CONF-980123--1

Radiation Control Coatings Installed on Rough-Surfaced Built-up Roofs — Initial Results

Thomas W. Petrie, Ph.D.
Phillip W. Childs
Jeffrey E. Christian
Energy Division
Oak Ridge National Laboratory

To be presented and published in the
ASHRAE Symposium Transactions
being held in San Francisco, California
January 1998

Research sponsored by
the Office of Building Technologies and
Department of Energy

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under contract No. DE-AC05-96OR22464

DISCLAIMER

Radiation Control Coatings Installed on Rough-Surfaced Built-up Roofs -- Initial Results

Thomas W. Petrie, Ph.D.
Member ASHRAE

Phillip W. Childs

Jeffrey E. Christian
Member ASHRAE

ABSTRACT

We have tracked the solar reflectance and thermal performance of small samples of various radiation control coatings on smooth surfaces for several years on a roof test facility in East Tennessee. The focus is on white coatings because of their potential to weather, causing the solar reflectance to decrease as the coatings age. Support of the federal New Technology Demonstration Program allowed us to extend our study to more small samples on smooth surfaces and entire rough-surfaced roofs at a federal facility in the Panhandle of Florida. Two rough-surfaced, moderately well-insulated, low solar reflectance built-up roofs (BURs) were spray-coated with a latex-based product with ceramic beads added to improve solar reflectance. Only a small patch was left uncoated on each BUR to gather data throughout the project on the performance with no coating for direct comparison to data from instrumented coated areas.

Because of the roughness of the gravel-topped BURs, solar reflectances for the fresh ceramic coatings on them were only 0.53. Reflectances of fresh ceramic and acrylic elastomeric coatings on smooth surfaces we are studying measured 0.23 to 0.32 higher. Weathered samples from our ongoing tests have measured solar reflectances about the same to 0.10 higher than the fresh ceramic coatings on the rough BURs.

In the first three months after installation, the fresh BUR coatings showed a significant decrease in both the outside-surface temperature and the heat flux through the roof insulation. Average sunlit values were generated to exclude nighttime data, data on cloudy days, and data when the uncoated patch on one roof was more strongly shaded in mid-afternoon on sunny days. Contributions from times in early afternoon when the instrumented coated area was more strongly shaded enhanced the apparent performance of the coating. The area with the effect of shading showed a 15% decrease in the average sunlit temperature; for the other roof, with no shading of the instrumented areas but a thermally massive roof deck, the decrease was 11%. Decreases in the average sunlit heat flux were larger: 55% and 36%, respectively. By contrast, during the same time period the sunlit averages for higher solar reflectance, fresh coatings on uninsulated roofs on our test facility in East Tennessee showed 26-28% decreases in outside-surface temperatures and 77-78% decreases in heat fluxes through the plywood roof decks.

The average power demand during occupied periods for the first month with the coating for the building with the thermally massive roof deck was 13% less than during the previous month without the coating. For the other building with a lightweight roof deck but high internal loads there were no clear average power savings due to the coating. We are continuing to monitor electricity use in these all-electric buildings to calibrate a model for the peak power and annual energy use of the buildings. Modeling results to be given at the end of the two year project will address the effect of roof R-value, geographic location, and solar reflectance, including the effect of weathering, on the performance of coated roofs. The calibrated models should allow us to segregate site-specific effects such as shading and large thermal mass.

KEYWORDS

Radiation Control Coatings; Built-up Roof; Weathering; Solar Reflectance

INTRODUCTION

In dealing with the heat load on buildings caused by solar irradiation of the exterior envelope, radiation control coatings are fundamentally appealing. They reflect a large fraction of the solar irradiation away before it is absorbed in the exterior surface of the envelope. They mitigate the need to retard the rate of heat transfer through the envelope by use of insulating materials or radiation barriers. They also lessen the degradation of envelope materials caused by high temperatures and thermal stresses.

Since radiation control coatings offer front line defense against effects of solar irradiation on the cooling load of buildings, it is not surprising that research, development and marketing efforts for them have been considerable. A large number of suppliers offer radiation control coatings for commercial and residential applications. This paper reports primarily on results from a project sponsored by the New Technology Demonstration Program (NTDP) of the Federal Energy Management Program (FEMP). One manufacturer of a radiation control coating made a technology submittal to the NTDP and was selected to cooperate with a U.S. national laboratory in a two-year demonstration of their coating on two roofs at a federal facility in northern Florida.

The objective of the project is to gather data over a long enough period to include the effects of decreased solar reflectance due to weathering and, by modeling, to extend the measurements to the range of conditions of interest to federal building managers who are considering radiation control coatings as an energy saving technology. Reagan and Acklam (1979) did early work on quantifying the solar reflectance of common building materials. Griggs and Courville (1989) used Reagan and Acklam's data and modeling of typical buildings in various U.S. climates to compare annual cooling energy requirements of high solar reflectance vs. low solar reflectance roofs. They found that coated roofs saved significant cooling energy but they did not account for effects of decreased solar reflectance due to weathering.

Other efforts to demonstrate the energy saving potential of radiation control coatings applied to roofs of residential and commercial buildings have been undertaken in Florida's climate (Parker, et al. 1995; Parker et al. 1996). Similar demonstrations are ongoing in California and New Mexico (Akbari, et al. 1992; Rosenfeld, et al. 1995). Support for the work of Akbari, et al., and Rosenfeld, et al., and partial support for the work of Parker, et al., is the Heat Island Project. The Heat Island Project seeks widespread adoption of both building- and city-scale measures, such as surfaces with higher solar reflectance than conventional surfaces and more shade trees, which mitigate the higher air temperatures on clear summer afternoons around typical cities compared to surrounding rural areas.

Our study complements these ongoing efforts. It builds on long-term field studies and radiative property measurements begun by Griggs and Shipp (1988) and continued by Anderson, et al. (1991) and Byerley and Christian (1992) that involved solar reflectance and thermal performance measurements for a 4 ft x 4 ft (1.2 m x 1.2 m) uncoated single-ply rubber membrane and an identical piece coated by a white latex coating. Byerley and Christian documented weathering effects on reflectance from more than three years of field exposure. Slight improvements in reflectance were seen by washing the weathered surfaces.

In our project involving entire roofs, whole building energy use is monitored to provide data on the overall effect of coating entire roofs. For details about the roof itself, two techniques are adopted from the work of Byerley and Christian, not only for their own merits, but to provide data similar to our ongoing work at our roof test facility in East Tennessee. One technique is to do simultaneous measurement of the thermal performance of coated and uncoated areas of the same roofs throughout the project. The other technique is to prepare a piece of loose roof membrane and coat it along with the rest of the roof. This extra piece is kept on the roof away from the instrumented areas so its coating weathers along with the coating on the roof. Despite the double thickness of membrane due to the loose piece, the small size of the loose membrane makes negligible the effect of the different thermal performance through it on whole building energy use. The different thermal performance is assumed not to affect the weathering, which is thought to be dominated by air-borne particles accumulating on the coating. Samples from the loose piece are cut off it periodically and sent to a laboratory where measurement of the possibly changing solar reflectance is made.

This paper is being written after the first summer of the demonstration project, before the modeling effort is underway. It will show results before the roofs were coated to establish the monitoring protocol. The installation of the coatings is described to document the effort needed to coat the roofs. Results with coatings on various membranes are then compared to those without coatings. More details are available in Petrie and Childs (1997).

PROJECT GOALS AND MONITORING PROTOCOL

Savings in energy required to cool a building are a primary benefit of radiation control coatings. The focus in this project is on measurements with two different types of white coatings because of the potentially severe effects of weathering on their initially high solar reflectances. We are seeking to evaluate the potential savings in cooling energy costs over the life of radiation control coatings installed on buildings in the federal sector with low-slope roofs. Potential savings due to extension of the service life of the roof are not addressed. Such savings are claimed because coatings seal roofs against leaks and allow the roof to operate cooler.

Buildings at a federal facility in the Panhandle of Florida were chosen for detailed monitoring because of the high cooling load of buildings in that area. The extent of the monitoring included the thermal performance of three low-slope roofs to which coatings were applied. Two were almost entirely coated; the third building had only small patches of its roof coated. Kilowatt-hour meters were installed to monitor the electrical energy used by the all-electric buildings under the two coated roofs.

For roof thermal performance, heat flow through the roof as a function of inside- and outside-surface temperatures is needed. We measured outdoor-air temperatures, too, in order to relate to the typical meteorological year (TMY) weather data near the site. TMY data will be used for whole building peak power and annual energy use modeling. Outdoor-air, outside-surface and inside-surface thermocouples and a heat-flux transducer imbedded in the middle of the insulation were used as instrumentation for each coated or uncoated area of interest. Measurement of the solar reflectance as a function of time also provides essential input for computer models to predict the measured roof performance and generalize it to other situations.

Thermal characteristics of low-slope roof systems do not usually vary significantly over the area installed on a particular building. Therefore, for this demonstration, two locations were chosen for thermal measurements on each of the three roofs. The locations were away from the edges of each roof and clear of local disturbances, such as penetrations for rooftop equipment. For the buildings with whole building energy monitors, to obtain an ongoing measure of roof performance, a small area was left uncoated as a control surface throughout the demonstration. On the third building, two small areas were coated with two different white coatings.

The size of the small areas is 2 ft x 2 ft (0.6 m x 0.6 m). The claim is that this area is sufficiently large that measurements in the middle of this area reflect one-dimensional heat transfer conditions. The 1-D assumption fails most severely at the boundary between an uncoated patch and a surrounding coated area, but becomes accurate away from the boundary. Using the thermal conduction equation, we estimated the steady-state heat flow at the mid-plane of the 2 in.

(5.1 cm) thick insulation in the metal-decked roof of one of the buildings whose roof was almost entirely coated. At the boundary between the uncoated patch and the rest of the coated roof, the vertical heat flux was halfway between the uncoated and coated heat fluxes at locations 1 ft (30.5 cm) away. The horizontal heat flux, in the uncoated to coated direction, was 33% of the vertical heat flux there. At 2.0 in. (5.1 cm) from the boundary in the uncoated patch, the vertical heat flux had increased to the one-dimensional uncoated heat flux. The horizontal heat flux was 2.3% of the one-dimensional value. Already at 3.0 in. (7.6 cm), the horizontal heat flux had diminished to less than 0.5% of the vertical heat flux, and one-dimensional heat flow was achieved. We are confident that, even in the middle of the uncoated patches and therefore for all the instrumented areas, the heat flux measurement is not affected by edge effects and the 1-D calibration performed for the heat flux transducers is applicable.

Our experience has shown that the solar reflectance of white-coated surfaces changes as the coatings weather. We prefer laboratory techniques to in-situ techniques for measuring the solar reflectance of roofs. Samples of roofs that are covered by weathered coatings must be removed periodically from the roofs to use a laboratory-based technique, but remain available for checks of their solar reflectance against that of future samples. In this project, to ensure that the samples were coated like the rest of the roofs, pieces of the same type of roof as those available for coating were secured from a roof tear-off and replacement project at the facility. Approximately 2 ft × 2 ft (0.6 m × 0.6 m) areas were stripped of adhered insulation and laid over one of the instrumented locations on each roof. Not only did this process ensure that the pieces were coated in the same way as the rest of the roof, but it also left behind the desired instrumented uncoated patch.

Figure 1 shows a coated piece that is to be used for solar reflectance samples on one of the roofs after the piece has been moved away from the area that lay under it during the coating process and became the instrumented uncoated patch. The instrumented location in the coated area is not visible in Fig. 1; it is as far to the left of the piece for samples as the uncoated patch is to its right. Paver blocks, 1 ft × 1 ft × 2 in. thick (0.3 m × 0.3 m × 5.1 cm thick), mark a walkway to the coated piece and provide perspective. A corner of the coated piece has already been cut off for a sample of the freshly coated surface.

The two types of white coatings focused on in this project are products with ceramic beads added to increase solar reflectance and acrylic elastomeric products with titanium dioxide added to increase solar reflectance. A ceramic coating was selected (see the Acknowledgments) for covering almost entirely the roofs of two buildings, a convenience store and a veterinary clinic. One patch on the roof of a third building at the facility, a fast food restaurant, was coated with this ceramic coating and another patch with an acrylic elastomeric coating.

The two buildings that received the ceramic coating have four-ply asphalt built-up roofs (BURs) with about 0.5 in. (1.3 cm) diameter gravel imbedded in the bituminous topping, a common roof system on federal buildings but not one ideally suited for radiation control coatings because of its roughness. Solar reflectance is better on smooth coated surfaces. Even though spray techniques can apply coatings uniformly to rough-surfaced roofs, the protruding particles tend to absorb more of the initially reflected radiation. Cross sections of the instrumented parts of the roofs of the buildings are shown in Fig. 2. The veterinary clinic roof has 2 in. (5.1 cm) of polyisocyanurate insulation over 2 to 4 in. (5.1 to 10.2 cm) of lightweight concrete, yielding an R-value of 12–13 $h{\cdot}ft^2{\cdot}°F/Btu$ (2.1–2.3 $m^2{\cdot}K/W$) (ASHRAE 1993). The deck is 3 in. (7.6 cm) of heavyweight concrete and is expected to delay the effect on this building of roof solar load to times later in the day than buildings with lightweight roofs like the convenience store. There is also a delay between the heat flux through the bottom of the concrete deck and the heat flux through the middle of the insulation on top of the concrete deck for the veterinary clinic.

The convenience store roof is extensively shaded by live oak trees. The shading effect is seen in Fig. 1 at the bottom of the photograph. The trees preferentially shade the instrumented coated area in the early afternoon and the area that was left uncoated in mid-afternoon. Given the extent of roof shading by the live oak trees, the decision was made to locate the instruments in areas with variable shading, near the south edge of the roof. The effect of shading could then be compared to the effect of the coating. Like the veterinary clinic roof, the convenience store roof in the instrumented locations has 2 in. (5.1 cm) of polyisocyanurate insulation.

The third building, the fast food restaurant, already had a smooth-surfaced, single-ply white membrane on its roof. Its smooth surface allowed two patches to be brush-coated with the ceramic and acrylic elastomeric coatings. Small extra pieces of white single-ply membrane were coated similarly and secured with paver blocks next to the coated patches on this roof to weather like the in-situ patches whose thermal performances are being monitored to directly compare the two types of white coatings. The fast food restaurant roof has 4 in. (10.2 cm) of polyisocyanurate insulation with R-value of about 22 $h{\cdot}ft^2{\cdot}°F/Btu$ (3.9 $m^2{\cdot}K/W$). Its plywood deck adds no significant thermal mass.

Modeling will be attempted for only the two buildings whose roofs were almost entirely coated. A simple approach was chosen to monitor the energy use in the buildings: a single pulse-initiating kilowatt-hour meter for monitoring the whole-building electricity use of each building. The buildings that ultimately became available with roofs that could be penetrated to install instrumentation for the demonstration are less suited to this simple approach than those available when the monitoring plans were formulated. Funds were not available for additional instrumentation. Two unshaded small buildings with approximately R-12 $h{\cdot}ft^2{\cdot}°F/Btu$ (2.1 $m^2{\cdot}K/W$) roof insulation and regular operating schedules were initially chosen for almost completely coated roofs. Hurricane Opal damaged their roofs, and the roofs were replaced and made unavailable for our project's instrumentation needs.

The veterinary clinic was chosen as one alternative. It is a small building with a moderately well insulated roof, a mostly weekday only operating schedule, but little internal load. Even the kennels are outdoors. It is heated and cooled by an electric heat pump. A single electric power monitor is adequate for it. The only other building available and deemed suitable for the project was the convenience store. It is a medium-sized building with a moderately well insulated roof, a 7-day-per-week schedule, but a significant internal load from refrigerators and freezers. The store itself is cooled by direct expansion coils in insulated supply ducts below the wood-decked roof and above a drop ceiling. Heating is by electric resistance coils in the supply ducts. The uninsulated return plenum is also above the ceiling. Fiberglass batt insulation is laid on top of the ceiling tiles. The instrumented locations in the convenience store were in the metal-decked insulated roof over a storeroom without a drop ceiling and open to the back of the store. The storeroom is cooled and heated by a through-the-wall electric heat pump. There are so many pieces of internal equipment, with several outside condensers and compressors to serve them, that submetering the equipment in the convenience store would be very expensive.

The two pulse-initiating kilowatt-hour meters were put in place early in the project. We have over six months of hourly whole building electricity use data from the veterinary clinic and the convenience store before the coatings were applied. These baseline performance data and detailed descriptions of the buildings should allow us, later in the project, to calibrate models of the hour-by-hour energy demand of the two all-electric buildings and use the models to discern the effect of the roof coatings.

INSTALLATION OF INSTRUMENTS

The federal facility's location in the Panhandle of Florida is considered ideal for a demonstration of the effects of radiation control coatings on roofs because of the high cooling load of its buildings. Energy management personnel at the facility provided a list of available buildings and general descriptions from which the initial candidate buildings were selected. A short trip was made to the facility to discuss the as-built drawings for the buildings and compare them to the actual buildings. Walk-throughs of the buildings were conducted with particular concern for the type and thickness of insulation in the roofs.

Three pairs of heat-flux transducers were calibrated in aged polyisocyanurate insulation, which luckily was the general type used at the facility. Not using the exact insulation for calibration is adequate for the relative comparisons that are of primary interest herein. Thermocouples were made long enough to go from the locations on each roof to a conveniently placed data logger in each building. Data loggers were requisitioned along with compatible modems and software to communicate with the data loggers remotely. To ensure reliable data collection, rechargeable battery packs and chargers were included to operate the data loggers on battery power at all times. The batteries recharge whenever 120-VAC power is available. In the event of an AC power outage, data continue to be collected for several months on stored battery power. The batteries automatically start recharging when AC power is restored.

The plywood deck of the fast food restaurant was able to be cut through to gain access to the insulation from below. In the convenience store and the veterinary clinic, pieces of the built-up roof membrane were cut out to gain access to the insulation from the top. About 1 ft (0.3 m) square pieces of insulation were removed. A depression for the 2 in. (5.1 cm) square by 0.125 in. (3.2 mm) thick heat flux transducers (HFTs) was cut in the middle of each piece of insulation, the HFTs were placed in them, the insulation was replaced, and the deck or membrane was repaired. Placing the HFTs in the insulation duplicated the calibration situation. As described later, we use a one-dimensional transient conduction program to generate heat fluxes and temperatures throughout the roof from measured boundary temperatures and the thermal properties and geometry of the roof materials. Small holes were drilled up through the insulation at the convenience store and the fast food restaurant to feed through the thermocouples for the outside-surface and outdoor-air temperatures. The concrete deck at the veterinary clinic necessitated running the wires on top of the roof. A track was made by scraping aside embedded gravel so the wires laid flat and the track was sealed with roof cement and the gravel replaced. An inside-surface thermocouple was taped and caulked to the deck under each HFT. The outdoor-air thermocouple measuring junction extended about three inches (eight centimeters) above the roof surface. The outside-surface thermocouples were bent against the surface and secured with roof cement on the roof of the veterinary clinic or with caulk on the roof of the fast food restaurant. They were left under the top ply of the BUR on the convenience store roof.

The thermocouples and heat-flux transducer leads were run to the respective data loggers and connected to them. The data loggers have built-in reference junction compensation for the T-type (copper-constantan) thermocouples we used. AC power was connected to the battery charger, and a telephone line was plugged into the modem. The data loggers were programmed and checks made that data collection was proceeding according to the programs. The programs included constants to reflect the calibration in a guarded hot plate apparatus of the particular pair of heat-flux transducers used in each building.

Figure 3 shows the heat fluxes and surface temperatures at both instrumented locations at the veterinary clinic for the first thirty days of monitoring in December 1995. The outdoor-air temperatures are not shown. They were identical at both locations on the veterinary clinic roof. Compared to the outdoor-air temperatures at the convenience store during the same time period, they were slightly lower at night. This is consistent with the inland location of the veterinary clinic compared to the location of the convenience store on an intercoastal waterway that borders the facility.

The roofs were coated in early July 1996. During this pre-coating phase of the project, there should also be no difference between the outside-surface and inside-surface temperatures or between the heat fluxes at what is labeled 'coated' and 'uncoated' locations (in anticipation of the coating installation in July 1996). This was true for the convenience store except for shading effects discussed later. In Fig. 3, the outside-surface temperatures on the veterinary clinic roof have slightly lower peaks on sunny days for the uncoated location than the coated location. This is likely due to slight differences in the roof geometry between the two locations. However, for reasons which required a change in analysis procedures, the inside-surface temperatures are sometimes noticeably different and the insulation heat fluxes are unacceptably different.

The inside-surface temperatures for the uncoated location in the veterinary clinic are from a spot on the concrete ceiling in a small unconditioned air handler room vented to the outside. Those for the location that would be coated are on the concrete ceiling in the unconditioned and unvented space above the ceiling tiles in an adjacent small storeroom. The desired spacing between instrumented patches on the roof did not allow both patches to be above the same unconditioned space. It is reasonable to expect that the temperatures in the air handler room are slightly cooler than the temperatures above the storeroom during late fall in northern Florida. Data collected later showed that the ceiling of the air handler room was slightly warmer than the ceiling of the storeroom at times during the air conditioning season.

The few cases where the 'coated' and 'uncoated' heat fluxes are different before day 10 and then the high 'uncoated' heat fluxes after day 17 are symptoms of a failing sensor. In subsequent months, this sensor indicated even higher heat fluxes, of the order of 30–40 Btu/h·ft^2

(95–126 W/m^2), day and night. After that, the output varied randomly. During the on-site visit in July 1996 to apply coatings, the lead wires and connectors were changed to no avail. Because of the occasional differences between the inside-surface temperatures in the storeroom and the air handler room, an analytical approach was adopted to calculate the uncoated heat flux using measured temperatures instead of replacing the failed heat-flux transducer six months into the project.

The data obtained before the sensor failed are enough to calibrate a computer program written by Wilkes (1989), called Simplified Thermal Analysis of Roofs (STAR). Once calibrated, it can predict heat fluxes and temperatures anywhere inside a particular roof, given the surface temperatures from the measurements, the roof geometry and the thermal properties of the roof materials. To correct for the differences between the inside-surface temperatures in the storeroom and the air handler room, STAR can predict the heat fluxes through the uncoated location using the inside-surface temperatures at the coated location and the outside-surface temperatures at the uncoated location. This mixing of boundary conditions allows direct comparisons to the measured heat fluxes from the reliable heat-flux transducer under the coated location.

When the heat-flux transducer for the uncoated location was functioning properly, pairs of reliable heat-flux measurements at a particular time in Fig. 3 were for sometimes different inside-surface temperatures. The data in Fig. 4, for days 14 through 21 of precoating monitoring, verify that the geometry and thermal properties of the veterinary clinic roof can be used to predict the heat flux at the interface between the insulation layers for various inside and outside boundary temperatures. The heavy solid line is the heat flux measured through the area to be coated in July 1996. This heat flux is reliable. The heavy dashed line is the heat flux measured through the area to remain uncoated. This area has the failing transducer.

Two predictions with the STAR program are shown. They are the best match for the geometry shown on the as-built drawings for the veterinary clinic and the variations in room temperature thermophysical properties with material density given in the *ASHRAE Handbook of Fundamentals* (ASHRAE 1993) for polyisocyanurate insulation, lightweight concrete and heavyweight concrete. The thickness of the BUR was varied, along with the density of the other materials, to generate a range of predictions from which to select the best match for each prediction. One is shown as a light solid line and labeled STARmixHF. The boundary conditions for this case are outside-surface temperatures for the patch that is to remain uncoated throughout the project and the inside-surface temperatures for the location that is to be coated in July 1996. The other is shown as a light dashed line and labeled STAR'uncoated'HF. It uses the outside-surface and inside-surface temperatures at the location that is to remain uncoated throughout.

The measured peak heat fluxes are reproduced very well by both predictions for all the reliable data. During days 14 through 17 in Fig. 3 there was no difference in inside-surface temperatures. During days 18 through 21 the inside 'uncoated' location was about 5°F (3°C) colder than the 'coated' location. Differences in inside-surface temperatures does not appear to affect the daytime predictions.

The minimum heat fluxes at night are reproduced adequately, especially since the greater interest is in the comparison between the coated and uncoated values during the daytime, when solar loads are possible. The largest differences between the predicted and measured reliable heat fluxes occur when outdoor temperatures are coldest, after day 18, but are less than about 0.3 Btu/h·ft^2 (0.95 W/m^2·K). The differences are thought to be related to the temperature dependence of properties. Thermophysical properties were put into the input file for STAR at room temperature and assumed to be constant. Evidence that the differences between measured and predicted values are related to temperature is the behavior in Fig. 4 after day 18 of the prediction STARmixHF. It falls below the prediction STAR'uncoated'HF these nights and all of the cold day 20. The inside-surface temperature for the 'coated' location used in STARmixHF is warmer than the inside-surface temperature for the 'uncoated' location in STAR'uncoated'HF during this especially cold time. This makes the temperature difference larger and, combined with the assumption of constant thermophysical properties, causes larger negative heat fluxes from STARmixHF.

INSTALLATION OF COATINGS AND ROOF SOLAR REFLECTANCES

After several months of pre-coating data collection from the veterinary clinic and the convenience store, three people from the coating manufacturer and one person from the national laboratory met at the federal facility to clean the built-up roofs, apply the coating, and check that the monitoring technology was functioning after the coating. Rainy weather immediately before the coating work was scheduled caused both roofs to have areas of ponded water in addition to twigs, leaves and loose gravel. The twigs were picked up, and the leaves and loose gravel were either swept off with a stiff broom or blown off with a leaf blower. Remaining water and more loose gravel in the ponded areas were removed with a wet/dry vacuum.

The roof surfaces remained very rough despite removal of loose gravel. Airless spray equipment was used to apply a single coat of the ceramic coating to increase roof solar reflectance. The appearance of the roofs was changed markedly. The roofs appeared continuously white afterwards with some unevenness due to overlaps in the spray pattern. Figure 1 shows the contrast in the appearance of the uncoated and coated roofs. At least four hours of drying time were allowed before the pieces for reflectance samples were moved away from the uncoated patches underneath them during the coating process. Then the sample of the fresh coating was cut off, leaving the missing corner on the piece shown in Fig. 1.

Application of the ceramic coating to a thickness of about 0.015 in. (0.38 mm) is recommended by the manufacturer. On a smooth surface this yields coverage of about 60 ft^2/gal (1.5 m^2/L). The manufacturer's personnel were experienced with the airless spray equipment that was used and applied the coating to a uniform thickness. Extra product was needed due to the embedded gravel that remained on the BURs. Almost 135 gal (510 L) of product were used for 5725 ft^2 (530 m^2) of roof area. Coverage was therefore about 40 ft^2/gal (1.0 m^2/L). The early 1997 price for the coating in the GSA Muffin system used by federal facilities is $166.95 per 5-gal (18.9-L) container. Roof clean-up and application of the coating took the crew of four about 12 h.

After completion of the spray-coating work, the person from the national laboratory went to the fast food restaurant roof with a gallon (3.8 L) of the coating as it had been mixed and applied to the convenience store roof. A like amount of an acrylic elastomeric coating with titanium dioxide added to increase solar reflectance had also been obtained from another manufacturer. Two areas of the white single-ply membrane, each approximately 2 ft (0.61 m) square and centered on the locations where thermocouples and heat-flux transducers had been installed, were cleaned with detergent. A free-floating strip of a similar membrane, approximately 9 in. wide by 3 ft long (23 cm wide by 0.9 m long), was laid beside each area. One area and its strip were coated by brushing on the ceramic coating in one direction and the other by brushing on the acrylic elastomeric in the same manner. A second coat of each coating was applied in the perpendicular direction after the first coat had dried for about an hour in the sun. The ceramic coating brushed on much thicker than the acrylic elastomeric. The former was about 0.057 in. (1.4 mm) thick after two coats; the latter was only about 0.009 in. (0.2 mm) thick. After the second coat had dried for about an hour, pieces of the strips were cut off and removed. The remaining strips were anchored by paver blocks and left on the roof to weather.

The samples of fresh sprayed-on coatings on the pieces of built-up roof from the veterinary clinic and the convenience store, along with a piece of the uncoated built-up membrane, and the freshly brushed-on coating samples from the fast-food restaurant were sent to a university laboratory and evaluated for solar reflectance (Yarbrough 1997). Table 1 shows the results of five measurements over the area of each fresh sample. For comparison, the table includes the average and standard deviation of the measurements for samples from the facility in Florida (labeled off-site in Table 1) as well as results for some coatings and membranes undergoing tests at a national laboratory in the climate conditions of East Tennessee (labeled on-site in Table 1). All the coatings for the on-site samples are about 0.020 in. (0.51 mm) thick except for sample TC1, whose thickness is 0.032 in. (0.81 mm). As long as the coating thickness exceeds about 0.020 in. (0.51 mm), thickness does not affect solar reflectance (Anderson et al. 1991). Only the coating RH3 is less than 0.020 in. (0.51 mm) thick, but it is the same coating as sample RH2, and the fresh values are essentially equal.

The solar reflectances, ρ, for the fresh coatings on smooth ethylene propylene diene monomer (EPDM) and atactic polypropylene polymer (APP)-modified bitumen surfaces—in Table 1, the samples designated as RH3, TC2, RH2, SOL, TC1, INS and RH1—are in the range from 0.75 to 0.85 with small standard deviations, σ, of the measurements from their respective averages. The fresh samples on rough surfaces coated along with the convenience store and veterinary clinic roofs (called SHP and VC in Table 1) have solar reflectances in the range from 0.50 to 0.55 with larger standard deviations for the five measurements. Due to the roughness of the gravel topping on the BURs, it was not possible to coat the BUR as uniformly nor measure reflectance as easily as for a smooth surface. The rough surface solar reflectances for fresh samples are already in the range of those for three samples on smooth surfaces weathered for almost 2 years (TC1 for 102 weeks and INS and RH1 for 94 weeks). The reflectance of the earlier sample TC1 weathered less than a year (41 weeks) was lower than the TC1 sample at almost 2 years and may have been from a particularly dirty part of the TC1 weathering strip. The fresh rough surface values fall below the 0.65 to 0.75 range for six samples weathered less than a year (RH3 and TC2 for 33 weeks, RH2 and SOL for 41 weeks and INS and RH1 for 42 weeks). The effect of weathering is to decrease the solar reflectance of coated smooth surfaces. The effect of less than half a year's weathering (17 weeks) on the reflectance of the samples RH3 and TC2 is already significant, a 9% decrease. After 33 weeks the decrease averages 14%.

Weathering through 33 weeks seems to have severely affected the reflectance of the coated rough surface on the convenience store but the reflectance of the coated rough surface on the veterinary clinic has been constant within the observed standard deviation of the measurements. The location of the convenience store next to the intercoastal waterway bordering the facility and the shading and debris from the live oak trees could weather the convenience store's coating more than the veterinary clinic's. The uncoated smooth and rough surfaces (UNC1, UNC2 and UNC3) have solar reflectances less than 0.10, and weathering (for UNC2 and UNC3) does not appear to affect the solar reflectance.

PRE-COATING VS. FRESH COATING RESULTS

Results from Veterinary Clinic in Florida Panhandle

Figures 5 and 6 show data for two weeks shortly before and after the roof of the veterinary clinic was coated on July 9, 1996. An electrical storm at the facility caused loss of stored data for the month of July 1996 at the veterinary clinic so data from early August 1996 are shown for the freshly coated roof. The lower half of Fig. 5 shows that the outdoor-air temperatures above both locations are identical while they are still uncoated in late June and when one is coated while the other remained uncoated in early August. Days 176 through 178 in late June were very hot and there were a few stormy days, especially day 225.

The power demand of the veterinary clinic is shown on the upper half of Fig. 5. The power shows significantly larger daytime peaks on the very hot days and somewhat lower peaks on the stormy days if the clinic was open. The energy management system for the building keeps power demand very low on weekend days when the clinic is closed. The operating schedule was somewhat erratic during the period shown. The clinic HVAC system seemed to be operating on day 175, Sunday, June 23, 1996 and on day 181, the following Saturday. From the hourly records of power demand reported by the pulse-initiating kilowatt-hour meter and outdoor-air temperatures reported by the two thermocouples above the instrumented locations on the veterinary clinic roof, average power and outdoor-air temperature were calculated for all of June and August. Only powers and outdoor-air temperatures were included in the averages when power was greater than 1.5 kW. This criterion is to eliminate effects of times when the clinic HVAC system was in summer energy conserving mode. The average power was 3.02 kW in June and 2.63 kW in August, a 13% decrease for August. With the same criterion, the average outdoor-air temperature was 87.3°F (30.7°C) in June and 88.3°F (31.3°C) in August, a 1% increase for August.

The lower half of Fig. 6 shows the outside-surface temperatures while the upper half shows the heat fluxes for the same time period as Fig. 5. During late June, with both locations uncoated, no effect of moving shadows is evident in the surface temperatures, which are directly measured, or in the three heat fluxes, of which two are predictions by the STAR program. On sunny days the temperatures and heat fluxes have smooth and symmetric peaks. The trend noticed in Fig. 3 continues in late June: a slightly lower peak temperature on sunny days at the uncoated location relative to the location that would be coated in early July.

Evidence that there are slight differences in the roof at the two locations is that the effect carries through to the heat fluxes shown in Fig. 6. The heavy dashed curve for the prediction STARcoatedHF uses the inside- and outside-surface temperatures of the coated location as boundary conditions. It exactly duplicates the measured results shown by the light solid curve labeled Meas.coatedHF except for insignificant differences at night. The heavy solid curve

STARmixHF, using the outside-surface temperature of the uncoated location and the inside-surface temperature of the coated location, falls slightly below that for the coated location in late June. By judicious choice of scale for the heat fluxes and temperatures on this figure, the differences in the peak heat fluxes are almost the same as those in the peak outside-surface temperatures. Note that both predicted heat fluxes agree better with the measured coated heat fluxes at night than they did in Fig. 4. This suggests further that the differences in Fig. 4 between the measured and predicted heat fluxes during cold weather are the effect of using thermophysical properties of the roof materials in STAR at room temperature.

After the roof is coated there is a clear decrease in the outside-surface temperatures and heat fluxes for the sunlit coated roof relative to results for the uncoated area. No significant difference is seen at night but there is a clear effect of the thermal mass of this roof. The heat flux through the insulation is negative for most of the night and fairly steady as the concrete heated from above through the insulation during the day (positive heat flux) loses energy through the insulation to the outside at night (negative heat flux).

To focus on the beneficial effect of the coating for decreasing the outside-surface temperature and heat flux through the sunlit roof, a sunlit criterion is proposed. For outside-surface temperature, the uncoated temperature must exceed the coated temperature by 5°F (3°C) to qualify. Pre-coating data show that the random differences between the outside-surface temperatures are less than 5°F (3°C). If the uncoated temperature is more than 5°F (3°C) higher than the coated temperature, the cause must be solar irradiation. The averages of these sunlit roof values and the percentage difference between the averages are listed for all of August and September 1996 for the veterinary clinic in Table 2. The average temperatures themselves show a slight seasonal effect. The average uncoated outside-surface temperature decreases from 110°F (43°C) in August to 105°F (41°C) in September and the average coated outside-surface temperature decreases from 98°F (37°C) to 94°F (34°C). The decrease in the average outside-surface temperature of the coated surface relative to the uncoated surface is about 11% for both months.

The sunlit criterion for heat fluxes is twofold: the coated heat flux must be positive and the uncoated heat flux must exceed it by 0.5 Btu/h·ft^2 (1.6 W/m^2). The first part of the criterion is to eliminate nighttime effects. The amount of difference that must be exceeded in the second part is the size of random fluctuations noticed in the pre-coating data. Table 2 lists the average uncoated and coated heat fluxes and the average decrease in heat fluxes through the insulation under the freshly coated location relative to the uncoated location on the veterinary clinic roof. The average uncoated and coated heat fluxes are constant at 2.6 and 1.7 Btu/h·ft^2 (8.2 and 5.4 W/m^2), respectively, for August and September 1996. The average decrease is about 35% for the two months. Due to the slightly lower peak outside-surface temperatures and heat fluxes for the uncoated location relative to the as yet not coated location during the pre-coating phase of the project, this average percent decrease is conservative.

Moreover, the effect of the thermal mass under the insulation delays but enhances the beneficial effect of the coating on heat fluxes through the roof. The output of the model STAR includes heat fluxes at the inside surface of the geometry, which is the bottom of the heavyweight concrete deck for the veterinary clinic roof. The prediction STARmixHF and the measured coated heat fluxes produce the results shown in Fig. 6 and Table 2, specifically, a 36.2% average decrease in heat fluxes during August 1996 through the middle of the insulation for the coated location relative to the uncoated location. For heat fluxes through the bottom of the deck in August 1996, using STARcoatedHF and STARmixHF, the average heat flux decrease is 50.1%. The same sunlit criterion was used as for the insulation heat fluxes. The data show a longer lag time. Compared to the criterion for the insulation, the criterion for the bottom of the deck is satisfied about two hours later on sunny days, but it then continues to be satisfied for about 7-9 hours afterwards just like for the insulation. The average occupied power demand decrease of 13% reported above in the discussion of Fig. 5 seems reasonable despite the predicted 50% decrease in heat flux through the deck under the coated roof. There is an unconditioned plenum space about 2 ft (0.6 m) high formed by a drop ceiling below the deck of the veterinary clinic which insulates the conditioned space from the roof heat flux.

Results from Convenience Store in Florida Panhandle

Figures 7 and 8 show data for the convenience store for the same two weeks as Figs. 5 and 6, just before and after the roofs were coated. The convenience store's roof was coated on July 10, 1996. The electrical storm that caused loss of stored data for the month of July 1996 at the veterinary clinic did not affect the stored data at the convenience store but for consistency with Figs. 5 and 6, data from early August 1996 are shown for the freshly coated roof. The lower half of Fig.7 shows that the outdoor-air temperatures above both locations are identical while they are still uncoated in late June and when one is coated while the other remained uncoated in early August. The weather patterns indicated by the outdoor-air temperatures at the veterinary clinic and the convenience store are identical since the sites are at the same facility. There are more fluctuations from a smooth curve in the daytime outdoor-air temperatures on sunny days at the convenience store because of a shadow from the live oak trees moving across the instrumented locations.

The power demand of the convenience store is shown on the upper half of Fig. 7. There is no significant difference in peak power demand for the three very hot days in late June compared to the peak power demand for the two milder days preceding them. The convenience store is operated seven days per week with the summer thermostat setpoint constant at 70°F. Inside-surface temperatures at the instrumented locations show that setpoint is not satisfied on hot days.

Regardless, the load is dominated by the large number of refrigeration compressors with external condensors running 24 hours per day to service the coolers and freezers in the convenience store. Hence, the base demand could be dependent on outdoor air temperature. A correlation was tried with data from February through July 1996, seeking a relation between base demand for electricity and nighttime (unoccupied) outdoor air temperature (Petrie and Childs 1997). The linear relation which was generated showed that electrical power for the convenience store increased with nighttime outdoor-air temperature but the scatter about the line of best fit was large (correlation coefficient r of 0.72 or $r^2 = 0.52$). With such erratic nighttime demand, no average effect of the roof coating could be discerned by applying a simple criterion such as was applied to the power data in Fig. 5. A goal for modeling of whole building energy use to be done later, when more data are available for the coated roofs, is to segregate the effect of the roof coating from that of the internal load.

The lower half of Fig. 8 shows the outside-surface temperatures while the upper half shows the heat fluxes for the same time period as Fig. 7. Note how different the nighttime behavior of the heat fluxes is for this lightweight metal-decked roof compared to the heavyweight concrete-decked roof of the veterinary clinic (see Fig. 6). There are negative heat fluxes for a short time early each night followed by nearly zero heat flux throughout the rest of the night.

The daytime behavior is more complicated. During late June, when both locations were uncoated, there is a clear effect of moving shadows both in the surface temperatures and the heat fluxes. Even on sunny days with smooth daytime profiles on Fig. 6, the temperatures and heat fluxes have jagged daytime behavior on Fig. 8. There are twin peaks, first a large one, then a small one. The behavior at the uncoated location is unchanged after the roof is coated. The peaks at the coated location are very much decreased. Figure 9 presents detailed behavior. The outside-surface temperatures and heat fluxes are shown hour-by-hour for June 21, 1996, before the roof was coated, and July 30, 1996, after the roof was coated. These days were selected by trial-and-error to show similar behavior of the uncoated outside-surface temperatures and heat fluxes.

Since the effect is caused by the shadow of the live oak trees moving across the coated location in early afternoon, when solar irradiation is highest, and then across the uncoated location later in the afternoon, when solar irradiation is less, the apparent performance of the coating is enhanced. The same sunlit criterion used for the outside-surface temperatures and heat fluxes for the veterinary clinic was applied to the data from the convenience store in July, August and September 1996. The averages of these sunlit roof values and the percentage difference between the averages are listed in Table 2. All show a seasonal decrease from July through September.

The most significant difference between the convenience store and the veterinary clinic roofs is the apparent improvement in the percent decrease in outside-surface temperatures and especially the heat fluxes through the insulation for the convenience store. Table 3 shows the results of applying the simple sunlit criterion to the data for July 30, 1996, the coated roof day displayed in Fig. 9. The percent decreases that are higher than the average, from noon through 2 p.m., are increased by the shading of the coated location. The shading of the uncoated location later in the afternoon causes data with lower percent decreases to be excluded from the average.

A simple criterion is not able to segregate the shading effect from the coating effect for the convenience store because the effects are of comparable magnitudes. The roof on the veterinary clinic is thermally massive, but its instrumented locations were not shaded. Whole building modeling with a model calibrated to each building that accounts for shading and thermal mass effects may be able to segregate such site-specific effects.

Results from Test Facility in East Tennessee

Two coatings whose solar reflectances are reported in Table 1, the ceramic coating SOL and the acrylic elastomeric coating RH2, were also monitored for thermal performance in the East Tennessee climate during Summer 1996. As Table 1 shows for fresh coatings, the SOL coating has slightly higher solar reflectance than the RH2 coating and both are significantly more reflective than the coatings on the veterinary clinic and convenience store roofs. At our test facility in East Tennessee, various radiation control coatings have been applied to 4-ft- (1.2-m-) square samples of single layers of low-slope roof membrane materials. An adjacent square of the membrane was left uncoated. The membranes are sealed in frames and placed over roof decks comprising three sheets of 0.5-in.- (1.3-cm-) thick plywood, with thermocouples on the top and bottom of the assembly and a heat-flux transducer and thermocouple at the top of the middle layer of plywood for both the coated and uncoated squares. The thermal resistance of these roofs is about 1.5 $h \cdot ft^2 \cdot °F/Btu$ (0.26 $m^2 \cdot K/W$), only 7–14% of the R-values of the Florida roofs. Low thermal resistance and high solar reflectance maximize the benefit of radiation control coatings to decrease the outside-surface temperature of roofs and heat fluxes through them.

Results from the tests on-site in East Tennessee are shown in Table 2 to complement the fresh-coating results from the off-site Florida tests. Because of the low R-value of the roofs and high solar reflectance of the fresh coatings, both the outside-surface temperatures and the heat fluxes for the coated membranes in the on-site tests are improved significantly more than in the off-site tests. The decrease in the outside-surface temperatures of the coated vs. the uncoated membranes is over 25%. The decrease is slightly more for the higher reflectance SOL coating than the RH2 coating. The decrease in the heat fluxes through the plywood deck under the coated membranes is over 77% less than under the uncoated membranes. Differences in the heat fluxes for the SOL and RH2 coatings due to the better solar reflectance of the SOL coating seem to have damped out at the location of the heat flux transducer between the middle and top sheets of plywood.

CONCLUSIONS

Pre-coating monitoring and monitoring for the first summer with fresh coatings have been completed for a 2-summer demonstration of radiation control coatings installed at a federal facility in the Panhandle of Florida. The use of instrumented locations with and without a radiation control coating on two entire roofs allows us to obtain direct comparisons throughout the project for outside-surface temperatures and heat fluxes through R-12 h·ft²·°F/Btu (R-2.1 m²·K/W) insulated roofs with and without coatings. On one roof the effects of shading enhance the apparent benefit of the coating. The other has a thermally massive roof deck, which also appears to benefit the coating. Both roofs have rough-surfaced built-up roofs (BURs), so initial solar reflectance is not as high as on smooth surfaces, including a smooth-surfaced, R-22 h·ft²·°F/Btu (R-3.9 m²·K/W) insulated roof at the facility in Florida and smooth-surfaced, R-1.5 h·ft²·°F/Btu (R-0.3 m²·K/W) insulated test sections at our facility in East Tennessee. At both sites, side-by-side tests are being done on latex-based coatings, with ceramic beads added to improve solar reflectance, and on acrylic elastomeric coatings, with titanium dioxide added to improve solar reflectance. Therefore, the data cover the range of parameters of interest for assessing the benefit of initially high solar reflectance coatings which our previous data show to have the potential to weather significantly.

Measured solar reflectances for the ceramic coating as applied in Florida on the two rough-surfaced BURs are 0.52 and 0.54, respectively. This is in the range of reflectances for coatings applied on smooth membranes and weathered 1–2 years in Tennessee. On the smooth surfaces in Florida, the ceramic coating and an acrylic elastomeric coating had initial reflectances of 0.76 and 0.80, respectively. The same acrylic elastomeric coating and a different ceramic coating on smooth surfaces in Tennessee showed initial reflectances of 0.81 and 0.85, respectively. These reflectances are in the same range as those we measured initially for other ceramic and acrylic elastomeric coatings.

The solar reflectance of a coating and the thermal characteristics of the roof to which it is applied affect the temperatures of the coated surface and the heat fluxes through the roof. The R-12 h·ft²·°F/Btu (2.1 m²·K/W) insulated roof with shading effects showed average decreases of 15, 13, and 10% in coated surface temperatures relative to uncoated surface temperatures in July, August, and September 1996, respectively. The heat fluxes through the insulation under the sunlit coated and uncoated locations yielded average decreases of 55, 54, and 51% in the same months. The heavyweight concrete decked roof with the same insulation thickness showed 11% outside-surface temperature decreases for the coated surface in both August and September 1996. The average decreases in heat fluxes were 36 and 35%, respectively. For R-1.5 h·ft²·°F/Btu (0.3 m²·K/W) insulated test sections coated to higher solar reflectances, results were more dramatic. Relative to a neighboring uncoated surface, the ceramic coating with 0.85 initial solar reflectance showed a 28% decrease in outside-surface temperature and a 77% decrease in heat flux for July 1996. The acrylic elastomeric coating with 0.81 reflectance showed a 26% decrease in sunlit surface temperatures and a 78% decrease in heat fluxes.

The effect of a radiation control coating on building electricity use is more complicated than its effect on surface temperatures or heat fluxes for the roof. The roof is only one component of the building heating or cooling load. More data and modeling planned in the next phase of the project are needed to make quantitative conclusions for the whole cooling season, although average power demand during occupied periods for the first month with the coating was 13% less than during the last month without the coating for the Florida building with a thermally massive roof and little internal load. Whole-building electricity use is being followed in the buildings to calibrate a model for the peak power and annual energy use of the buildings. By varying parameters in the model, we hope to sort out the effects of variations in solar reflectance, thermal characteristics of the roof and climatic differences among locations.

ACKNOWLEDGMENTS

The work reported in this paper was done with the support of the U.S. Department of Energy Federal Energy Management Program (FEMP) and carried out under terms of the Stevenson-Wydler Cooperative Research and Development Agreement ORNL96-0403. The formal agreement is between Lockheed Martin Energy Research Corporation and ThermShield International, Ltd. Lockheed Martin Energy Research Corporation manages Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy under contract No. DE-AC05-96OR22464. 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 are 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 (BTC) at ORNL. 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.

REFERENCES

Akbari, H., H. Taha, D. Sailor, and W. Bos. 1992. "Measured savings in air conditioning from shade trees and white surfaces," *Proceedings of the 1992 ACEEE Summer Study on Energy Efficiency in Buildings, 9*, pp. 9.1-9.10. Washington, D.C.: American Council for an Energy Efficient Economy.

Anderson, R.W., D.W. Yarbrough, R.S. Graves, and R.L. Wendt. 1991. "Preliminary assessment of radiation control coatings for buildings," *Insulation Materials: Testing and Applications, 2nd Volume*, pp. 7-23. ASTM STP 1116, R.S. Graves and D.C. Wysocki, Eds. Philadelphia: American Society for Testing and Materials.

ASHRAE. 1993. *1993 ASHRAE handbook—Fundamentals*, Chapter 22, Table 4. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Byerley, A.R., and J.E. Christian. 1994. "The long term thermal performance of radiation control coatings," *Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings*, 5, pp. 5.59-5.71. Washington, D.C.: American Council for an Energy Efficient Economy.

Griggs, E.I., and G.E. Courville. 1989. Changes in the heating and cooling energy use in buildings due to lowering the surface solar absorptance of roofs, Oak Ridge National Laboratory Report ORNL/TM-10339. Oak Ridge, TN: Oak Ridge National Laboratory.

Griggs, E.I., and P.H. Shipp. 1988. The impact of surface reflectance on the thermal performance of roofs: An experimental study, Oak Ridge National Laboratory Report ORNL/TM-10699. Oak Ridge, TN: Oak Ridge National Laboratory.

Parker, D.S., S.F. Barkaszi, Jr., S. Chandra, and D.J. Beal. 1995. "Measured cooling energy savings from reflective roofing systems in Florida: Field and laboratory research results," *Proceedings, Thermal Performance of the Exterior Envelope of Buildings VI*, pp. 489-500. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Parker, D.S., J.R. Sherwin, J.K. Sonne, and S.F. Barkaszi, Jr. 1996. Demonstration of cooling savings from light colored roof surfacing in Florida commercial buildings: Our Savior's School, Florida Solar Energy Center Report FSEC-CR-904-96 (June 1996). Cocoa, FL: Florida Solar Energy Center.

Petrie, T.W., and PW. Childs. 1997. Radiation control coatings installed on federal buildings at Tyndall Air Force Base. Volume 1: Pre-coating monitoring and fresh coating results, Oak Ridge National Laboratory Report ORNL/CON-439/V1. Oak Ridge, TN: Oak Ridge National Laboratory.

Reagan, J.A., and D.M. Acklam. 1979. "Solar reflectivity of common building materials and its influence on the roof heat gain of typical southwestern USA residences, *Energy and Buildings, 2*, pp. 237-248.

Rosenfeld, A.H., H. Akbari, S. Bretz, B.L. Fishman, D.M. Kurn, D. Sailor, and H. Taha. 1995. "Mitigation of urban heat island: Materials, utility programs, updates," *Energy and Buildings, 22,* pp. 255-265.

Wilkes, K.E. 1989. Model for roof thermal performance, Oak Ridge National Laboratory Report ORNL/CON-274. Oak Ridge, TN: Oak Ridge National Laboratory.

Yarbrough, D.W. 1997 (and earlier). Private communications of measurement results using Devices and Services Company Model SSR-ER Version 5 Solar Spectrum Reflectometer. D.W. Yarbrough, Chairman and Professor, Department of Chemical Engineering, Tennessee Technological University, Cookeville, Tenn.

TABLES

Table 1. Solar reflectances of coated and uncoated membranes

Location[a]	Sample	Coated/ Uncoated	Substrate[b]	Fresh $\rho \pm \sigma$ [c]	Weathered ρ (if available)
Off-site, store	SHP	Coated	Rough surface	0.544±0.073	0.464 (after 17 wks) 0.424 (after 33 wks)
Off-site, clinic	VC	Coated	Rough surface	0.518±0.051	0.501 (after 17 wks) 0.517 (after 33 wks)
Off-site	UNC3	Uncoated	Rough BUR surface	0.090±0.009	
Off-site, restaurant	RH3	Coated	Smooth EPDM	0.797±0.004	0.722 (after 17 wks) 0.698 (after 33 wks)
Off-site, restaurant	TC2	Coated	Smooth EPDM	0.763±0.010	0.697 (after 17 wks) 0.639 (after 33 wks)
On-site	RH2	Coated	Smooth APP	0.806±0.008	0.711 (after 41 wks)
On-site	SOL	Coated	Smooth APP	0.853±0.005	0.741 (after 41 wks)
On-site	TC1	Coated	Smooth APP	0.790±0.005	0.515 (after 41 wks) 0.558 (after 102 wks)
On-site	UNC2	Uncoated	Smooth APP	0.060±0.001	0.061 (after 102 wks)
On-site	INS	Coated	Smooth EPDM	0.773±0.006	0.662 (after 42 wks) 0.569 (after 94 wks)
On-site	RH1	Coated	Smooth EPDM	0.809±0.002	0.689 (after 42 wks) 0.539 (after 94 wks)
On-site	UNC1	Uncoated	Black EPDM	0.068±0.001	0.072 (after 70 wks)

[a]Off-site=federal facility in Panhandle of Florida; On-site=outdoor test facility at U.S. national laboratory in East Tennessee

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

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

Table 2. Average outside-surface temperatures and heat fluxes for sunlit uncoated and coated membranes

Location and time period	Average uncoated Tos (°F)	Average coated Tos (°F)	(Tu-Tc) /Tu*100	Average uncoated HF(Btu/h·ft²)	Average coated HF(Btu/h·ft²)	(Hu-Hc) /Hu*100
Veterinary Clinic, Aug. 96	109.6	97.7	10.9	2.60*	1.66	36.2
Veterinary Clinic, Sept. 96	105.2	93.7	10.9	2.60*	1.70	34.6
Convenience Store, July 96	110.3	94.0	14.8	3.22	1.46	54.6
Convenience Store, Aug. 96	103.1	90.0	12.7	2.70	1.25	53.7
Convenience Store, Sept. 96	95.5	85.9	10.0	2.17	1.06	51.4
On-site/SOL, mid-June thru July 96	111.5	80.8	27.5	18.15	4.14	77.2
On-site/RH2, mid-June thru July 96	111.5	82.1	26.4	18.05	4.05	77.5

* Estimated with program STAR using measured inside- and outside-surface temperatures

Table 3. July 30, 1996 data for the convenience store with and without sunlit criterion: uncoatedTos -coatedTos > 5°F; coatedHF > 0 and uncoatedHF - coatedHF > 0.5 Btu/h·ft²

Time (h)	uncoated Tos (°F)	coated Tos (°F)	uncT to Sunlit	ctdT to Sunlit	(Tu-Tc) /Tu*100	uncHF (Btu/h·ft²)	ctdHF (Btu/h·ft²)	uncHF to Sunlit	ctdHF to Sunlit	(Hu-Hc) /Hu*100
0	75.0	74.2				-0.102	0.080			
100	74.3	73.7				-0.008	0.093			
200	74.1	73.7				0.086	0.143			
300	73.8	73.3				0.104	0.127			
400	73.5	73.0				0.100	0.109			
500	73.9	73.3				0.228	0.186			
600	74.9	74.4				0.328	0.285			
700	75.2	74.8				0.369	0.292			
800	78.1	76.2				0.821	0.439			
900	88.4	79.5	88.4	79.5	10.1	2.353	0.836	2.353	0.836	64.5
1000	103.6	87.6	103.6	87.6	15.4	3.826	1.628	3.826	1.628	57.5
1100	119.7	98.2	119.7	98.2	18.0	5.169	2.384	5.169	2.384	53.9
1200	137.4	104.5	137.4	104.5	23.9	6.592	2.252	6.592	2.252	65.8
1300	142.6	100.8	142.6	100.8	29.3	5.090	1.208	5.090	1.208	76.3
1400	123.7	93.3	123.7	93.3	24.6	1.557	0.484	1.557	0.484	68.9
1500	109.9	91.2	109.9	91.2	17.0	0.360	0.708			
1600	100.6	99.8				0.317	2.096			
1700	109.9	102.6	109.9	102.6	6.6	2.959	1.836	2.959	1.836	37.9
1800	112.8	99.8	112.8	99.8	11.5	2.369	1.227	2.369	1.227	48.2
1900	105.4	94.1	105.4	94.1	10.7	0.980	0.618			
2000	94.6	87.0	94.6	87.0	8.0	-0.147	0.068			
2100	86.5	82.4				-0.396	0.003			
2200	82.8	80.6				-0.164	0.140			
2300	79.5	78.3				0.043	0.227			
Avg.	94.6	85.3	113.5	94.4	15.9	1.368	0.728	3.739	1.482	59.1

FIGURE CAPTIONS

Fig. 1. Uncoated patch *(upper right)* and coated piece for solar reflectance samples *(upper left)* on a coated built-up roof at the federal facility in Florida used for the project.

Fig. 2. Cross sections of built-up roofs on a convenience store and a veterinary clinic at the federal facility in Florida used for the project.

Fig. 3. Initial monitoring of heat fluxes and temperatures for the veterinary clinic before coating.

Fig. 4. Prediction by the STAR model of heat flux through uncoated patches on the veterinary clinic roof.

Fig. 5. Outdoor-air temperatures and building electrical power demand for the veterinary clinic for two weeks just before and after its roof was coated.

Fig. 6. Outside-surface temperatures and heat fluxes through the insulation for the coated and uncoated locations on the veterinary clinic roof for two weeks just before and after it was coated.

Fig. 7. Outdoor-air temperatures and building electrical power demand for the convenience store for two weeks just before and after its roof was coated.

Fig. 8. Outside-surface temperatures and heat fluxes through the insulation for the coated and uncoated locations on the convenience store roof for two weeks just before and after it was coated.

Fig. 9. Hourly outside-surface temperatures and heat fluxes through the insulation for the coated and uncoated locations on the convenience store roof for similar sunny days just before and after the roof was coated.

Figure 1

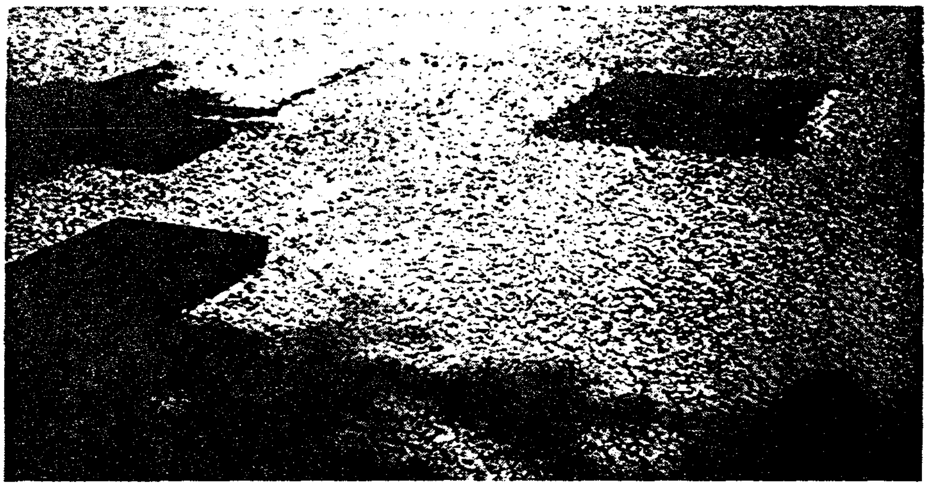

Figure 2

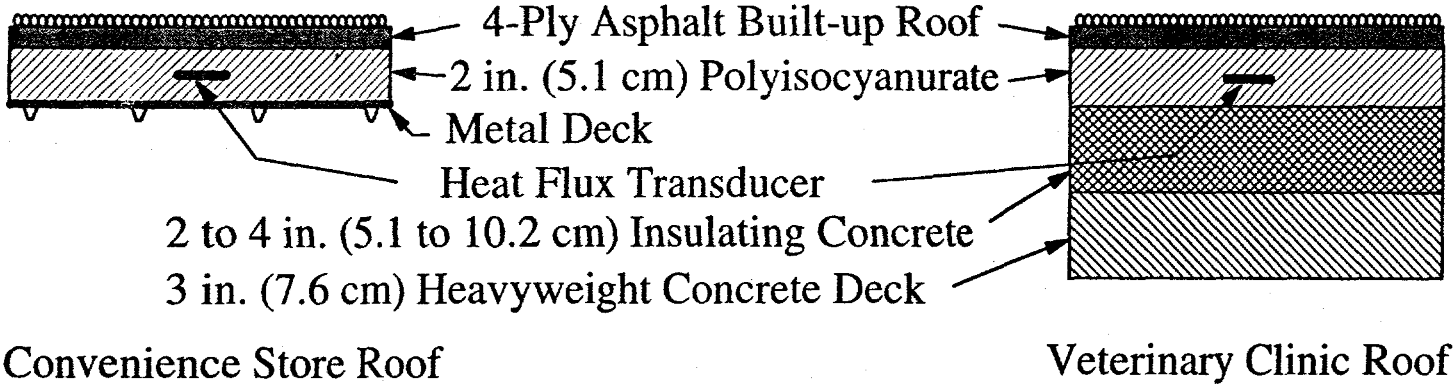

Figure 3

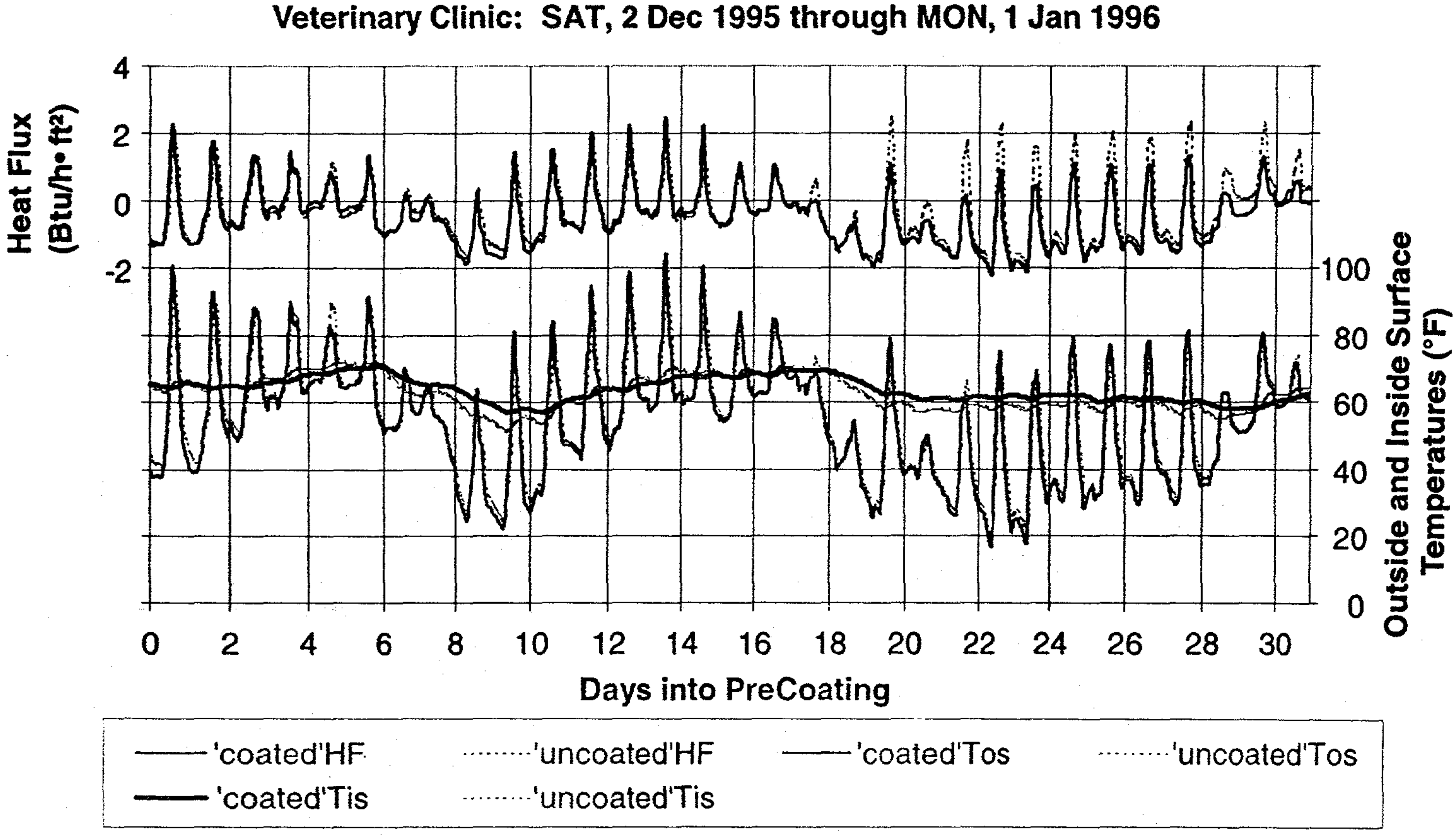

Figure 4

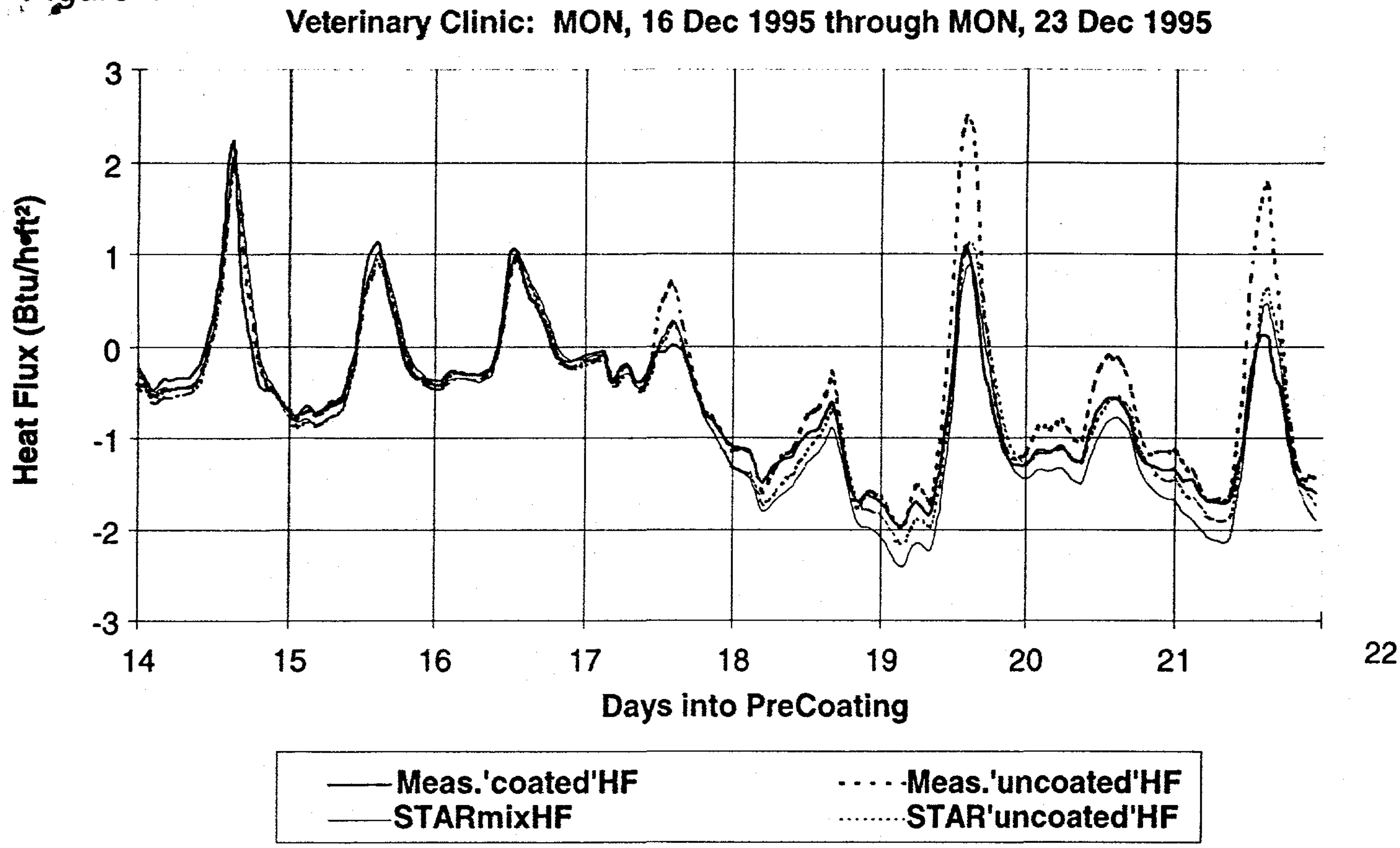

Figure 5

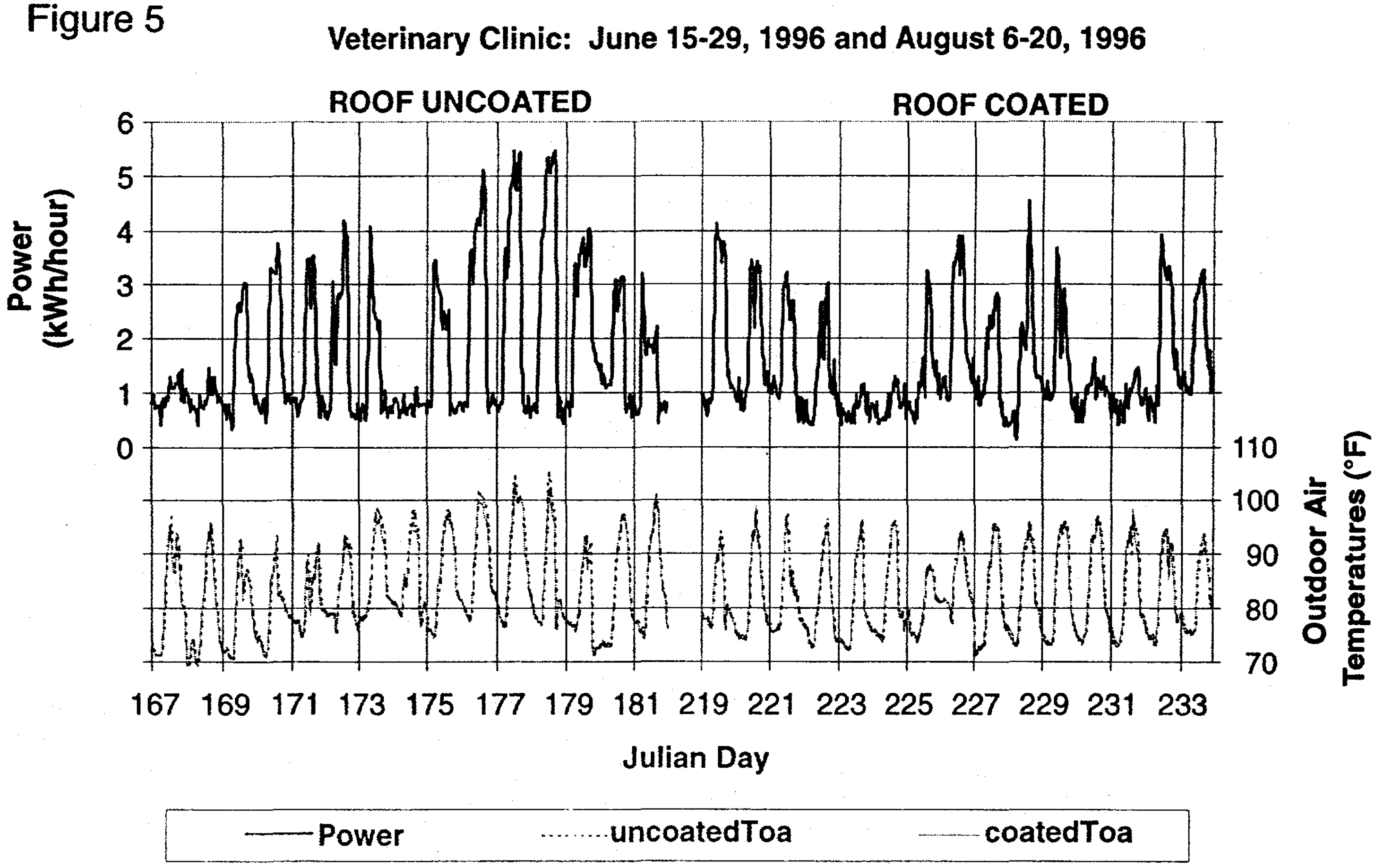

Figure 6

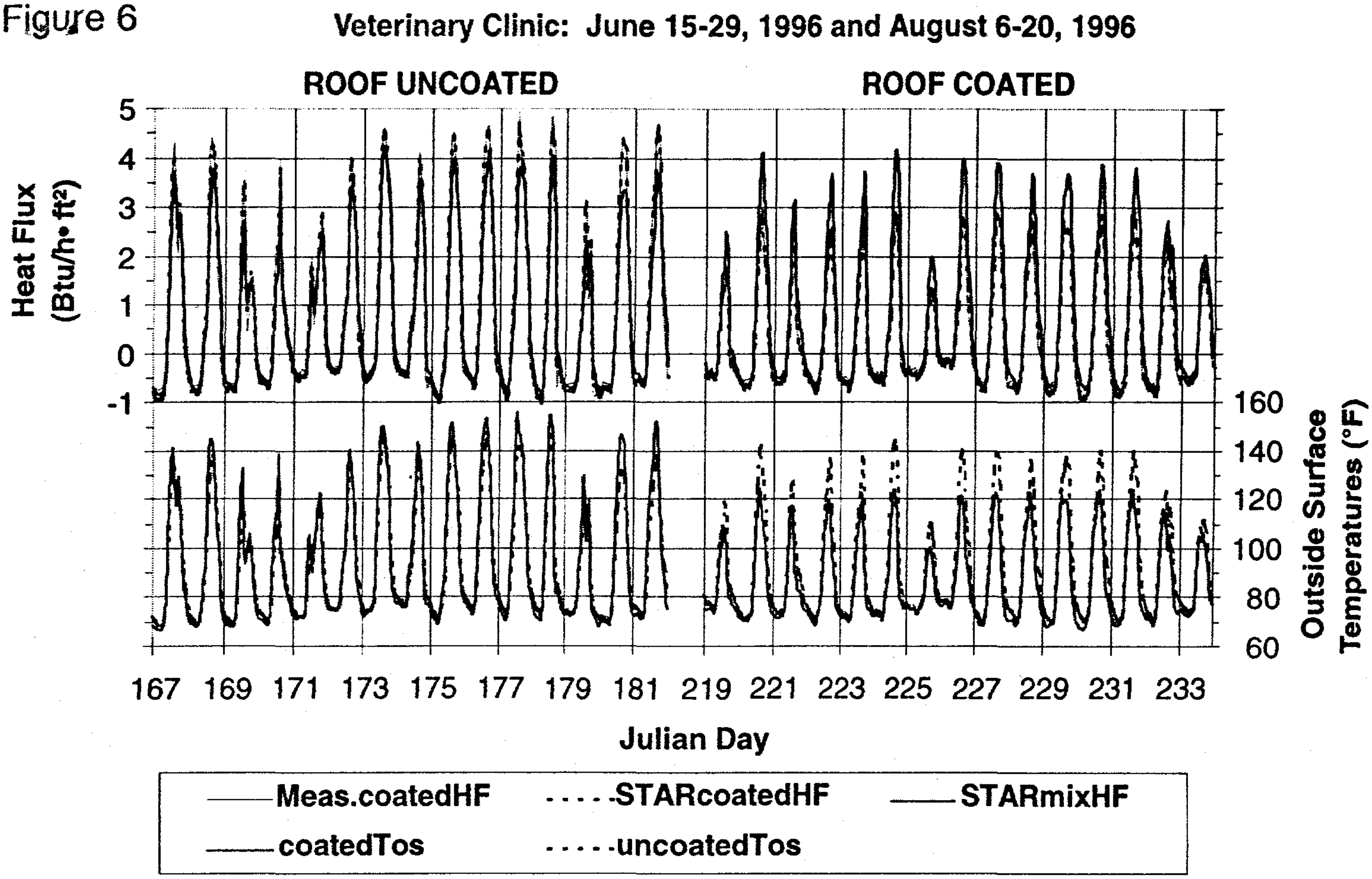

Figure 7

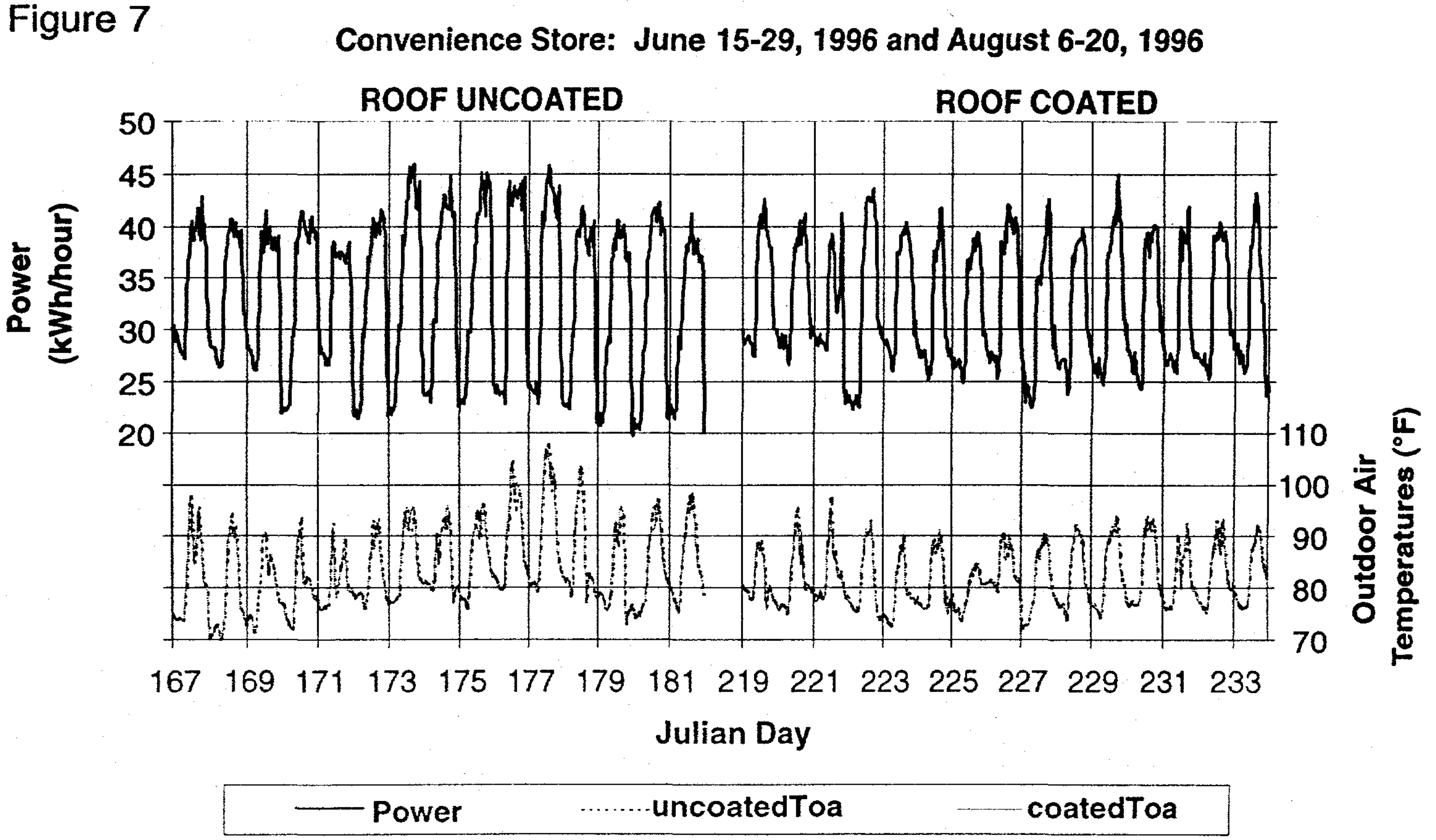

Figure 8

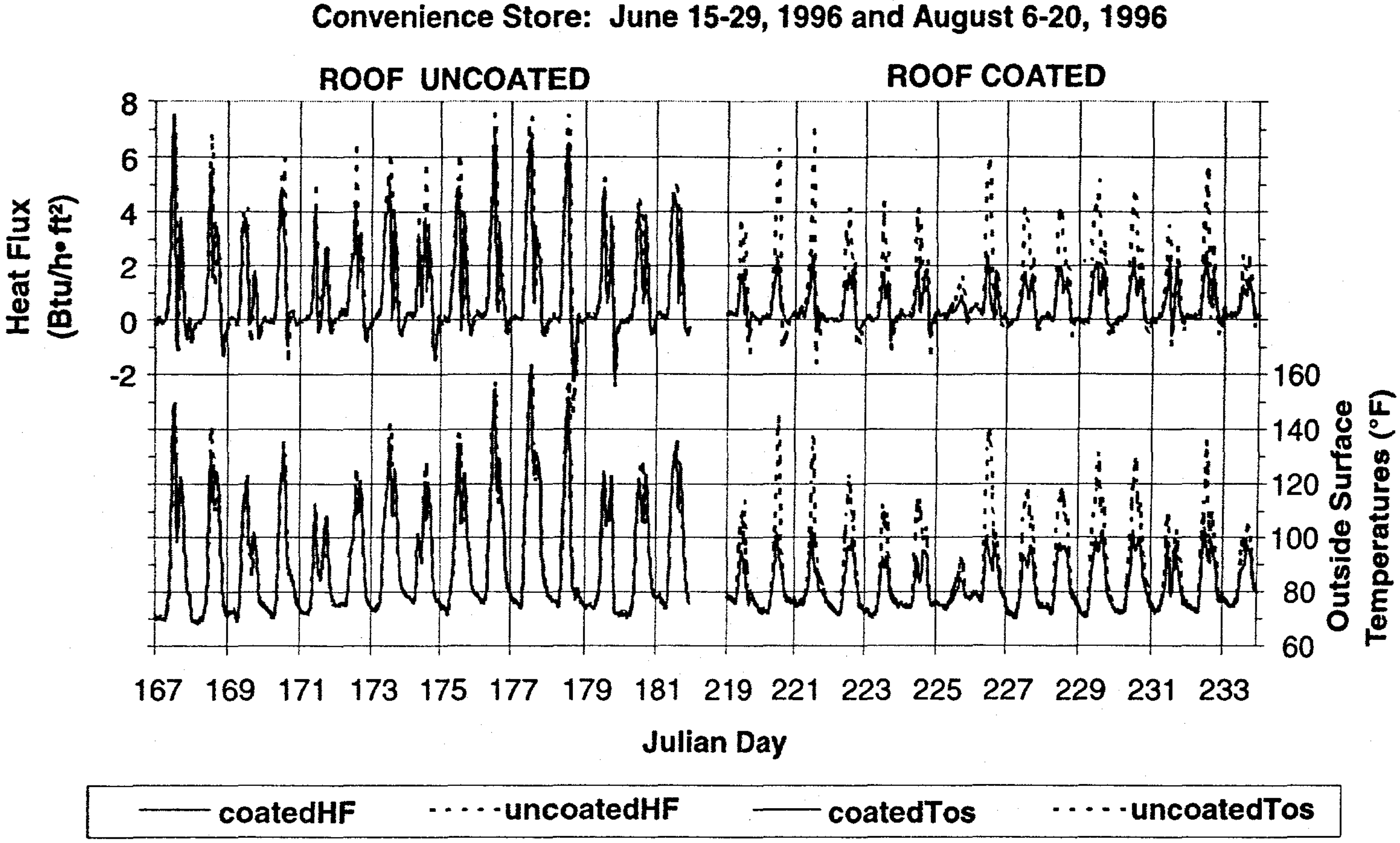

Figure 9