only 40 ft^2/gal (1.0 m^2/L), compared to the manufacturer's experience of 60 ft^2/gal (1.5 m^2/L) on smooth surfaces. It took four people 12 hours to clean up and apply the coating to 5725 ft^2 (530 m^2) of rough-surfaced BUR area. If the roofs had been smooth, it is estimated that only 8 hours would have been needed. With labor costs estimated at \$25 per hour and the coating cost at \$166.95 per 5-gal (510-L) container, installation cost is figured to be \$1.05/ft^2 for the rough surface (cases A through C′) and \$0.70/ft^2 for the smooth surface (cases D through F). These costs are divided by the savings per square foot per year to yield the simple payback times shown in Fig. 7.

Case C′ is for the freshly coated rough-surfaced BUR ($\rho = 0.525$) with 2 in. (5.1 cm) of polyisocyanurate foam insulation but no plenum. Case D is for the weathered coating on the smooth-surfaced metal roof ($\rho = 0.525$) with 2 in. (5.1 cm) of foam insulation but no plenum. Since the foam insulation thicknesses and surface solar reflectances are equal for cases C′ and D, it is reasonable that the payback times are approximately equal. The BUR in case C′ adds a little insulation value and thermal mass, making for a slightly longer payback time. For the electricity costs and climate of the Florida Panhandle, only case F, with the weathered coating on the uninsulated metal roof and no plenum, shows a payback time that is less than the nominal service life of 10 to 15 years for a coating. Installation of a radiation control coating on anything but a poorly insulated smooth surface is difficult to justify on the basis of savings in energy costs alone. Figure 7 does not include any effects of other possible savings due to coatings, such as possible extension of the service life of the roof before replacement or re-cover.

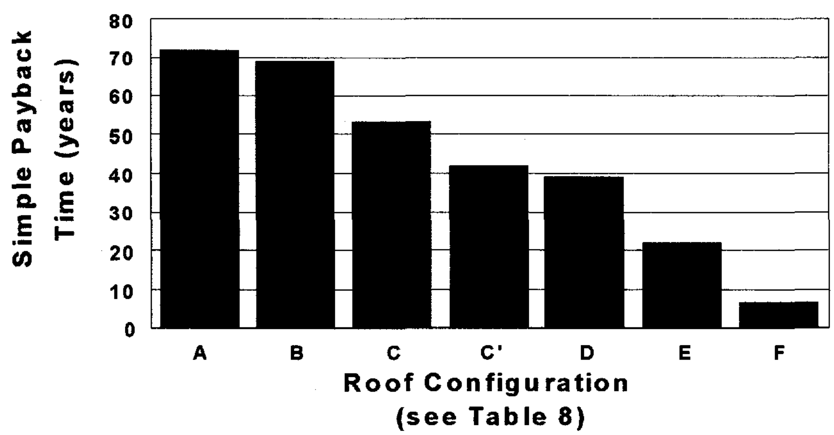

Fig. 7. Simple payback times for the roof configurations on the modified veterinary clinic building.

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Inventions

No inventions were made or reported during the conduct of this project.

Commercialization Possibilities

The technology demonstrated in this project is commercially available and can be applied to all manner of roof surfaces. Whether or not it should be applied to a particular roof is a decision best made on a case-by-case basis.

Plans for Future Collaboration

No future collaboration with Thermshield International, Ltd., is anticipated as an outgrowth of this project. A more comprehensive project is underway to study the long term thermal performance of radiation control coatings on smooth, low-slope roof surfaces. It collaborates with the Roof Coatings Manufacturers Association and several other individual manufacturers, but does not involve Thermshield International.

Conclusions

Support from the federal New Technology Demonstration Program (NTDP) allowed us to determine the effect of radiation control coatings on two rough-surfaced roofs at Tyndall AFB in the Florida Panhandle. One of the roofs, over a convenience store, was significantly shaded by large live oak trees. The other, over a veterinary clinic, had a thermally massive deck of heavyweight concrete.

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 (Table C1). 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.

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, we compared results from a one-dimensional transient heat conduction program, using measured inside-surface and outside-surface temperatures as boundary conditions, 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 (Table C2). Values are larger because the heat fluxes are the result of temperature differences.

Table C1. Average decreases (%) in sunlit temperatures of coated roofs, August–October 1996 and 1997

Monthly temp. decrease	Shaded roof	Heavy roof
Aug. 1996	14.4	12.1
Sept. 1996	11.7	12.0
Oct. 1996	12.5	12.9
Av. 1996	*12.9*	*12.3*
Aug. 1997	13.4	9.9
Sept. 1997	10.1	10.6
Oct. 1997	12.2	11.6
Av. 1997	*11.9*	*10.7*

Table C2. Average decreases (%) in heat flux through decks of coated roofs, August–October 1996 and 1997

Monthly heat flux decrease	Shaded roof	Heavy roof
Aug. 1996	55	50
Sept. 1996	53	52
Oct. 1996	66	63
Av. 1996	*58*	*55*
Aug. 1997	43	45
Sept. 1997	47	49
Oct. 1997	55	51
Av. 1997	*48*	*48*

Although the solar reflectances for white coatings on the rough-surfaced BURs did not increase as much as for white coatings on smooth surfaces, the increase was still significant. With weathered coatings, relative to uncoated BURs, temperatures of the roof surfaces and heat fluxes through the roof decks were decreased by over 10% and 45%, respectively, during sunlit periods. Fresh coatings performed slightly better, with temperature decreases over 12% and deck heat flux decreases over 55%.

An unconditioned plenum under the veterinary clinic roof and under three-fourths of the convenience store roof prevents us from directly interpreting deck heat flux decreases as decreases in building cooling load. To produce data for decreases in building cooling load, we constructed whole-building DOE 2.1E models with the architectural details and operational features of each building. These models were subjected to Typical Metereological Year (TMY) climatic data for Apalachicola, Florida, near Tyndall AFB. Model accuracy was verified by comparing measured and predicted building power for 8 weeks throughout the project when air temperatures measured above the roofs approximately matched the TMY dry bulb temperatures.

The convenience store with the shaded roof had very high internal loads. The shading and the coating were equally effective in decreasing cooling and total load (Table C3), but neither had a very great effect because of the building's internal loads. The heating percentage increases are large because of the small amount of heat required by buildings in the Florida Panhandle.

The veterinary clinic with the heavyweight concrete-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 (Table C3).

Table C3. Effects on annual energy use of shading and coating of roof (% change)

	Formula[a]	Total	Cooling	Heating
Shaded roof				
Effect of shading on coated roof	[(UnS − S) / UnS] × 100	+0.08	+0.9	−7.8
Effect of coating on shaded roof	[(UnC − C) / UnC] × 100	+0.08	+0.8	−6.3
Heavy roof				
Effect of coating on slightly shaded roof	[(UnC − C) / UnC] × 100	3.2	+7.4	−6.0

[a] UnS = unshaded, S = shaded, UnC = uncoated, C = coated.

Within the limits of DOE 2.1E for handling thermally massive components and plenums, additional modeling was done for the veterinary clinic to study the effect of the roof surface, the insulation level, and the plenum, holding all other features in the model constant. These data for annual energy savings were combined with data for installing the coatings to yield annual savings in energy costs, installation costs, and simple payback times.

In the modeling the thermally massive roof deck was replaced by a lightweight deck. Then the plenum was removed. Without a plenum, a smooth-surfaced metal roof was postulated and its foam insulation was decreased from 2 in. (5.1 cm) to none. The fresh coating on the thermally massive veterinary clinic roof saved 7.4% annual cooling energy without modifications. The modifications showed progressively more and more annual cooling energy use as the effective amount of insulation in the uncoated roof decreased. Percentage savings with the fresh coating increased to 43% in the final case with the 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 solar reflectances for weathered coating. Otherwise, estimates of savings due to improved thermal performance will be overly optimistic (for this case, estimates of savings due only to improved thermal performance were about 50% too optimistic). Using weathered coating reflectances, simple payback times exceeded the projected coating life of 10 to 15 years except in the case of the uninsulated metal roof.

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