Energy Savings for Stucco Walls Coated with Cool Colors

Thomas W. Petrie, PhD
Member ASHRAE

Jerald A. Atchley

Phillip W. Childs

André O. Desjarlais

ABSTRACT

Solar radiation control is an effective means to decrease energy needs for cooling. Cool colors, with the same appearance as standard colors but higher solar reflectance in the infrared, are of interest for walls. Walls can be coated for possible energy savings without disturbing the existing structure. However, solar radiation control cannot be as effective on walls as it is on roofs because walls do not receive maximum solar load during the peak cooling season. In order to quantify potential energy savings, field tests were done on adjacent walls coated with and without cool colors. Data from a year of tests in Oak Ridge, TN were used to validate a DOE 2.2 model of a south-facing wall. A model for a single-story residence was configured with stucco-coated wood-framed and concrete masonry unit (CMU) exterior walls. It was exercised in cooling and mixed climates. Annual cooling energy savings for use of a cool color (solar reflectance of 0.495) instead of a standard coating with the same color (solar reflectance of 0.238) were 4% to 13% (4% to 9% in the cooling climates). Whole house peak cooling load savings due to the cool walls averaged 3% to 4%. The annual heating energy penalties for cool walls compared to conventional walls were 4% to 24% (4% to 10% in the mixed climates). They exceeded cooling energy savings for moderate heating needs. If annual energy savings are the sole criterion for application of cool colors on the walls of the modeled residence, 65°F heating degree-days (18°C heating degree-days) should be less than about 2800 (1560) for CMU walls or about 3300 (1830) for wood-framed walls. Atlanta has 3090 (1720) heating degree-days.

INTRODUCTION

Solar radiation control is an effective means to decrease energy needs for building cooling. White surfaces have long been used for this purpose. Cool colors are a recent development for applications such as steep-slope roofs where white is not an acceptable color. They have the same appearance as standard colors in the visible part of the electromagnetic radiation spectrum, but have higher solar reflectance in the near infrared. The reason for higher solar reflectance in the near infrared is the presence of so-called infrared blocking pigments (IrBPs) to reflect infrared radiation. When a thin coat of a coating with IrBPs is applied over a white primer, total solar reflectance is significantly higher than if the coating has standard pigments.

Cool colors for steep-slope roofs can also be used for walls, but solar radiation control cannot be as effective on walls as it is on roofs. Vertical surfaces, especially south-facing walls that are shaded by overhangs, do not receive maximum solar load during peak cooling times of the day or of the year. When the noontime sun is low enough for high solar load on walls, the building may need heating rather than cooling. However, coating a wall with cool colors is a potential energy saving improvement that can be done without disturbing the structure of the building. This is valuable for retrofits.

A project was initiated in May 2004 to compare the thermal performance of walls coated with cool and standard colors. Prior to this project there was a lack of data on the thermal performance of exterior walls with cool colors. By the combination of field tests and generalizations with a validated model,

***T.W. Petrie** is a research engineer, **J.A. Atchley** is an engineering technologist, **P.W. Childs** is a staff engineer, and **A.O. Desjarlais** is a group leader in the Building Envelopes Group, Engineering Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN.*

© 2007 ASHRAE.

the project quantifies the potential energy savings from cool colors on walls. This project follows extensive work on solar radiation control, first for low-slope roofs on commercial buildings that led to the solar radiation control calculator for low-slope roofs (Petrie, *et al*. 2001) and then for steep-slope roofs on residential buildings that led to the steep-slope calculator.

This paper explains the test procedures that were followed and describes the test sections that were configured for the cool wall project. The procedures included using the computer program PROPOR to judge the consistency of the data. Data are then presented for walls coated with cool and standard colors on a test building at a U.S. national laboratory in Oak Ridge, Tennessee. Differences in solar reflectance cause different outside surface temperatures and inside heat fluxes under the cool and standard coatings. Daily variations of these quantities are discussed and annual summaries are generated.

Models of the test walls and validation with the test data are described. Models of a single-story residence are formulated in which the walls are coated with and without IrBPs in the coatings. The models are exercised in several cooling and mixed climates to show differences in annual whole house energy use and peak cooling loads due to the IrBPs. The differences in annual energy use are generalized in terms of heating degree-days for breakeven energy savings from use of cool colors.

DESCRIPTION OF PROCEDURES AND TEST SECTIONS

The procedures used in this project have been refined over more than a decade of monitoring the thermal performance of low-slope and steep-slope roofs. Test sections with and without solar radiation control are placed side-by-side and instrumented identically. A heat flux transducer measures the instantaneous rate of heat flow through each assembly. Thermocouples are placed on surfaces in each assembly, including the exterior and interior surfaces, to measure the temperature profile. Concurrently, weather data are acquired in order to establish the conditions imposed on the assemblies. At several times during a long test, solar reflectance of the exterior surfaces is measured.

A manufacturer of coatings provided the coatings and expertise in their application for this project. The company makes colored coatings with and without IrBPs. They are intended for application over a white primer. A test building at a U.S. national laboratory in Oak Ridge, Tennessee had an uncoated stucco wall test section that was available for the project. Oak Ridge has a mixed climate, with significant cooling and heating needs. This gave an opportunity to observe the cooling savings as well as the severity of the heating penalties due to use of IrBPs in wall coatings.

The test sections and instrumentation are sketched in Figure 1. Since heat flux transducers are most accurate if buried in solid materials, they should be inside test sections. To avoid the need to cut into the existing wall, a 2 ft x 2 ft (0.61 m x 0.61 m) square of gypsum board was prepared for each test section. A heat flux transducer was placed in the middle of one surface of each square flush with the surface. Therefore, the heat flux transducers were used between gypsum surfaces near room temperature. They were calibrated in the same configuration using a heat flow meter apparatus according to ASTM C518-98: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.

The inside and outside of the side-by-side test sections in Oak Ridge are shown in Figure 2. The left side of Figure 2 shows the gypsum panels added at the inside of the test sections. The right side shows the reconfiguration of the south-facing, stucco-coated, ventilated wall. The inlet vents at the bottom of the wall were covered with metal tape. A pyranometer was added to the wall to complement the horizontal solar pyranometer that is part of a complete weather station nearby. The thermocouples on the outside were attached with caulk that was allowed to cure before the coating was done. The 4-ft (2.4-m) width of the test section spans three stud spaces in the wall. The middle stud space was instrumented for previous experiments. The instrumentation was left undisturbed and monitored during this project for additional insight.

The entire stucco-coated area was primed with the manufacturer's white primer. A strip of the primer was left exposed. After the primer had dried thoroughly, the area over the east stud space and the upper half of the center stud space was coated with a coating containing IrBPs (IR test section). The area over the west stud space and the lower half of the center stud space was coated without them (non-IR test section). This pattern is difficult to see in the right side of Figure 2 because the colors of the two coatings are the same to the human eye.

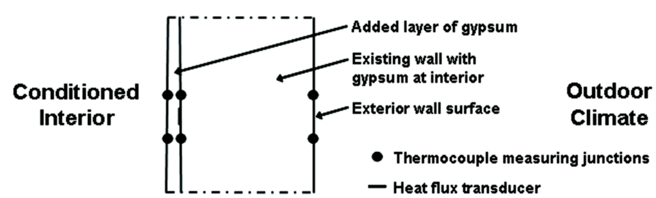

Figure 1 *Arrangement of instrumentation and added gypsum layer to comprise test sections.*

Figure 2 *Inside view of the test sections (left) and coated areas on the stucco-coated test wall (right) at the test site in Oak Ridge, Tennessee.*

PROPOR Computer Program

The computer program PROPerties Oak Ridge (PROPOR) was available for estimation of the thermal properties of test sections from field measurements. It was developed as a specific application of parameter estimation techniques by Professor J.V. Beck (Beck and Arnold 1977) and validated for use with components of building envelopes by Beck, *et al.* (1991).

PROPOR uses the measured temperatures at the surfaces of a test section as boundary conditions for the transient heat conduction equation in finite difference form. Trial values of the thermal conductivity and volumetric heat capacity are generated to predict heat flux and temperature internal to a test section. Differences between the internal predictions and measurements are used to select the best estimates of the property values from the trials. The output from a convergent run of PROPOR includes a calculation of the confidence regions about the estimates.

PROPOR was used to show the consistency of the evolving data relative to expected thermal resistance and thermal mass for each test section. Consistent data are needed for validation of models for the thermal performance of assemblies with and without solar radiation control. PROPOR cannot be used without data from a particular test. Therefore, its estimates are limited to the conditions of the test. Validated models can be configured with characteristics other than the ones for the validation task and can be exercised for a variety of climatic conditions.

OBSERVED BEHAVIOR OF TEST WALLS

Solar Reflectance

The reflectance of the coatings over the white primer and the primer itself was measured at four times during the year of monitoring according to ASTM C 1549, Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer. The reflectometer reports reflectance over the solar spectrum after different paths through atmospheric air. Air Mass 0 is for the extraterrestrial solar spectrum. Air Mass 1 is for the spectrum after a beam of solar radiation with a solar zenith angle of 0° (directly overhead) arrives at the Earth's surface. Air Mass 1.5 is for the spectrum with a solar zenith angle of 48.2°. Air Mass 2 is for the spectrum with a solar zenith angle of 60°. Outputs from the four detectors in the reflectometer are combined to yield the reflectance for the different air masses.

Table 1 shows the annual average solar reflectance for the surfaces. The overall reflectance, shown in the last column, is the average of measurements for Air Mass 2 taken at the beginning and end of the progression of values, shown in the other columns, over the range of air mass settings and detectors in the instrument. The values for individual detectors correspond approximately to reflectance in the portions of the solar spectrum indicated by their labels in Table 1 (Petrie, *et al.* 2000).

The values of reflectance for AM2 (overall), AM1.5 and AM1 are not much different for each surface. The reflectance for AM0 is lower but of little practical consequence for terrestrial applications. The infrared detector gives a significantly higher reading for the IR coating compared to the non-IR coating. This behavior continues somewhat into the red. The blue and ultraviolet readings are essentially the same for both coatings. The higher infrared and red detector responses for the IR coating lead to its higher overall reflectance.

The reflectance of the white primer is higher than the corresponding reflectance of the colored coatings for all full spectrum values and for all detectors except the infrared detector for the IR coating. Solar radiation that is transmitted through the IR coating reflects off the white primer and goes back through the IR coating. Significantly more infrared absorption occurs in the non-IR coating so its solar reflectance is less.

The white primer and both coatings did not undergo much weathering during the test on the vertical surface. The primer, although not intended to be exposed, showed reflectance remaining within -0.05 of the fresh value for this year. Our experience with white coatings indicates that reflectance changes an average of -0.27 on low-slope roofs in the first two years of weathering (Petrie, *et al.* 2001). The colored coatings showed less variability, remaining within ±0.006 of their average values over the year. This is less than the ±0.008 confidence level for the reflectometer.

Results from Use of PROPOR

Hourly averages of the temperatures and heat fluxes during 13 four-week periods ("months") were prepared as input to PROPOR. Figure 3 shows the resulting best estimates of the R-value and volumetric heat capacity of the side-by-side test sections of identical construction. The values in Figure 3 are for the test sections without the added gypsum panel. The first month is most of August 2004; the last is most of July 2005. The middle months are during the winter season in

Table 1. Annual Average In-Situ Solar Reflectance over Air Masses and Detectors Using a Portable Solar Spectrum Reflectometer for Coatings on the Test Sections

Surface	AM1.5	AM1	AM0	Infrared	Red	Blue	Ultraviolet	Overall
Exposed Primer	0.685	0.684	0.654	0.628	0.728	0.760	0.224	0.690
Non-IR Coating	0.237	0.236	0.232	0.245	0.238	0.243	0.146	0.238
IR Coating	0.500	0.483	0.472	0.702	0.489	0.246	0.157	0.495

Table 2. Details of the Test Wall in Oak Ridge, Tennessee

Component	Thickness*, in.	R-value†, h·ft²·°F/Btu	ρc‡, Btu/(ft³·°F)
Stucco	1.0	1.03	3.84
Air	0.75	0.9-4.1	0.002
OSB	0.5	0.71	1.24
Fiberglass	3.5	11.01	0.059
Gypsum	0.5	0.42	1.04
	6.25 (sum)	14.1 (low sum)-17.3 (high sum)	3.8 (stucco only)- 6.2 (volume weighted)

* Multiply thickness in in. by 25.4 for mm
† Multiply R-value in h·ft^{2}·°F/Btu by 0.1761 for m^{2}·K/W
‡ Multiply volumetric heat capacity in Btu/(ft^{3}·°F) by 66.99 for kJ/(m^{3}·K)

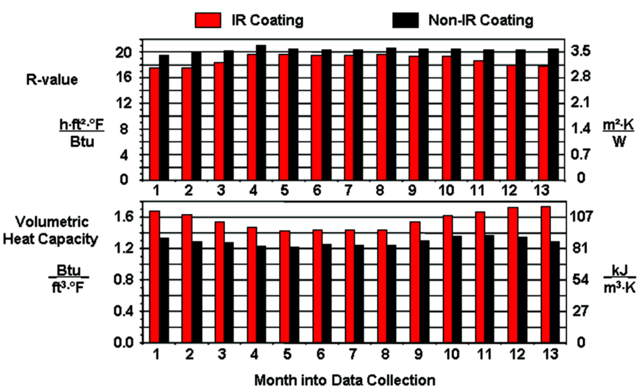

Figure 3 *Best estimates of R-value and volumetric heat capacity for the test sections in Oak Ridge, Tennessee.*

Tennessee. The results show a slight seasonal variation in the R-values and thermal mass. The R-value is higher during winter, which is reasonable behavior for solid materials as average temperature decreases.

The average R-value estimated over the year is 18.8 h·ft^{2}·°F/Btu [3.31 m^{2}·K/W] for the IR test section and 20.3 h·ft^{2}·°F/Btu [3.57 m^{2}·K/W] or 8% higher for the non-IR test section. The confidence intervals for both test sections are less than ±2% of the best estimates, indicating good confidence. The average volumetric heat capacity is 1.6 Btu/(ft^{3}·°F) [107 kJ/(m^{3}·K)] for the IR test section and 1.3 Btu/(ft^{3}·°F) [87 kJ/(m^{3}·K)] or 19% lower for the non-IR test section. Confidence intervals are good, less than ±3%.

Table 2 lists the components through the insulation path in the wall, their thicknesses, and values of their properties at room temperature taken directly or deduced from the ASHRAE Handbook of Fundamentals (ASHRAE 2005). Annual average temperature of the test sections is 68°F to 70°F (20°C to 21°C) so properties at room temperature are appropriate. The last row of the table is for the whole test section. The total thickness is the sum of the component thicknesses. Likewise, the total R-value is the sum of the R-values for the components in series. The higher effective R-value of the air space assumes the air is perfectly still. A more likely value for the R-value of a 0.75-in.(19-mm)-thick vertical air space bounded by non-metallic surfaces is 0.9 h·ft^{2}·°F/Btu [0.16 m^{2}·K/W] (ASHRAE 2005). Total R-value of the test section from the properties of its components is 14.1 to 17.3 h·ft^{2}·°F/Btu [2.48 to 3.05 m^{2}·K/W]. The average R-18.8 (RSI-3.3) from PROPOR for the IR test section is closer to the upper end of this range than the R-20.3 (RSI-3.6) from PROPOR for the non-IR test section.

The higher value of total volumetric heat capacity in the last row and column of Table 2 is the volume-weighted average over all components. This assumes thermal mass is equally effective wherever it occurs in the test section. The most effective thermal mass is that which sees significant temperature fluctuation. By this criterion, volumetric heat capacity would be lower and approximately that of the stucco. Accordingly, volumetric heat capacity of both test sections is 3.8 to 6.2 Btu/(ft^{3}·°F) [255 to 415 kJ/(m^{3}·K)]. The 1.6 (107) from PROPOR for the IR test section is closer to the lower end of this range than the 1.3 (87) from PROPOR for the non-IR test section.

The data from Oak Ridge yield consistent estimates by PROPOR of R-value and volumetric heat capacity from month to month. Because of this, they are considered suitable for validation of a model for the thermal behavior of walls with and without IrBPs in their coatings. The estimates from PROPOR are significantly higher than the expected R-value and lower than the expected volumetric heat capacity for the test sections. This is attributed to the fact that PROPOR treated each test section as a homogeneous material between the outside surface and the gypsum interface.

The estimates for the IR test section are closer to the expected values. On this basis, the measurements for the IR test section are considered more accurate. This is despite identical instrumentation and test procedures for both test sections. Peak outside surface temperatures for the IR test section were

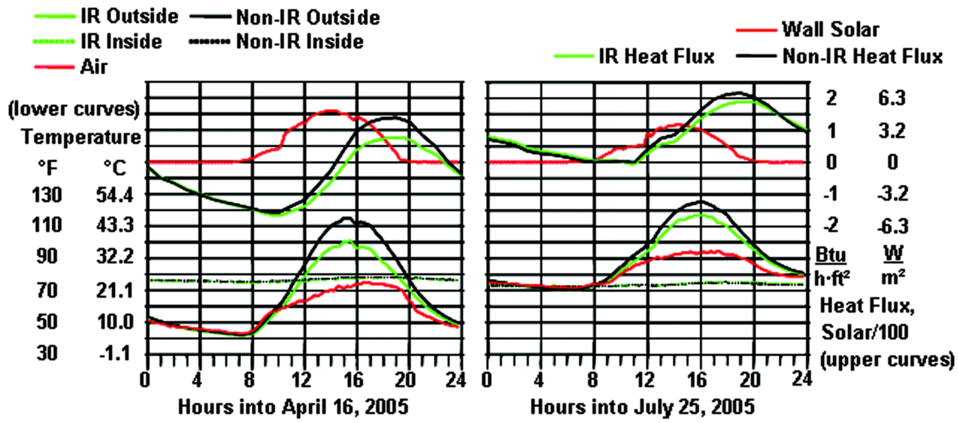

Figure 4 *Comparison of temperatures and heat fluxes with IrBPs (IR) and without IrBPs (non-IRs) for a spring and summer day in Oak Ridge, Tennessee.*

lower, as were the peak internal temperatures and heat fluxes used by PROPOR to produce its estimates and confidence in them. Regardless, this should not cause a difference in accuracy for the two test sections.

Measurements of Outside Surface Temperature and Inside Heat Flux

Daily Variation. Figure 4 is an example of the side-by-side behavior of the non-IR and IR test sections during the year of monitoring. Temperatures are on the lower curves of the figures and heat/solar fluxes are on the upper curves. A clear spring day is shown on the left and a clear summer day is shown on the right. The outside air temperature goes from 40°F (4.4°C) at night to 75°F (24°C) at midday for the spring day. It goes from 70°F (21°C) to 95°F (35°C) for the summer day. The peak solar radiation incident on the wall is higher in spring than in summer due to the lower peak solar altitude in spring. Solar heat gain through the wall is desirable on the spring day. On the summer day solar radiation control is desirable to decrease load due to solar absorption.

The temperature inside the test building is maintained between 70°F (21°C) and 75°F (24°C) year round for conditioning of materials and for the comfort of researchers. Inside and outside surface temperatures behave as expected on both days. Inside surface temperatures are always about equal and constant. Outside surface temperatures are the same under the non-IR and IR coatings at nighttime, in the absence of solar effects. They become nearly equal to the air temperature when daytime solar effects damp out.

During daytime the peak outside surface temperature of the non-IR coating is higher than that of the IR coating because of the lower solar reflectance of the non-IR coating. In response to the higher wall solar heat flux for the spring day, the difference between peak outside surface temperatures under the non-IR and IR coatings is slightly larger for the spring day than for the summer day. This is an indication that the IR coating over the white primer is performing as expected.

The heat fluxes through the gypsum interface also behave as expected. The nighttime heat fluxes become equal for both coatings when solar effects damp out. At night for the spring day, they become negative because the outside surface temperature is below the inside temperature. At night for the summer day, they tend to zero because the outside and inside temperatures are both about 72°F (22°C). Peaks in heat fluxes for both test sections occur about four hours after peaks in the outside surface temperature. This is because the stucco coating adds thermal mass to the otherwise lightweight wall.

The difference between the peak heat fluxes under the non-IR and IR coatings is larger for the spring day than for the summer day. There is more solar flux incident on the wall during the spring day. Reduction of peak heat flux on the July day is of more interest for potential peak load savings during the cooling season. For this particular situation, the IR coating yields 13% less peak heat flux than the non-IR coating.

For all of the spring day, the outside air temperature is below the inside air temperature. The building needs heating all day. The positive heat fluxes through the wall, which supply some of this heat, are less for the IR wall than the non-IR wall. This is an example of what is termed a heating penalty associated with solar radiation control.

Annual Summary. Annual averages of outside surface temperature and annual cooling/heating loads at the gypsum interface are proposed to permit quantitative comparisons to predictions by a model. Table 3 lists these results for the 8760 hours in the year of monitoring. Data were acquired at 1 minute intervals and were averaged hourly before the data in Table 3 were generated.

Temperatures are measured by thermocouples with an uncertainty of ±0.5°F (±0.3°C) but averaging over multiple sensors and multiple measurements is taken to improve this to ±0.05°F (±0.03°C). To this level of uncertainty, the outside surface of the non-IR wall is significantly warmer on average than the IR wall. The 2.7°F (1.5°C) difference over the year is reason-

Table 3. Annual Average Measured Temperatures at the Outside Surface and Cooling/Heating Loads at the Gypsum Interface for the ORNL Test Sections

	IR	Non-IR	Non-IR – IR
Average outside surface temperature, °F (°C)	65.3 (18.5)	68.0 (20.0)	2.7 (1.5)
Cooling load, Btu/ft^2 (kJ/m^2)	1035 (11760)	1302 (14780)	267 (3020)
Heating load, Btu/ft^2 (kJ/m^2)	–4903 (–55680)	–4642 (–52720)	261 (2960)

able considering that the walls have the same outside surface temperature for many hours when there are no solar effects.

To generate cooling and heating loads, inward-directed and outward-directed heat fluxes, respectively, were summed with the same constraints as used for our solar radiation control calculators (Petrie, *et al.* 2001). For cooling loads, inward-directed heat fluxes are included only if hourly outside air temperature is greater than 75°F (23.9°C). For heating loads, outward-directed heat fluxes are included only if outside air temperature is less than 60°F (15.6°C). Air temperatures were available from the weather station nearby. These constraints on the sums of the heat fluxes are meant to duplicate the deadband where a building does not need cooling or heating.

Measured heat fluxes are considered uncertain to at least ±5%, or ±60 and ±240 Btu/ft^2 (±700 and ±2700 kJ/m^2) for the magnitude of cooling and heating loads, respectively, in Table 3. To the level of uncertainty of the cooling load, it is significantly higher for the non-IR wall than the IR wall, which is consistent with the higher outside non-IR surface temperatures. To the level of uncertainty in the heating loads, not much significance can be attributed to the difference between them, even though it is about the same as the difference in cooling loads. Since many outward-directed heat fluxes occur at night, when no difference is expected in the thermal behavior of the two test sections, this small difference is reasonable. Regardless, the heating load is slightly larger for the IR wall than the non-IR wall. This is consistent with the IR wall being less absorptive and, therefore, cooler than the non-IR wall when solar effects could help with heating by decreasing the temperature difference from inside to outside.

VALIDATION OF DOE 2.2 MODEL OF WALLS

Preparation of Input

The goal of the modeling task is validated models for the walls of whole buildings in various climates with different wall configurations. Buildings usually have four walls that face in different directions. The walls receive solar radiation directly and by reflection from the ground and the sky. Overhangs and other architectural features, as well as landscaping and nearby buildings, create shading that affects the amount of solar radiation that strikes the walls. The public domain program DOE 2.2 (Hirsch 2003) was selected as the modeling tool in this project because it accounts for solar insolation of walls from the sun, sky and ground and can model shading.

The south-facing wall in the model of a single-story residence with wood-framed walls was modified to accommodate the features of the test sections. DOE 2.2 assumes that wall surfaces have the infrared emittance of common non-metallic materials. It requires an estimate of the solar reflectance of all exterior wall and roof surfaces and assumes that they are opaque. For the non-IR and IR surfaces, overall annual average solar reflectance in Table 1 was used. The solar reflectance of the ground seen by each exposure is also required. The range suggested in the DOE2 support documentation is 0.08 for dark soil or asphalt to 0.24 for dry grass. Separate runs were made in each case of interest for ground reflectance of 0.08 and 0.24.

To allow direct comparison of predicted and measured results, the weather and solar conditions to DOE 2.2 were generated from the hourly averages of the measured climatic conditions. DOE2 has a utility to take user-generated weather files in proper format and pack them for use by DOE 2.2. Table 4 lists what DOE 2.2 requires, its units or values, and how it was obtained. Records from the weather station from August 5, 2004 through August 4, 2005 and the procedures in Table 4 yielded 8760 entries for a DOE 2.2 weather file. The entries were rearranged to go from January 1 through December 31, checked for consistency at the end of August 4, put into proper format and packed by the DOE2 weather utility.

Predictions of Outside Surface Temperature and Inside Heat Flux

Daily Variation. DOE 2.2 has an hourly report feature, which permitted outside surface temperatures predicted for the south-facing walls at the Oak Ridge site to be output to a spreadsheet. There they were compared to the measured average surface temperatures. Graphs for several clear days during the project verified that the predictions and measurements agreed in terms of nighttime and peak behavior. The agreement was qualitative in that only visual comparisons were made.

Predicted heat fluxes at the interface between the layers of gypsum in the walls required use of the program STAR (Wilkes 1989). Internal heat fluxes are not available from the transfer functions used in DOE 2.2. STAR was used with specified temperatures as boundary conditions. For the respective test sections, the inside boundary condition for STAR was the temperature measured at the inside surface. Two sets of outside boundary conditions were used, comprising the outside surface temperatures predicted by DOE 2.2 for ground reflectance of 0.08 and 0.24, respectively. Graphs were

Table 4. Weather File Data Requirements for DOE 2.2 and Source of Data for Validation Task

Weather File Entry	Units or Values	Procedure to Obtain Entry
Month	—	Weather station record
Day	—	Weather station record
Hour	—	Weather station record
Wet-bulb temperature	°F	Utility fragment*
Dry-bulb temperature	°F	Weather station outside temperature
Atmospheric pressure	in.-Hg	Weather station outside pressure
Cloud amount	#: 0 to 10	From weather station pyrgeometer†
Snow flag	#: 0,1	Set to 0 (assumes all snow counted as rain)
Rain flag	#: 0,1	1 if weather station Δrain > 0.01 in. for hour
Wind direction	#: 0 to 15	Weather station wind vane, ranges of ° to #
Humidity ratio	—	Utility fragment*
Moist air density	lb/ft^3	Moist ideal air from P, T, humidity ratio
Moist air enthalpy	Btu/lb	Utility fragment*
Horizontal solar	$Btu/(h \cdot ft^2)$	Weather station pyranometer
Direct solar	$Btu/(h \cdot ft^2)$	Utility fragment*
Cloud type	#: 0,1,2	Set to 1
Wind speed	Knots	Weather station anemometer, mph to knots

* Code in DOE2 utilities compiled to yield weather file entries from station location and data.
† Order of statements in STAR program reversed in a spreadsheet to use sky temperature from pyrgeometer record to yield cloud amount. STAR (Simplified Transient Analysis of Roofs) is a program written by K.E. Wilkes (1989) to do finite-difference, transient, one-dimensional, thermal conduction in multilayer assemblies. Climatic conditions can be specified at the outside boundary, for which STAR has an algorithm to convert cloud amount to sky temperature.

prepared for the same clear days used to compare the outside surface temperatures. The same qualitative agreement was achieved between predictions and measurements.

Annual Comparisons. Annual averages were generated for the predicted outside surface temperatures. To obtain cooling and heating loads, sums of predicted inward-directed and outward-directed heat fluxes through the gypsum-gypsum interface were constrained by outside air temperatures like they were for measured cooling and heating loads in Table 3. Table 5 lists the predicted annual average outside surface temperatures and cooling and heating loads for each test section and the limiting values of ground reflectance. Measured summaries are repeated from Table 3. The data in Table 5 convey quantitatively how well the predictions by DOE 2.2 (with STAR) agree with the measurements for the IR and non-IR test sections.

Over the year of testing for the situation in Oak Ridge, predicted outside surface temperatures and cooling loads for ground reflectance of 0.08 are closer to the measurements than those for ground reflectance of 0.24. The ground directly in front of the test sections is covered with gravel, apparently closer in reflectance to dark soil than dry grass. As expected, ground reflectance makes little difference for the heating loads.

Using the predictions for ground reflectance of 0.08, agreement between predictions and measurements for the IR test section is within 1% for the average outside surface temperature and within 4% for the cooling load. For the non-IR test section the agreement is within 3% for the temperature and within 22% for the cooling load. Predicted heating loads are 15% larger than measured for both test sections. The lack of excellent agreement between measured and predicted surface temperatures and cooling loads for the non-IR test section is roughly consistent with the conclusion from use of PROPOR on the measurements. It showed that the results from the non-IR test section were less accurate than those from the IR test section by about 10% to 20%.

Conclusions about Model Validation

The model for this project seeks to predict the difference in performance of walls coated with and without IrBPs. Despite the excellent agreement for the IR test section between measurements and predictions with ground reflectance of 0.08, the difference between predicted non-IR and IR annual average outside surface temperatures is 4.0°F (2.2°C) from DOE 2.2 with ground reflectance of 0.08. This is 48% more than the 2.7°F (1.5°C) from the measurements. For ground reflectance of 0.08, predicted difference between non-IR and IR cooling loads at the gypsum interface is 594 Btu/ft^2

Table 5. Annual Measured and Predicted Average Temperatures at the Outside Surface and Cooling/Heating Loads at the Gypsum Interface for the ORNL Test Sections

	IR	Non-IR
Measured outside surface temperature, °F (°C)	65.3 (18.5)	68.0 (20.0)
DOE 2.2 with ground reflectance of 0.08	65.8 (18.8)	69.8 (21.0)
DOE 2.2 with ground reflectance of 0.24	66.9 (19.4)	71.3 (21.8)
Measured cooling load, Btu/ft^2 (kJ/m^2)	1035 (11760)	1302 (14780)
STAR from DOE 2.2 Tos with ground reflectance of 0.08	999 (11350)	1593 (18090)
STAR from DOE 2.2 Tos with ground reflectance of 0.24	1223 (13890)	1924 (21850)
Measured heating load, Btu/ft^2 (kJ/m^2)	–4903 (–55680)	–4642 (–52720)
STAR from DOE 2.2 Tos with ground reflectance of 0.08	–5624 (–63870)	–5323 (–60460)
STAR from DOE 2.2 Tos with ground reflectance of 0.24	–5516 (–62640)	–5208 (–59150)

(6750 kJ/m^2). This is 120% more than the 267 Btu/ft^2 (3020 kJ/m^2) from the measurements.

Using the DOE 2.2 model to quantify the difference in thermal performance of walls coated with and without IrBPs for conditions other than those of the field tests is likely to give a larger difference than measurements would yield. If results from a model cannot be expected to be the same as results from measurements, and they usually cannot in complex situations, then it is hoped that the model is conservative. That has not been proven true for this project.

APPLICATION OF DOE 2.2 MODEL IN COOLING AND MIXED CLIMATES

Whole House Model

To do hour-by-hour estimates of energy use for a whole building, DOE2.2 needs hourly weather information and a description of the building, its occupants, its equipment and how it is operated. A carefully chosen base is important to put into proper perspective the effect of using a wall coating with IrBPs instead of one without them. The walls should have typical size and configuration so that the effect of coating them with IrBPs is typical. The rest of the energy use by the house should also be typical. The small house, whose south-facing wall was modified to validate the handling of wall loads in DOE 2.2, is considered such a base. Many houses with the floor plan of the modeled house have been built by Habitat for Humanity and energy use due to its thermal envelope has been compared to measurements (Petrie *et al.* 2002, Petrie et al. 2005).

Two different configurations of walls were specified. In one the walls were nominal 2x4 (38 mm x 89 mm) wood-framed walls with studs 16 in. (406 mm) oc and R-11 (RSI-1.9) batt insulation between them. Concrete stucco 1-in. (25-mm)-thick and a ¾ in. (19 mm) unvented air layer were outside over the sheathing. A single layer of ½-in.(13-mm)-thick gypsum was inside. The other configuration of walls was considered more typical of houses in severe cooling climates. Concrete masonry units (CMUs), 8-in. (20-mm)-thick, were coated outside with 1 in. (25 mm) of concrete stucco. They were covered by R-5 (RSI-0.9) foam and ½-in.(13-mm)-thick gypsum on the inside. The effect was included of typical eave overhangs that extend 2 ft (0.61 m) out from the walls. For residential applications, dry grass is considered typical of the ground cover near the walls. A ground reflectance of 0.24 was specified in all climates.

Energy use of occupants is very important for determining the total energy use of a house. The Building America Performance Analysis Resources (NREL 2004) were used to obtain the energy use profile for the three occupants of the three-bedroom home. The resources provide daily and hourly schedules for occupancy, lighting, hot water use, appliance loads and plug loads.

Four cooling climates (Miami, Phoenix, Las Vegas and Bakersfield) and three mixed climates (Richmond, VA, Knoxville, TN and Sacramento) were selected to show the response of the residence to having its walls coated with and without IrBPs. Weather data from the TMY2 set were used (NREL 1995). The forced-air HVAC system chosen as typical for the climates used an air-to-air heat pump sized for each climate. Typical peak efficiency was input and electric resistance supplemental and emergency heating were specified. DOE 2.2 defaults were used for heat pump heating capacity and for all part load curves. DOE 2.2 summary reports provided annual totals of energy use for heating, cooling and other major uses, as well as component and total loads for the respective peak cooling and heating hours during the whole year.

Whole House Energy Usage and Wall Peak Cooling Loads

For the seven climates arranged in order of decreasing cooling degree-days, the top half of Table 6 lists cooling, heating and total energy needs and wall peak cooling loads of the single-story houses with wood-framed walls. The walls are coated with coatings that do not contain IrBPs. The bottom half of Table 6 shows the same data for CMU walls coated without IrBPs. Peak cooling loads for the houses generally occurred between 5 pm and 7 pm on a day in late June or early July.

Table 6. Annual Electricity Needs and Peak Wall Cooling Loads in Various Climates for Occupied Single-Story Residences with No IrBPs in the Wall Coatings

Annual House Electricity Needs Peak Wall Cooling Loads	Cooling, kWh	Heating, kWh	Total, kWh	Load, kBtu/h (kW)
Walls: Wood Studs + R-11 (RSI-1.9) Batts				
Miami (4126; 141)*	5172	8	12958	2.51 (0.74)
Phoenix (3814; 1154)	4794	245	12996	3.79 (1.11)
Las Vegas (3066; 2293)	3483	851	12602	3.39 (0.99)
Bakersfield (2367; 2100)	2729	863	11961	3.28 (0.96)
Richmond, VA (1458; 4097)	1501	4300	14608	2.74 (0.80)
Knoxville, TN (1366; 3662)	1610	3804	14219	2.77 (0.81)
Sacramento (1144; 2794)	1387	1650	11679	2.99 (0.88)
Walls: Concrete Masonry Units + R-5 (RSI-0.9) Foam				
Miami (4126; 141)	5540	10	13328	2.96 (0.87)
Phoenix (3814; 1154)	5185	339	13481	4.89 (1.43)
Las Vegas (3066; 2293)	3739	1124	13131	4.69 (1.38)
Bakersfield (2367; 2100)	2915	1152	12436	4.48 (1.31)
Richmond, VA (1458; 4097)	1568	5085	15460	2.98 (0.87)
Knoxville, TN (1366; 3662)	1693	4549	15047	2.80 (0.82)
Sacramento (1144; 2794)	1388	2133	12163	2.98 (0.87)

* (cooling; heating degree-days base 65°F). For base 18°C, multiply by 5/9.

The data in Table 6 show that the extra thermal mass of the CMUs does compensate somewhat for the lower R-value of the CMU walls compared to the wood-framed walls. The annual electricity use in any category and location and the peak wall cooling load for any location are only slightly higher for the CMU-walled house. As the houses are configured, annual heating and cooling needs are about one-quarter to one-half of the total electricity use. Fixed annual energy uses for both houses include 1330 kWh for lights and 4250 kWh for appliance and plug loads. Energy for hot water varies with location because of climate-dependent inlet water temperature. The variation is from 2200 kWh in Miami to 3230 kWh in Richmond, VA despite the same amount of use.

Wall peak cooling loads average 20% of the total (sensible + latent) peak cooling load for the houses with wood-framed walls. The variation is from 15% in the humid climate of Miami to 22% in the dry climate of Bakersfield. The average is 23% with variation from 17% to 28% for the houses with CMU walls. Note that the variation with cooling degree-days is more random for peak cooling loads than annual cooling energy.

Net Energy and Peak Load Savings Due to IrBPs in Wall Coatings

Table 7 presents the total annual cooling savings and heating penalties for the houses when the exterior walls are coated with IrBPs instead of without them. The net savings are the cooling savings less the heating penalties. As the houses are configured, they use electricity for all energy needs. A highly efficient heat pump is used to convert the electricity to cooling and heating. The peak wall cooling load savings are the differences between the peak wall cooling loads without IrBPs and the corresponding peak wall cooling loads with IrBPs.

The annual maximum in the solar altitude during the cooling season and the shading from the overhang on the south wall impact the cooling savings for walls. Peak incident solar energy does not occur on the south wall during the peak of the cooling season. Savings are, therefore, modest. For the wood-framed walls, the houses with IrBPs on the walls have 4% to 9% (4% to 6% in the cooling climates) less cooling energy needs than houses without IrBPs on the walls. For the CMU walls, the walls with IrBPs save 6% to 13% (6% to 9% in the cooling climates) compared to the walls without them.

The decrease in solar altitude from summer to winter makes for significant heating penalties for walls. Relative to roofs, more solar energy impinges on south-facing walls and is blocked by the IrBPs when it could help with heating. For the wood-framed walls, the houses with IrBPs on the walls require 4% to 14% (4% to 7% in the mixed climates) more heating energy than houses without them. For the CMU walls, the houses with IrBPs require 5% to 24% (5% to 11% in the mixed climates) more heating energy than houses without them. Percentages for net savings are generated using the same basis as for cooling energy savings, that is, with respect to the cooling energy needs for houses with no IrBPs in the wall coatings. With wood-framed walls, the variation is from -3% to 4% (3% to 4% in the cooling climates). With CMU walls, the variation is from -6% to 6% (1% to 6% in the cooling climates).

Table 7. Annual Cooling Savings, Heating Penalties and Net Electricity Savings and Peak Wall Cooling Load Savings in Various Climates with IrBPs in the Wall Coating Relative to No IrBPs for Occupied Single-Story Residences

Annual House Electricity Savings Peak Wall Cooling Load Savings	Cooling Savings, kWh	Heating Penalties, kWh	Net Savings, kWh	Wall Load Savings, kBtu/h (kW)
Walls: Wood Studs + R-11 (RSI-1.9) Batts				
Miami (4126; 141)*	215	1	+214	0.40 (0.12)
Phoenix (3814; 1154)	238	34	+204	0.42 (0.12)
Las Vegas (3066; 2293)	184	91	+93	0.31 (0.09)
Bakersfield (2367; 2100)	170	80	+90	0.89 (0.26)
Richmond, VA (1458; 4097)	107	157	-50	0.48 (0.14)
Knoxville, TN (1366; 3662)	123	139	-16	0.62 (0.18)
Sacramento (1144; 2794)	126	112	+13	0.50 (0.15)
Walls: Concrete Masonry Units + R-5 (RSI-0.9) Foam				
Miami (4126; 141)*	352	2	+350	0.45 (0.13)
Phoenix (3814; 1154)	357	82	+275	0.56 (0.17)
Las Vegas (3066; 2293)	251	209	+42	0.52 (0.15)
Bakersfield (2367; 2100)	252	168	+84	1.07 (0.31)
Richmond, VA (1458; 4097)	164	260	-96	0.60 (0.18)
Knoxville, TN (1366; 3662)	187	245	-58	0.76 (0.22)
Sacramento (1144; 2794)	180	223	-43	0.64 (0.19)

* (cooling; heating degree-days base 65°F). For base 18°C, multiply by 5/9.

At the peak cooling hour, average savings in peak wall cooling load due to the IR coating on the wood-framed walls are 17%. This is larger than the 13% savings in peak heat flux observed in Figure 4 for the wood-framed test wall. As concluded from the validation effort, the model predicts non-conservative differences. The CMU walls show 19% average peak wall cooling load savings. Over all locations, the cooling loads for the wood-framed and CMU walls without IrBPs average 20% and 23% of the respective total loads. The smaller wall loads with IrBPs are 17% and 19% of their respective slightly smaller total loads. Multiplying average wall savings by percentage of total load for non-IR walls yields at most only 3% whole house peak load savings for IrBPs on wood-framed walls and 4% for IrBPs on CMU walls of the residence.

Cool Walls vs. Cool Roofs

Table 7 shows that, for the occupied single-story residence, heating penalties have caused negative net energy savings from coating the walls with IrBPs in Richmond, VA and Knoxville, TN. Such strong heating penalties are not our experience with use of solar radiation control on roofs (Petrie, *et al.* 2001). Table 8 is presented to show the difference between cool walls and cool roofs on the same house for these locations. Data from Table 7 for the wood-framed and CMU walls are repeated. Additional data show the effect of coating the roof with and without IrBPs.

A roof assembly is modeled in DOE 2.2 like a sloped exterior wall. The attic is an unventilated, sloped air space greater than 4-in. thick. For the house with wood-framed exterior walls coated without IrBPs, its roof is coated without and with IrBPs. The solar reflectance of the wall coatings is assumed to be achieved on a steep-slope roof surface by use, for example, of coated metal. The rest of the house model is the same as it was for the wall cases.

According to DOE 2.2, a well insulated roof is less sensitive to the effect of heating penalties than walls. In Table 8, the ceiling has the same R-26 (RSI-4.6) level of insulation that was used for all wall comparisons. At this level, neither location yields a net penalty for coating the roof with IrBPs, although Richmond, VA is near the breakeven point. In general, solar radiation control is more effective for lower R-value components. This is shown by the results in Table 8 for the poorly insulated roof with R-11 (RSI-1.9) ceiling insulation. Net savings increase in both locations relative to the well insulated roof, but more in Knoxville, TN than in Richmond, VA. Knoxville has fewer heating degree-days than Richmond, but neither has severe heating requirements. The shift from a net energy penalty with IrBPs on walls to net savings with IrBPs on roofs for these locations is a significant result.

Table 8. Trials with DOE 2.2 to Explore Wall vs. Roof Cooling Savings and Heating Penalties in Knoxville, TN and Richmond, VA

Annual Effect of Coatings with IrBPs, kWh	Knoxville, TN			Richmond, VA		
	Cooling Savings	Heating Penalties	Net Benefit*	Cooling Savings	Heating Penalties	Net Benefit*
Wood-framed Walls	123	139	–16	107	157	–50
CMU Walls	187	245	–58	164	260	–96
R_{US}-26 (R_{SI}-4.6) Roof	118	89	+29	100	99	+1
R_{US}-11 (R_{SI}-1.9) Roof	234	172	+62	200	188	+12

* If the net benefit is less than zero, there is a net annual energy penalty for using IrBPs under the circumstances of each application.

Breakeven Energy Savings for Walls vs. Heating Degree-Days

In Table 7, the cooling savings generally decrease and the heating penalties increase as the location of the single-story house goes from cooling to mixed climates. Rates of change with location in the savings and penalties are different for wood-framed and CMU walls. There is a breakeven situation for use of solar radiation control that occurs when less cooling energy is exactly offset by more heating energy. Table 8 implies that the breakeven annual energy savings occur at fewer heating degree days for walls than roofs. This may limit the use of IrBPs on walls more than on roofs. Benefits other than energy effects are not addressed by this breakeven criterion. These include possible durability benefits due to the cooler surface temperatures of the IR wall and the benefits of savings in peak loads.

To quantify where the breakeven occurs, Figure 5 was prepared from DOE 2.2 results for the climates in Table 7 except Miami and Phoenix. Atlanta and Memphis were substituted because they each have about 3100 heating degree-days base 65°F (HDD_{65F}) (1722 HDD_{18C}) and show net annual energy savings near zero. A best-fit straight line is shown for each wall configuration on Figure 5. The mild climate of Sacramento yields the most deviation from the line for each wall. Breakeven occurs at 3350 HDD_{65F} (1860 HDD_{18C}) for the wood-framed wall and at 2850 HDD_{65F} (1580 HDD_{18C}) for the CMU wall. If the decision to coat walls with IrBPs is based solely on potential energy savings for this house, then the walls should not be coated with IrBPs unless the location has fewer heating degree-days than the breakeven level. Atlanta, with 3090 HDD_{65F} (1720 HDD_{18C}), is between the breakeven level for the two walls.

DOE 2.2 can be expected to produce accurate estimates of cooling and heating energy needs if the features of the specific building are accurately described to the model. This would be very important for buildings with high internal loads, possibly to the extent of not showing heating penalties with solar radiation control. For such cases Figure 5 would not apply.

The DOE 2.2 results in this paper are for an occupied single-story house with an all-electric heating and cooling system most suitable for cooling climates. According to

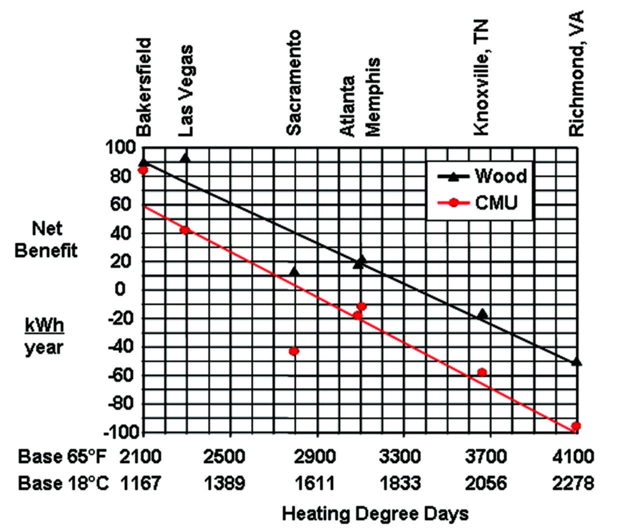

Figure 5 Breakeven annual energy savings with IrBPs in coatings on wood-framed and CMU walls.

Figure 5, the heating penalties exceed the cooling savings for IrBPs on the walls in climates with more severe heating needs than Atlanta. Cooling climates are of most interest. Making the results more general, for example, in the form of a cool wall companion to the cool roof calculators, would require effort to generate and access a database that includes the range of parameters of interest for walls.

Parameters not addressed in this paper include other wall constructions, varying wall heights and widths of overhangs (including single-story vs. multistory), different wall colors as they affect solar reflectance, and different house aspect ratios and orientations. The DOE 2.2 model for this project is not conservative for the effect of IrBPs on the walls of the house. Nonetheless, it indicates at most 6% net energy benefit in cooling climates for use of wall coatings with IrBPs compared to cooling energy without IrBPs. Savings in peak cooling load for the whole house due to IrBPs on the walls are only 3 to 4% on average for all climates. Producing the comprehensive database and devising access to it would not likely be worth the effort.

CONCLUSIONS

A project, begun in May 2004, gathered field data and validated a model for the thermal performance of walls coated with infrared blocking pigments (IR walls) and without them (non-IR walls). IR and non-IR test sections in a south-facing wall at a U.S. national laboratory provided data for validation of a model using the public domain whole building energy use program DOE 2.2. The solar reflectance of the IR and non-IR coatings remained constant at 0.495 and 0.238, respectively, during the year. The ground in front of the test wall was judged to have an average solar reflectance near 0.08.

Annual average outside surface temperatures and both cooling and heating loads due to unit area of a south-facing wall were generated from the measurements. DOE 2.2 predictions were compared to the measurements for the two test sections. The annual average outside surface temperature predicted by DOE 2.2 and annual cooling load generated from the outside surface temperatures predicted by DOE 2.2 agreed almost exactly with the measurements for the IR wall. Agreement for the non-IR wall was not as good. There were no significant differences among the annual heating loads because of lack of significant solar effects in them. The agreement for the IR wall supports the conclusion that the model is valid. Because of the poorer agreement for the non-IR wall, the validation process did not prove that the model conservatively predicts the performance of the IR wall relative to the non-IR wall.

This non-conservative model for the effect of infrared blocking pigments on the exterior walls of a single-story house was exercised in various climates. IrBPs in colored coatings on stuccoed wood-framed walls generated cooling energy savings from 4% to 9% (4% to 6% in the cooling climates). When using IrBPs in colored coatings of stuccoed CMUs, cooling savings varied from 6% to 13% (6% to 9% in the cooling climates). Heating penalties are intrinsic to use of passive solar radiation control, here in the form of IrBPs in wall coatings. They make net savings from use of IrBPs relative to cooling energy without IrBPs vary from -3% to 4% (3% to 4% in the cooling climates) for wood-framed walls and from -6% to 6% (1% to 6% in the cooling climates) for the CMU walls. Savings in whole house peak cooling load were 3% on average over all climates for the use of IrBPs on wood-framed walls and 4% for their use on CMU walls.

The heating penalties exceed the cooling savings due to IrBPs on the walls in climates with relatively few heating degree-days. A plot and linear fit of net annual energy savings as a function of heating degree-days show that zero net energy savings occur at 3350 HDD_{65F} (1860 HDD_{18C}) for wood-framed walls and at 2850 HDD_{65} (1580 HDD_{18C}) for CMU walls. If the decision to coat the walls with IrBPs is based solely on potential energy savings for this house, coating with IrBPs is not advised for locations with heating needs more severe than those of Atlanta (3090 HDD_{65F} or 1717 HDD_{18C}). This conclusion does not account for other possible benefits of the IrBPs such as more durability due to lower surface temperatures and small but positive peak cooling savings.

REFERENCES

ASHRAE. 2005. *2005 Handbook—Fundamentals*, Chapter 25, Table 3; Chapter 39, Table 1. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Beck, J.V. and Arnold, K.J. 1977. *Parameter Estimates in Engineering and Science*. New York: John Wiley and Sons.

Beck, J.V., Petrie, T.W., and Courville, G.E. 1991. “Using Parameter Estimation to Analyze Building Envelope Thermal Performance,” pp. 161-191, *Special Report 91-3, In-Situ Heat Flux Measurements in Buildings: Applications and Interpretations of Results*, S.N. Flanders, ed. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

Hirsch, James J. and Associates. 2003. DOE 2.2 Building Energy Use and Cost Analysis Program. See http://www.doe2.com.

NREL. 1995. TMY2. Typical Meteorological Years Derived from the 1961-1990 National Solar Radiation Data Base. Data Compact Disk. Golden, CO: National Renewable Energy Laboratory.

NREL. 2004. Building America Performance Analysis Procedures. Revision 1. NREL/TP-550-35567 (June 2004). Golden, CO: National Renewable Energy Laboratory. See also http://www.eere.energy. gov/buildings/building_america/pa_ resources.html.

Petrie, T.W., Atchley, J.A., Childs, P.W., and Desjarlais, A.O. 2001. “Effect of Solar Radiation Control on Energy Costs – A Radiation Control Fact Sheet for Low-Slope Roofs,” Proceedings on CD, Performance of the Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes. Practices Session VIB. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. See also http://www.ornl.gov/sci/roofs+walls/facts/SolarRadiation-Control. htm and http://www.ornl.gov/sci/roofs+walls/SteepSlopeCalc/index.htm.

Petrie, T.W., Desjarlais, A.O., Robertson, R.H., and Parker, D.S. 2000. “Comparison of Techniques for *In Situ*, Non-damaging Measurement of Solar Reflectances of Low-Slope Roof Membranes,” pp. 1613-1628, *International Journal of Thermophysics, 22.*

Petrie, T.W., Kony, J., Desjarlais, A.O, Atchley, J.A., Childs, P.W., Ternes, M.P., and Christian, J.E. 2002. “How Insulating Concrete Form vs. Conventional Construction of Exterior Walls Affects Whole Building Energy Consumption: Results from a Field Study and Simulation of Side-by-Side Houses,” pp. 1.235-1.246, *Proceedings 2002 Summer Study of the American Council for an Energy Efficient Economy.* Washington, D.C.: American Council for an Energy Efficient Economy.

Petrie, T.W., Atchley, J.A., Childs, P.W., and Desjarlais, A.O. 2005. “Testing and Modeling of an Autoclaved Aerated Concrete-Walled House in Rossville, Georgia,” submitted to J.K. Kilpatrick, Public Power Institute, Tennessee Valley Authority, March 5, 2005.

Wilkes, K.E. 1989. *Model for Roof Thermal Performance*. ORNL/CON-274. Oak Ridge, TN: Oak Ridge National Laboratory.