Engineering Science and Technology Division
Building Envelope Group

ENERGY SAVINGS FOR STUCCO WALLS COATED WITH COOL COLORS

by

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NOMENCLATURE

BDL	Building Description Language, a programming language required for preparation of input files for DOE 2.2 and earlier versions of the program
BTC	Buildings Technology Center, a technical center at the Oak Ridge National Laboratory in which the research for this report and preparation of it were done
CDD	Cooling degree-days, the difference between average daily outside dry bulb temperature at a location and a reference temperature, when the average temperature is above the reference temperature, *e.g.*, 65°F (18°C) for CDD$_{65}$. If summed over a year, cooling degree-days are a measure of the severity of annual cooling requirements for the location
CMU	Concrete Masonry Unit, commonly known as a concrete block
COP	Coefficient of performance, the ratio of desired output to required input in the same units. Used to indicate the energy efficiency of an air conditioner or heat pump
DOE	U.S. Department of Energy
DOE 2.2	Version 2.2 of the public domain computer program for estimation of annual building energy usage, developed for the U.S. Department of Energy
ESRA	Envelope Systems Research Apparatus, a building at the Oak Ridge National Laboratory that was used for test sections in this project
HDD	Heating degree-days, the difference between a reference temperature and average daily outside dry bulb temperature at a location, when the average temperature is below the reference temperature, *e.g.*, 65°F (18°C) for HDD$_{65}$. If summed over a year, heating degree-days are a measure of the severity of annual heating requirements for the location
HVAC	Heating, ventilating and air conditioning
IR	Designation in this report for a test section having its external surface coated with a coating that contains infrared blocking pigments
IrBP	Infrared blocking pigments, an additive to colored coatings to enhance solar reflectance in the near infrared part of the solar spectrum
LBNL	Lawrence Berkeley National Laboratory, a U.S. National Laboratory noted in this report, along with James J. Hirsch and Associates, for development and technical support of DOE 2.2
Non	Designation in this report for a test section having its external surface coated with a coating that does not contain infrared blocking pigments
ORNL	Oak Ridge National Laboratory, a U.S. National Laboratory noted in this report as home to the Buildings Technology Center and the primary site for the field tests described in this report

PROPOR	PROPerties Oak Ridge, a computer program developed for the Oak Ridge National Laboratory in order to estimate the thermal properties of a test section from a one-dimensional geometric description of it and measurements of temperature and heat flux in it
R-value	Thermal resistance, a property of a test section whose value gives the resistance of the test section to the flow of heat by conduction through it
SEER	Seasonal energy efficiency ratio, a purported seasonal measure of the energy efficiency of an air conditioner that uses electricity to produce a cooling effect. Its units are Btu/(watt·h)
SHPF	Seasonal heating performance factor, a purported seasonal measure of the energy efficiency of an electric heat pump in heating mode. Its units are Btu/(watt·h)
STAR	Simplified Thermal Analysis of Roofs, a computer program developed at the Oak Ridge National Laboratory to predict the one-dimensional temperatures and heat fluxes through a solid assembly in response to geometric and thermal properties of the components of the assembly. It is intended for modeling low-slope roofs when provided boundary conditions for climatic conditions above the roof and room conditions below the roof. In this report it is used with specified surface temperatures to generate heat fluxes internal to the IR and Non test sections at ORNL
TMY2	Test Meteorological Year data derived from the 1961-1990 National Solar Radiation Data Base, a convenient compilation of hourly weather and solar conditions for typical months over the entire year at 235 locations in the U.S., Puerto Rico and the Pacific territories

ABSTRACT

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. They have the same appearance as standard colors but have higher solar reflectance in the infrared. 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 do not receive maximum solar load during peak cooling. When they do, heating may be needed. However, coating a wall with cool colors is an energy saving improvement that can be done without considerable deconstruction and rebuild. To quantify the energy savings, field tests were done at three sites on walls coated side-by-side with and without cool colors. Data from Phoenix and Jacksonville showed the effect of different constructions, orientations and climates. Data from a year of tests in Oak Ridge, TN were judged suitable for validation of a model of a south-facing wall. The DOE 2.2 model of a single-story residence whose south wall was the focus for validation was reconfigured with stucco-coated wood-framed and concrete masonry unit (CMU) exterior walls with typical overhangs. Building America Performance Analysis Resources were used to specify schedules for occupants and their energy consumption. The house model including walls with and without cool colors was exercised in cooling and mixed climates. Annual cooling energy savings for use of cool colored (solar reflectance of 0.495) instead of conventional coatings with the same green hue (solar reflectance of 0.238) were 4% to 13% (4% to 9% in cooling climates). The higher percentages were for the CMU walls with lower R-value. The annual heating penalty was 4% to 24% (4% to 10% in the mixed climates) and exceeded cooling savings for moderate numbers of heating degree-days. Analysis was done for annual base 65°F (18°C) heating degree-days from 2100 to 4100. If annual energy savings are the sole criterion for application of cool colors on the walls of the residence as modeled, HDD_{65} should be less than about 3300 for wood-framed walls or about 2800 for CMU walls. Atlanta has 3090 HDD_{65}.

EXECUTIVE SUMMARY

A project, begun in May 2004, sought to gather field data and validate a model for the thermal performance of walls coated with and without infrared blocking pigments. A validated model allows the effect of IrBPs to be estimated for different wall constructions and different climates than in the field tests. Solar radiation control on walls is not expected to be as effective as it is on roofs because vertical surfaces do not receive their maximum solar load during peak cooling. However, coating a wall with IrBPs is an energy saving improvement that can be implemented without considerable deconstruction and rebuild. The use of IrBPs in exterior wall finishes enables walls of any hue to have beneficial levels of solar reflectance.

The test procedure for the project built on experience with testing low-slope and steep-slope roofs and modeling their energy saving benefits due to solar radiation control. These previous efforts led to two calculators on our web site to aid in specification of solar radiation control for low-slope and steep-slope roofs. The test procedure entails side-by-side placement of assemblies with and without solar radiation control. Data from thermocouples and heat flux transducers document thermal performance concurrently with a record of imposed weather and solar conditions. The procedure was modified slightly to embed the heat flux transducer for each test section in a 2 ft x 2 ft square of gypsum board that could be added to the inside walls without cutting into the existing walls at the field test sites.

The field test sites included residences in Phoenix, AZ and near Jacksonville, FL. Walls coated with IrBPs were termed IR test sections. Walls coated without IrBPs were termed Non test sections. The Phoenix site had three IR test sections and one Non test section, but they varied in construction features and orientation. They produced data over the peak Phoenix cooling season that qualitatively showed the effect of heat flux transducer sensitivity, wall orientation and wall construction features, including shadowing effects. The Jacksonville site had side-by-side IR and Non test sections on a south-facing wood-sided wall. The data obtained there were not consistent with the construction features of the light weight walls. They showed that putting a coating with IrBPs over a coating without them yielded less than maximum benefit. Priming with a white primer then color coating is the application sequence recommended by the manufacturer of the coatings. It was not done in Phoenix and Jacksonville to minimize possible impact on the appearance of the already coated houses.

Test sections in a south-facing wall at the Oak Ridge National Laboratory proved to be most suitable to produce data for validation. The public domain whole building energy use program DOE 2.2 was selected for the modeling task because it is able to accurately account for solar radiation incident on walls from the Sun, sky and ground. The model of the south wall of a small residence, described in DOE 2.2's building description language from previous work, was modified to conform to the construction features of the ORNL test wall. Solar reflectance of the wall surfaces coated with and without IrBPs was measured at four times during the full year of data acquisition within ±0.008 uncertainty. The solar reflectance of the IR coating remained constant at 0.495 during the year. The Non coating remained at a solar reflectance of 0.238. A weather file for DOE 2.2 was prepared from the weather and solar conditions recorded continuously

at the ORNL site. The ground in front of the test wall was judged to have a solar reflectance between 0.08 and 0.24 during the project.

DOE 2.2 predictions of outside surface temperature for ground reflectance of 0.08 and 0.24 were compared to the measurements for several clear days throughout the project. Anomalies in the measurements ruled out a conclusion about overall goodness of agreement. Annual averages of the hourly values were generated. The predicted average outside surface temperature of the IR wall for ground reflectance of 0.08 agreed with that for the measurements within 0.5°F. Annual average temperatures are judged uncertain to ±0.05°F. Looking for consistency among the predictions for ground reflectance of 0.08 and 0.24 and the measurements led to speculation that the average for the Non wall was about 1.0°F low.

The one-dimensional finite difference heat conduction model STAR predicted internal heat fluxes at the location of the heat flux transducers for comparison to the measurements. DOE 2.2 only yields detailed data at the inside and outside surfaces. Measured inside surface temperatures were used in STAR for one boundary condition. Measured and predicted outside surface temperatures were used for the other. Heat fluxes were separated into outward and inward directed values to focus on solar effects. There were no significant differences among the annual averages for the outward directed heat fluxes because of lack of solar effects in them. The annual average inward heat flux from the outside surface temperatures generated by DOE 2.2 agreed within 0.002 Btu/(h·ft^2) with that for the measurements for the IR wall. Measured annual average heat fluxes are uncertain to about ±0.03 to ±0.05 Btu/(h·ft^2). STAR predictions are considered equally uncertain. The annual average of the measurements for the Non wall seemed more consistent with all the other heat flux averages if 0.082 Btu/(h·ft^2) was added to it. This addition was consistent with the speculated 1.0°F addition to the average measured outside surface temperature for the Non wall.

The goodness of agreement of predictions with measurements for the IR wall supports the conclusion that the DOE 2.2 model is valid. A statistics-based estimate of the thermal properties of the walls at the test sites, made from the evolving monthly data with the program PROPOR (<u>PROP</u>erties <u>O</u>ak <u>R</u>idge), indicated more confidence at the ORNL site in the IR data than the Non data. Less than complete confidence in the Non wall measurements means that the observed less satisfactory agreement between predictions and measurements for the Non wall does not rule out the conclusion that the model is valid. DOE 2.2 is considered most useful to determine the effect on the annual energy use of a building due to single changes in its configuration or operation. Although the validation process did not prove the model conservative, the model was used to show the energy effects of coating walls with and without IrBPs for different wall constructions in various climates.

The single-story residence whose south wall was the focus for validation was reconfigured to have typical stucco-coated walls. Wood-framed walls with stucco and an air layer made up one configuration. Stucco-coated concrete masonry units, including a 1-in.-thick layer of foam on the inside, comprised the other. The three-bedroom houses had three occupants with Building America Performance Analysis Resources used for schedules of occupancy, lighting use, appliance and plug loads, and domestic hot water use. The walls were shaded by typical eave overhangs. Ground reflectance of 0.24, considered typical for dry grass facing the walls, was imposed for all exterior walls. The solar reflectance for all exterior walls was set to 0.495 and 0.238 to model the effects of coatings with IrBPs and without them, respectively.

The four house models were run for weather files compiled from TMY2 data for Miami, Phoenix, Las Vegas and Bakersfield. These typical cooling climates were intended to show the maximum cooling energy savings due to walls coated with IrBPs. Weather in three mixed climates, Richmond, VA, Knoxville, TN and Sacramento, was also imposed to show the effect on net energy savings of the heating penalty intrinsic to solar radiation control. The forced-air HVAC system in the houses used an air-to-air heat pump with electric resistance supplemental heat. High seasonal efficiencies were specified and judged to be attainable in the climates. The year round thermostat schedule was 68°F for heating and 76°F for cooling. The cooling capacity of the air conditioner was autosized for each climate then rounded up to commercial sizes, 36,000 Btu/h for all climates except 42,000 Btu/h for Miami. Heating capacity and part-load features in both cooling and heating modes were DOE 2.2 defaults for air-to-air heat pumps.

The total energy use of the houses without IrBPs in the wall coating was consistent with location and wall construction. For the wood-framed walls, total annual use in the cooling climates and in Sacramento was about 12,000 kWh. It was about 14,000 kWh in Richmond, VA and Knoxville, TN. The CMU-walled house had slightly more use in all climates, from 370 kWh more in Miami to 850 kWh more in Richmond, VA. Heating and cooling was 26% (Sacramento) to 40% (Richmond, VA) of total use for the houses with wood-framed walls. The percentages varied from 29% to 43% for the CMU-walled houses.

The most encouraging results for the use of IrBPs on walls are the cooling energy savings. When using IrBPs on stucco over wood-framed walls, savings compared to cooling energy without IrBPs varied from 4% to 9% (4% to 6% in the cooling climates). Amounts of annual savings varied from 240 kWh in Phoenix to 110 kWh in Richmond, VA. When using IrBPs on stucco over concrete masonry units, cooling savings varied from 6% to 13% (6% to 9% in cooling climates). Amounts varied from 360 kWh in Phoenix to 160 kWh in Richmond, VA.

A heating penalty is intrinsic to use of passive solar radiation control, here in the form of IrBPs in the wall coatings. The percentages, compared to heating energy for houses with wood-framed walls coated without IrBPs, varied from 4% to 14% (4% to 7% in the mixed climates). Amounts of increased energy for heating varied from 160 kWh in Richmond, VA to 30 kWh in Phoenix. Miami was considered to have negligible heating needs. The percentages for CMU-walled houses varied from 5% to 24% (5% to 10% in the mixed climates). Amounts of increases varied from 260 kWh in Richmond, VA to 80 kWh in Phoenix. If the cooling savings are decreased by the heating penalty to yield net savings and compared again to cooling energy for the house with Non walls, the percentage savings decrease significantly. Net savings vary from -3% to 4% (3% to 4% in the cooling climates) for the houses with wood-framed walls and from -6% to 6% (1% to 6% in the cooling climates) for the houses with CMU walls.

The most significant conclusion from this project is that, unlike roofs, the heating penalty for walls with IrBPs in their coatings is greater than the cooling savings for climates with relatively few heating degree days. For proof, DOE 2.2 was run with and without IrBPs on the roof of the house as modeled without IrBPs on the wood-framed exterior walls. Cooling savings for this roof exceeded the heating penalty even in

Richmond, VA with 4100 HDD_{65}. The conclusion for walls is reasonable. Unlike roofs, walls do not receive their annual peak solar load in the cooling season because the Sun has high altitude and overhangs are most effective. Rather, peak solar load on walls occurs when the Sun is lower and the building may already need heating. This combination yields relatively less cooling savings and relatively more heating penalty for walls compared to roofs.

Net annual energy savings were determined as a function of HDD_{65} for the houses with wood-framed and CMU walls. Data were generated for Las Vegas, Bakersfield, Richmond, VA, Knoxville, TN, Sacramento and two additional mixed climates, Atlanta and Memphis. The additional climates each have about 3100 HDD_{65} and show net annual energy savings near zero. Figure ES1 shows the results along with best-fit lines through the data. Sacramento showed the most deviation from the best-fit lines. Zero net savings occur between 3300 and 3400 HDD_{65} for the wood-framed walls and between 2800 and 2900 HDD_{65} for the CMU walls. If the choice of coating walls with IrBPs or without them is to be based solely on potential energy savings for this house, then its wood-framed walls should not be coated with IrBPs unless HDD_{65} are less than about 3300. For CMU walls, HDD_{65} should be less than about 2800. Positive energy savings from cool colors on walls do not appear possible for locations with heating needs that are more severe than those of Atlanta.

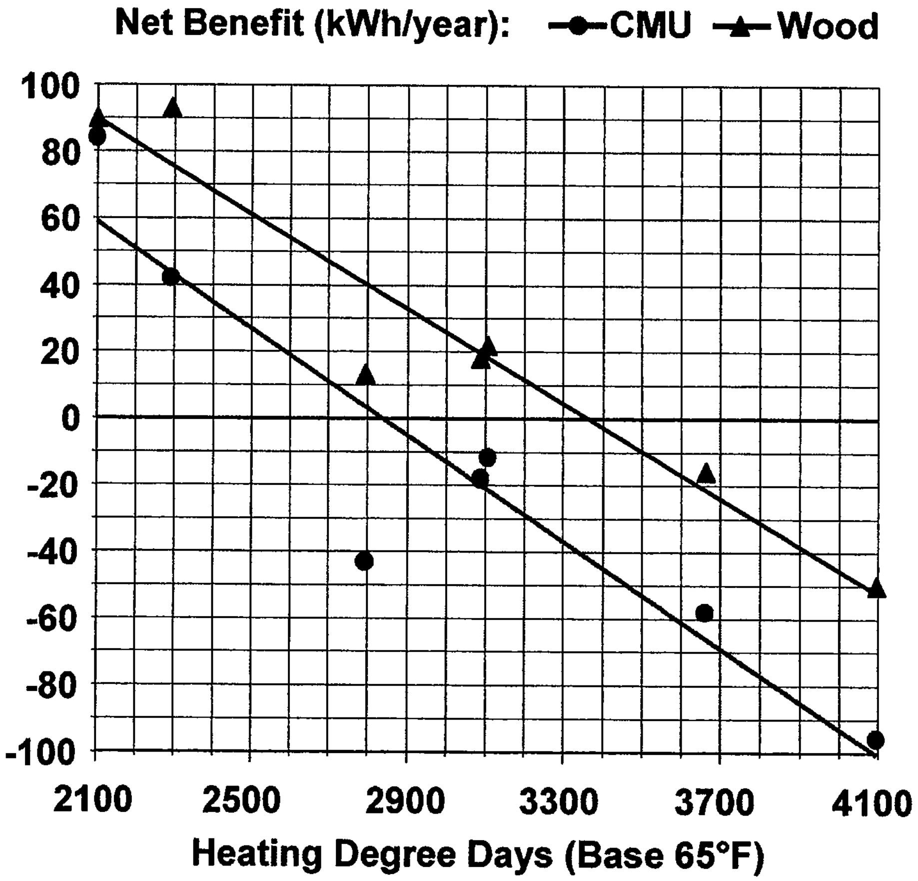

Fig. ES1 Breakeven Annual Energy Savings with IrBPs in the Coatings on the Wood-Framed and CMU Walls of a Simple Residence

The DOE 2.2 results for this project are for one simple house with all-electric heating and cooling most suitable for cooling climates. Making the results more general, for example, in the form of a companion to the cool roof calculators on our website, would require effort far beyond the scope of the project to generate a database that includes results over the wide range of parameters for walls. The DOE 2.2 model for the house used herein is not conservative yet it indicates at most 6% net benefit for use of IrBPs on walls in cooling climates compared to cooling energy without IrBPs. The effort would not likely be worth it.

INTRODUCTION

A project was initiated in May 2004 to compare the thermal performance of walls coated with cool and standard colors. Cool colors are ones with high solar reflectance in the near infrared due to the presence of infrared blocking pigments (IrBPs). In the visible they have the same reflectance as 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, the project seeks to quantify the potential energy savings from cool colors on walls.

This report begins with background on solar radiation control for building envelopes and the role of the project in it. The test procedure is presented and a computer program used to judge the consistency of the test data is described. The solar reflectance data for the project are summarized. There were three test sites for the project: a residence in Phoenix, Arizona; a residence near Jacksonville, Florida; and, a research building on the Oak Ridge National Laboratory (ORNL) campus in Oak Ridge, Tennessee. The application of the test procedure at each site is described. Typical data are presented along with analysis of all the data for consistency and suitability for use in validation of a model for the thermal behavior of walls coated with IrBPs and without them. The model and its validation with the ORNL data are described. The model is applied in several cooling and mixed climates to show the annual energy use for a typical one-story residence due to stucco walls coated with cool colors compared to standard colors. The results are generalized into a breakeven criterion for use of cool colors on walls as a function of heating degree-days for the location.

BACKGROUND

Solar radiation control is a well-developed technology to save energy during operation of cooling systems in residential and commercial buildings. By reflecting sunlight away from an exterior surface before it can be absorbed, solar radiation control keeps the exposed building surface cooler than without solar radiation control. This decreases the temperature difference between the inside and the outside of the roof or wall. Temperature difference drives heat into the building; the smaller the difference, the smaller the heat flow rate. Reflecting sunlight away also diminishes the effects of high temperature and intense sunlight on the exterior surfaces.

Solar radiation control is achieved by formulating and applying exterior surface materials or coatings that have high reflectance over the spectrum of incident solar radiation. The spectrum includes the electromagnetic wavelength range from 250 to 2500 nanometers, spanning the near ultraviolet through the near infrared. The narrow range from 400 to 800 nanometers is where the human eye sees visible light from blue to red. Solar radiation control is currently limited to passive technologies. The solar properties of the exposed surfaces do not change in response to weather conditions.

For surfaces that are out of sight, such as low-slope roofs on commercial buildings, the emphasis for solar radiation control is on white surfaces. They appear white because they have a high solar reflectance, especially in the visible range. They reflect away the maximum amount of solar radiation leading to the maximum summer cooling savings compared to black low-slope roof surfaces.

White surfaces cause a heating penalty relative to black surfaces during the heating season. The white surfaces reflect away sunlight even though the heating effect from absorbed solar radiation would be beneficial. This penalty does not necessarily offset the entire cooling savings, depending upon the building and the climate. Net energy savings for radiation control with white surfaces can be negligible in severe heating climates. When base 65°F (18°C) heating degree days exceed about 5500 per year, white surfaces yield annual savings less than $0.005 per square foot at current energy costs and equipment efficiencies in buildings with small internal loads. Regardless, summer cooling peak savings and internal loads may be significant for a building and help to justify solar radiation control even in heating climates.

The Oak Ridge National Laboratory (ORNL) has done extensive work to document and generalize the effects of solar radiation control on low-slope roofs. See the bibliography of ORNL publications on solar radiation control for low-slope roofs after the list of references cited herein. The work resulted in the publication of a solar radiation control fact sheet and accompanying estimating tools on the Building Envelope Program website: http://www. ornl.gov/sci/roofs +walls/facts/SolarRadiationControl.htm. Initially, savings were estimated due only to decreased energy use by low-slope roofs with solar radiation control. Savings may now include those due to decreased peak demand, which occurs with large facilities subject to an electrical demand charge. Most recently an entirely new tool was added to estimate savings due to decreased energy use by steep-slope roofs with solar radiation control: http://www.ornl.gov/sci/roofs+walls/SteepSlopeCalc/index.htm. A bibliography of ORNL publications on solar radiation control for steep-slope roofs follows the one for low-slope roofs at the end of this report.

For steep-slope roofs and exterior walls, the appearance of the surface becomes a significant factor. Owners of residential and commercial buildings want colors other than white for exterior surfaces that can be seen from street level. To address this desire, cool colors are available through use of infrared blocking pigments (IrBPs) added in the formulation of exterior surface materials for colored roofs and walls. In the visible part of the spectrum, cool and conventional pigments cause essentially equal reflectance. To the human eye sensing the light reflected off them, they appear to have the same color. However, their solar reflectance is high in the near infrared. If a coating is formulated with cool pigments and applied over a white primer, total solar reflectance is significantly higher than for the same colored coating with conventional pigments. For example, a typical brown vs. a cool brown surface has 9% vs. 32% solar reflectance. A typical green vs. a cool green surface has 25% vs. 50% solar reflectance.

The thin film of colored coatings with IrBPs transmits solar radiation somewhat. The highly reflective primer causes solar radiation that is transmitted through the coating to reflect and go back out through the coating. Thus, the label "cool coating" should be reserved for the system of a colored coating with infrared blocking pigments over a highly reflective primer.

Solar load in summer is not as intense on exterior walls as it is on roofs, justifying the attention paid first to low-slope then to steep-slope roofs. However, there are limited opportunities to improve the thermal performance of wall systems without considerable deconstruction and rebuild. Coating with cool colors is such an opportunity. In cooling-dominated climates, highly reflective exterior wall surfaces can increase the wall's energy efficiency without adding thickness. To be acceptable to building owners, wall coatings must be available in a wide variety of pleasing colors, not just white. The use of IrBPs in exterior wall finishes enables walls of any hue to have beneficial levels of solar reflectance. The question this project seeks to answer is how much energy is saved by the attainable levels of solar reflectance.

TEST PROCEDURE

A technique that has proven itself over more than a decade of monitoring the thermal performance of low-slope and steep-slope roofs is the following. 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, especially at the exterior and interior surfaces, to measure the temperature profile. Concurrently, weather data are monitored in order to establish the conditions imposed on the assemblies. At several times during a long term field test, typically every six months, solar radiation properties of the exterior surfaces are measured. The data give evidence to validate computer models for the thermal behavior of each assembly.

Temperatures and heat fluxes throughout an assembly can be predicted by the models. Comparison to measurements is the best way to validate the models. Validated models can be exercised for the range of wall parameters and different climates, not just those studied in the field tests. The results can show in general the potential energy savings with solar radiation control.

Textured Coatings of America, Inc. formulates colored coatings without and with cool pigments and markets them as Texcote Supercoat and Texcote Supercoat Platinum coatings, respectively. They are intended for application over Texcote Classic white primer. Through their contacts with their residential customers, they located residences in Phoenix, Arizona and near Jacksonville, Florida whose owners were willing to cooperate with researchers from ORNL in the collection of field data. A test building on the ORNL campus had an uncoated stucco wall test section that was available for the project. The Arizona and Florida sites are in cooling climates, which are of primary interest for solar radiation control. Oak Ridge has a mixed climate, with significant heating and cooling needs, which gives an opportunity to observe the severity of the heating penalty for walls.

The houses in Phoenix and near Jacksonville were already coated with Texcote coatings. The availability of the ORNL building with its uncoated test section prompted the decision to simply recoat parts of the walls on the Arizona and Florida houses. No attempt was made to strip off the existing coatings and start from a primed surface for fear of ruining the appearance of the houses. Subsequent experience confirmed that the colored coating with IrBPs does not perform with maximum effect if applied over a coating that is not highly reflective.

The houses in Phoenix and near Jacksonville were occupied, although the house in Phoenix was undergoing remodeling by its owner. The heat flux transducers are most accurate if they are buried in solid materials. To minimize the impact of the installation on the existing houses, a 2 ft x 2 ft square of gypsum board was prepared for each test section. A heat flux transducer was placed in a depression routed out of the middle of one of its surfaces so that the transducer was flush with the surface. The squares of gypsum were attached with drywall screws to the existing interior gypsum walls in the middle of the test sections. The heat flux transducers were used between gypsum surfaces near room temperature. For consistency, the same method was used at the ORNL test site. Pictures of the squares of gypsum in place at each test site will be shown as part of the discussion of the field data. In general, the test sections and instrumentation consisted of the arrangement in Fig. 1.

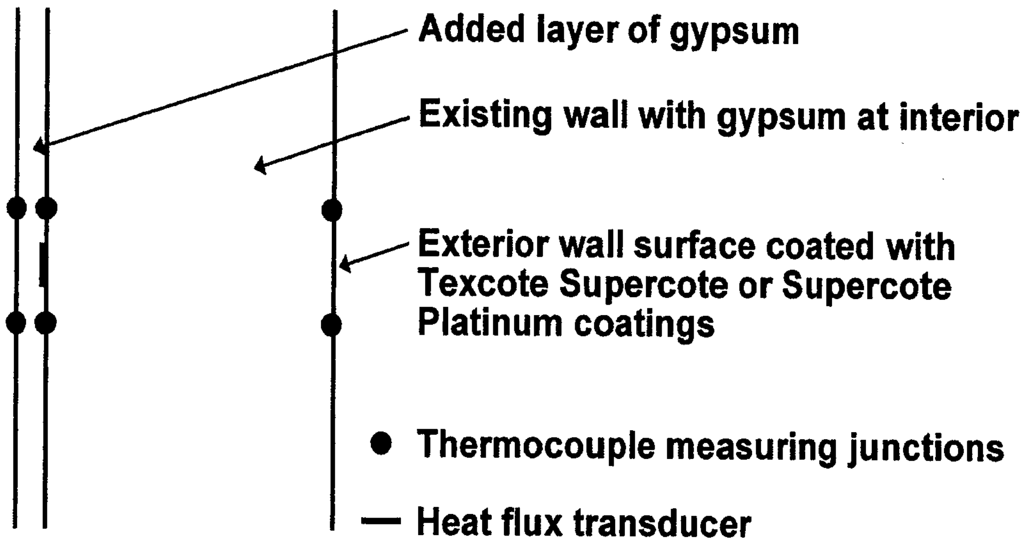

Fig. 1 Arrangement of Instrumentation and Added Gypsum Layer to Comprise Test Sections at Each Site

The heat flux transducers were calibrated using a heat flow meter apparatus operated according to ASTM C-518, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. The apparatus was used to determine the response of the heat flux transducers to a known heat flux at room temperature. The heat flux transducers are thermopile devices that produce millivolts of EMF in response to the small temperature difference that heat flow generates across them. The calibration constants that are obtained by this procedure vary slightly, depending upon the material in which the heat flux transducer is installed and the material it faces. For example, the heat flux transducers used in this project at the ORNL test site had been calibrated and used previously in wood fiberboard facing wood fiberboard. Results from the previous calibration and the current calibration in gypsum facing gypsum are as follow. East and West refer to their placement in the ORNL test section.

Calibration Constant, [Btu/(h·ft^2)]/mV	ORNL East	ORNL West
In fiberboard facing fiberboard	0.4313	0.4495
In gypsum facing gypsum	0.4875	0.5099

The placement in gypsum facing gypsum was used for calibration and for application of all heat flux transducers in this project. Since the calibration constant is related to the Seebeck coefficient of the thermoelectric materials that form the thermopile, it does not vary with normal variations in the room temperature of occupied and conditioned houses.

PROPOR COMPUTER PROGRAM

The current project is another case in which ORNL researchers used field measurements for the thermal evaluation of building envelope components. The computer program PROPerties Oak Ridge (denoted PROPOR) is a tool available at ORNL 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 estimates the best values of the thermal conductivity and volumetric heat capacity to fit measurements of heat flux and/or temperature internal to a test section. The measured temperatures at the surfaces of the test section are used as boundary conditions for the transient heat conduction equation in finite difference form. Trial values of the thermal conductivity and volumetric heat capacity yield predictions of the internal heat flux and/or temperature for comparison to the measurements. Statistical methods are used to select the best estimates of the property values from the trials. If the data require that the properties vary with temperature, PROPOR can be requested to estimate properties with temperature dependence.

Besides the estimates of the property values, the output from a convergent run of PROPOR includes a calculation of the confidence regions about the estimates. Small confidence regions generally indicate good estimates. Other output is available to judge the goodness of the estimates. Sensitivity coefficients indicate the suitability of the data for the desired properties. Residuals indicate the correctness of the assumed temperature dependency of the properties. For field data that show diurnal variation due to the day-night cycle, heat flux measurements are needed for accurate estimates of thermal conductivity. A companion internal temperature measurement is needed to simultaneously estimate volumetric heat capacity (Beck, *et al.* 1991). Both measurements were done in the current project. Constant thermal conductivity and volumetric heat capacity were assumed from month to month for each test section. This avoided the need for temperature dependent properties to cover seasonal variations in average temperature.

The measured thickness of a test section divided by its thermal conductivity yields the thermal resistance or R-value of the test section. Volumetric heat capacity is the product of density and specific heat. It is a measure of the thermal mass inherent to a test section. The thermal resistance and thermal mass characteristics for the Phoenix and Jacksonville test sections were known from architectural drawings and discussions with the home owners. At the ORNL test site, the construction drawings for the test section were available. The properties of the gypsum panel added to each test section were also known, with apparent thermal conductivity measured with a heat flow meter apparatus.

Month by month throughout the project PROPOR was requested to estimate the average values of thermal conductivity and volumetric heat capacity for each test section. The estimates are independent of surface properties and wall orientation since they are based solely on the measured temperatures and heat fluxes for test sections whose internal structure did not change month by month. Time into each test should matter only as it affects average temperature for the month and, thereby, the average thermal conductivity and specific heat for the month.

PROPOR was used herein only to show the consistency of the evolving data with expected thermal resistance and thermal mass for each test section. Consistent data are needed for validation of a model for the thermal performance of walls with solar radiation control. PROPOR cannot be used without data from a particular test. Therefore, its estimates are limited to the conditions of the test. A validated model can be applied with wall characteristics and climate conditions other than the ones used in the validation task.

SOLAR REFLECTANCE OF COATINGS

Models for the thermal performance of building envelope components respond to imposed climatic conditions and the input characteristics of the components. Their purpose is to predict the response of the components, that is, the temperature and heat flow profiles through them, to these conditions and characteristics. An important and generally variable property of surfaces needed for thermal models is solar reflectance.

Numerous measurements were made during the project of the solar reflectance of the test surfaces. The technique used was ASTM C 1549, Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer. The provisional precision statement for the method at the level of reflectance for the coatings (0.24 to 0.50) gives 95% repeatability of ±0.008 or better. To ensure this low level of uncertainty, the instrument zero is adjusted with a black cavity and the gain is set to yield the 0.82 reflectance of a white ceramic reference material before measurements are made with the instrument.

Our portable solar spectrum reflectometer was not available to take along on the trips to Phoenix to begin and end the field tests there. Cans of the Mountain Gray-colored coatings installed there were brought to Oak Ridge and samples were prepared on plywood primed with Texcote Classic white primer. Samples were also prepared on plywood of Undersea-colored coatings over Classic white primer and over Undersea Supercote Platinum and white primer. To document the solar reflectance when not coating over the primer, the reflectometer was taken to Jacksonville at the end of the field tests to measure the reflectance of the Undersea-colored coatings on that wall. The reflectance of the Undersea-colored coatings over primer on the south wall of the ESRA at the Oak Ridge National Laboratory was measured at four times during the year of monitoring.

Table 1 shows the results for the various surfaces and times. The overall reflectance in the last column is the average of Air Mass 2 measurements at the beginning and end of the progression over the range of air mass settings and detectors in the instrument. The results for the progression are in the other columns. Air Mass 0 is the extraterrestrial solar spectrum. Air Mass 1 is 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 (1.5 times Air Mass 1) is the spectrum for a solar zenith angle of 48.2°. Air Mass 2 (twice Air Mass 1) is the spectrum for a solar zenith angle of 60° and is considered the average terrestrial solar spectrum in this report. Outputs from the four detectors in the instrument are weighted appropriately and combined by firmware in the instrument to yield the different air mass values. The values for individual detectors are rough measures of reflectance in the portions of the solar spectrum indicated by their labels in Table 1.

In general, the values of reflectance for AM2 (overall), AM1.5 and AM1 are not significantly different for each coating. The reflectance for AM0 is lower but of little practical consequence for terrestrial applications. The infrared detector gives a significantly higher reading for each IR coating compared to the companion Non coating. This behavior continues somewhat into the Red. The Blue and Ultraviolet readings are essentially the same for each IR and Non pair. The higher Infrared and Red detector responses for the IR coatings lead to their higher overall reflectance.

Table 1. Solar reflectance over air masses and detectors using a Devices & Services Solar Spectrum Reflectometer for coatings at various times in the project

Coating	AM1.5	AM1	AM0	Infrared	Red	Blue	Ultraviolet	Overall
Mountain Gray Non Sample	0.300	0.302	0.292	0.229	0.330	0.375	0.180	0.304
Mountain Gray IR Sample	0.438	0.434	0.418	0.448	0.469	0.398	0.187	0.440
Undersea Non over Primer	0.246	0.245	0.239	0.260	0.241	0.247	0.139	0.246
Undersea IR over Primer	0.520	0.501	0.489	0.748	0.499	0.242	0.147	0.513
Undersea Non over IR	0.258	0.256	0.251	0.291	0.245	0.247	0.142	0.257
Undersea IR over IR	0.518	0.500	0.489	0.749	0.494	0.242	0.148	0.512
Jacksonville Non 12/8/2004	0.236	0.236	0.231	0.229	0.239	0.253	0.149	0.237
Jacksonville IR 12/8/2004	0.398	0.389	0.374	0.467	0.436	0.245	0.155	0.398
ORNL Primer 8/4/2004	0.702	0.702	0.670	0.653	0.743	0.777	0.222	0.713
ORNL Non 8/4/2004	0.238	0.236	0.232	0.243	0.240	0.242	0.141	0.238
ORNL IR 8/4/2004	0.498	0.481	0.470	0.695	0.490	0.244	0.161	0.493
ORNL Primer 9/27/2004	0.663	0.663	0.635	0.596	0.705	0.750	0.234	0.668
ORNL Non 9/27/2004	0.237	0.236	0.236	0.251	0.239	0.246	0.157	0.242
ORNL IR 9/27/2004	0.507	0.490	0.479	0.711	0.494	0.249	0.164	0.501
ORNL Primer 5/18/2005	0.711	0.709	0.677	0.663	0.754	0.772	0.220	0.716
ORNL Non 5/18/2005	0.234	0.233	0.228	0.237	0.234	0.241	0.142	0.235
ORNL IR 5/18/2005	0.496	0.478	0.469	0.698	0.486	0.245	0.155	0.493
ORNL Primer 8/3/2005	0.662	0.662	0.632	0.598	0.710	0.741	0.220	0.664
ORNL Non 8/3/2005	0.238	0.238	0.233	0.247	0.239	0.243	0.146	0.239
ORNL IR 8/3/2005	0.499	0.482	0.471	0.703	0.485	0.245	0.149	0.494
ORNL Primer Average	**0.685**	**0.684**	**0.654**	**0.628**	**0.728**	**0.760**	**0.224**	**0.690**
ORNL Non Average	**0.237**	**0.236**	**0.232**	**0.245**	**0.238**	**0.243**	**0.146**	**0.238**
ORNL IR Average	**0.500**	**0.483**	**0.472**	**0.702**	**0.489**	**0.246**	**0.157**	**0.495**

The sample of the Mountain Gray Non coating prepared in the lab shows better reflectance overall than the Undersea Non over Primer, Undersea Non over IR, Jacksonville Non and ORNL Non coatings. The reflectance of the Mountain Gray IR coating is higher than that of the Jacksonville IR coating but lower than that of the Undersea IR over primer, Undersea IR over IR and ORNL IR coating. To assess energy saving potential, the difference between the overall reflectance for the IR and Non coatings is important. The Mountain Gray color used in Phoenix shows a 0.136 difference, less than the 0.161 difference for the Jacksonville Undersea and the 0.255 to 0.267 differences for Undersea over primer, Undersea over IR and the ORNL Undersea.

The Jacksonville IR coating was applied over several layers of previous coatings, the last of which, considered the substrate for the field test, was likely a Non coating. This conclusion is based on results for samples prepared at the Jacksonville site during the initial coating for the project and brought back to Oak Ridge. These results are not in Table 1. What was initially put on the IR location in Jacksonville had an overall reflectance of 0.352 and the Infrared detector indicated 0.370. What was put on the Non location had an overall reflectance of 0.450 and the Infrared detector indicated 0.636. Due to this confusion, the Jacksonville test sections were recoated on July 9, 2004 by Texcote personnel. The opportunity to measure their solar reflectance did not occur until December 8, 2004.

The reflectance of the primer is higher than the corresponding reflectance of the Undersea-colored ORNL coatings for all detectors except the Infrared detector and for all full spectrum values. Solar radiation that is transmitted through the IR coating can reflect off the white primer and transmit back through the IR coating. The Undersea IR over IR sample (with primer underneath the first coat) shows that two coats of IR seem to act as one. If solar radiation encounters a previous layer of Non coating, it is more likely to be absorbed, judging from what the substrate does to the final Jacksonville IR coating. The substrate, even if the white primer, does not seem to matter for the Non coating. Apparently solar absorption occurs in the Non coating and what radiation is reflected is reflected off the Non surface.

Judging from the overall reflectance over time at ORNL, the primer and both the Non and IR coatings at ORNL did not undergo any significant weathering during the year of exposure. Our previous weathering experience with coatings is on low-slope roofs. White coated surfaces showed significant change in reflectance in the first year of exposure, typically a monotonic decrease of -0.15 (Petrie *et al.* 2001). The white primer, although not intended to be exposed, showed a non-monotonic trend in Table 1. Reflectance remained within -0.05 of the fresh value. Weathering would not be expected to be as severe for a wall surface as it is for a low-slope roof surface. Intensity of incident solar radiation during summer to a wall is not as high as it is for a low-slope roof. If contaminants impinge on a vertical wall surface, rain can wash them off. Rainwater does not pond on a wall like it does on a typical low-slope roof.

The colored coatings did not show the variability of the primer, remaining at their average values ±0.006 over the year and varying less than the ±0.008 confidence level for the instrument in this range of reflectance. This is impressive and the average values for the year, 0.238 for the Non coating and 0.495 for the IR coating, can be used with ±0.008 confidence to model the thermal behavior of the ORNL wall over the test period.

FIELD TEST RESULTS

The test procedure was carried out at three field test sites: a residence in Phoenix, Arizona, a residence near Jacksonville, Florida, and on a test building on the Oak Ridge National Laboratory campus in Oak Ridge, Tennessee. This section contains the following for each site. The installation and instrumentation of the test sections are described. Data for a typical day during the monitoring are presented and discussed. Evaluation is made month-by-month of the consistency of the data and their overall suitability is assessed for validation of a model for the thermal performance of coatings on walls. This assessment is done with results from the program PROPOR.

Phoenix Test Site

Installation and instrumentation

The Phoenix residence selected as a test site is a single-story house with a vaulted ceiling in the extensively remodeled area used for a family room, dining room and kitchen. Figure 2 is a photograph of the south face of the house with two insets to show the locations of the four test sections on walls with four different orientations. There was not enough undisturbed space on any south-facing exposure or inside it for side-by-side test sections. One inset shows the outside of the southwest and southeast walls of an office in the west wing. The other shows the outside of the south and east walls of an exercise room in the east wing.

Figure 3 shows photographs taken inside the house. The office is on the left and the exercise room is on the right. The gypsum panels added to contain the embedded heat flux transducers are clearly visible in each view. Each panel was placed so its heat flux transducer was in the middle of the corresponding coated area that was prepared on the exterior wall. The gypsum panels had thermocouples on their inner and outer surfaces to sense the temperature at the inside surface and between the added and existing layers of gypsum. Thermocouples on the exterior surfaces were attached with caulk that was allowed to cure before the test sections were freshly coated with Texcote Supercote on the southwest exposure and Texcote Supercote Platinum (with IrBPs) on the other three exposures. All were Mountain Gray color to match the existing color.

In addition to the different directions that the test sections face on this house, the wall constructions vary. All walls have gypsum wallboard as the inside surface. The east wall, 6¼ in. thick, is a standard frame wall with nominal R-11 insulation between nominal 2x4 studs but little thermal mass except for the stucco coating. The southwest and southeast walls, 10¾ in. thick, are made from a local masonry block, coated with stucco, with no additional insulation. The south wall, 15 in. thick, is also made from the stucco-coated masonry block. Added to its inside was a frame wall insulated with R-11 fiberglass insulation, like the east wall.

The thermocouple leads and the heat flux transducer leads for the sensors inside the office were fed through a hole drilled in the southwest wall. Drilling the holes for the leads also allowed us to measure the thickness of the walls. These leads were combined with those from the outside thermocouples on the southeast and southwest walls and placed in a shallow trench dug across the sandy, grass-free front yard. They were fed through a hole drilled in the south wall of the exercise room, along with those from the outside thermocouples on the east and south walls. In addition to the thermocouples and

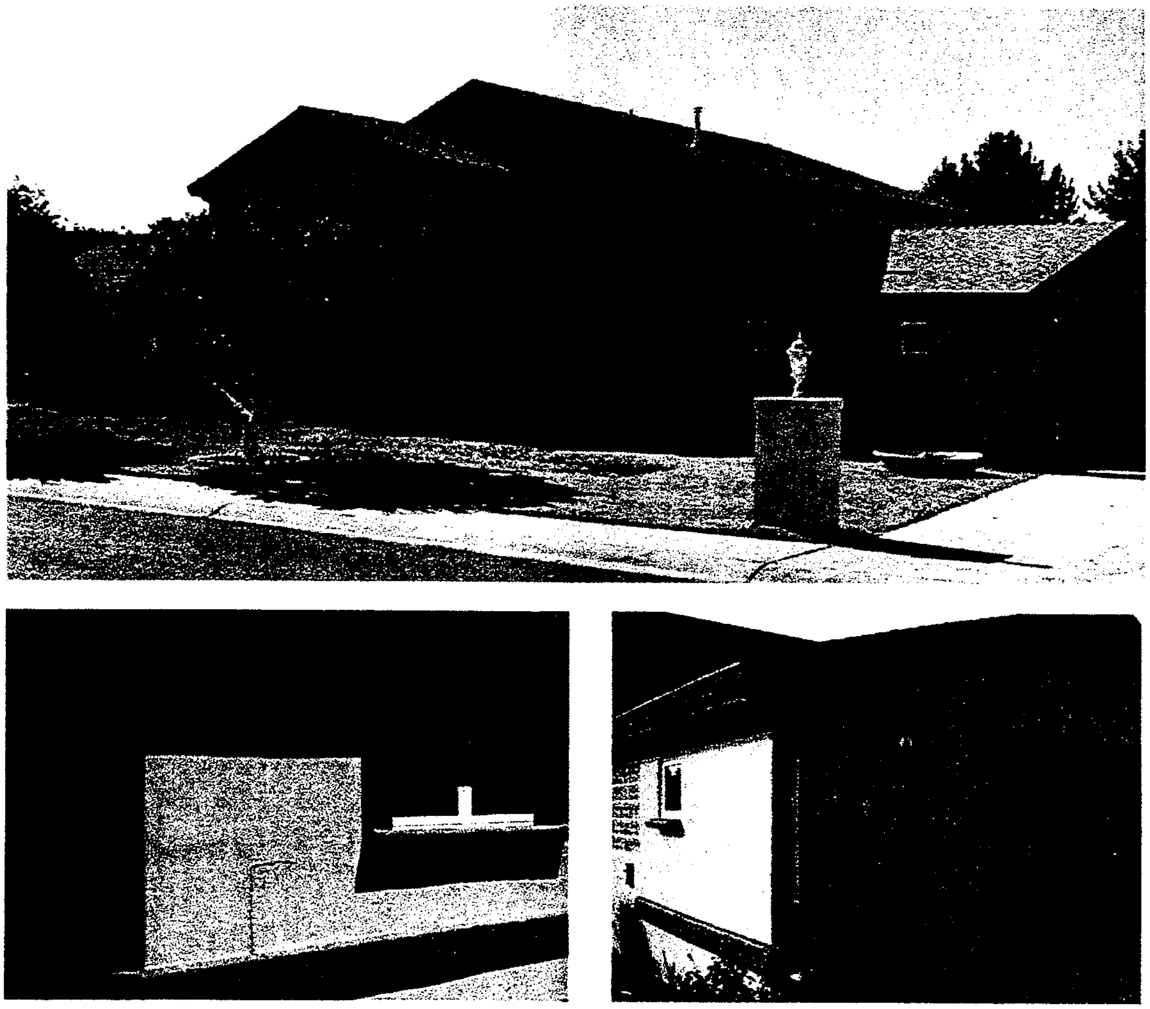

Fig. 2 Residence in Phoenix, Arizona Used as Test Site for the Project with Insets of the Southwest and Southeast Exposures (left) and the South and East Exposures (right)

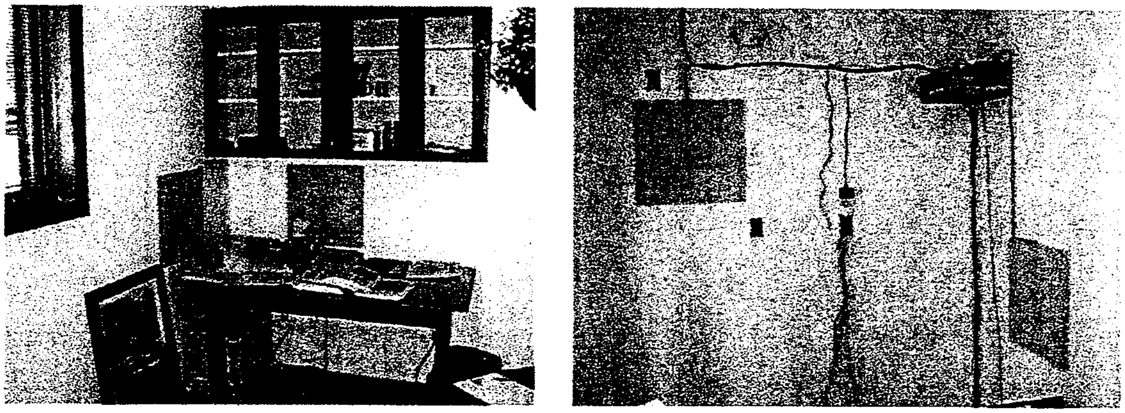

Fig. 3 Gypsum Panels Added to Office Walls (left) and Exercise Room Walls (right) Inside the Test Sections at the Phoenix Test Site

heat flux transducers for the test sections, a thermocouple to measure outside air temperature and a pyranometer to measure total horizontal solar radiation were installed at the top of the roof of the east wing. Leads were brought in through the ceiling of the exercise room.

All leads were attached to a Campbell Scientific 23X data logger. The photograph of the inside of the exercise room in Fig. 3 shows the data logger on a shelf that the Phoenix homeowner installed near the ceiling. The data logger was connected to a modem and dedicated telephone line for the project. Data were collected at one minute intervals. Fifteen minute averages were stored in the data logger and transmitted to a computer at the Buildings Technology Center in Oak Ridge for archiving and analysis. Data were collected from May 2, 2004 through November 30, 2004. The sensors and data logger were removed on December 2, 2004.

Typical data

Figures 4 and 5 are examples of the daily variation in observed temperatures and heat fluxes from the four test sections in Phoenix. The day chosen is July 25, 2004, one of many clear and hot days during a summer in Phoenix. Horizontal solar radiation intensity is repeated in both figures for a reference and peaks at 300 Btu/(h·ft^2). The computer to which the data were archived was on Eastern time so it was kept also for the data logger. Thus, the solar radiation heat flux peaks at 1600 Eastern time. The air temperature in Fig. 5 peaks at nearly 110°F at 1900.

Figure 4 shows data for the east and southwest exposures, both of which were coated with coatings containing IrBPs (labeled IR). The time interval between the peaks of the outside surface temperatures on the east and southwest exposures is consistent with the orientations. Figure 5 shows data for the southeast exposure, coated with the standard coating without IrBPs (labeled Non), and the south exposure, with IrBPs. The peak outside surface temperature for the Non coating is slightly less than the peak temperatures for both IR coatings in Fig. 4. The peak temperature of the IR coating on the south exposure in Fig. 5 is about the same as the peak air temperature. Both behaviors indicate shadowing by the decorative overhang at the eave of the roof of the single-story east and west wings of the house. There may also be effects of less than maximum solar reflectance due to putting the IR coatings over the existing coatings. The outside surface temperatures on the east and southwest in Fig. 4 do not become equal at night. Those for the southeast and south exposures in Fig. 5 do at a level that is roughly the average of the outside surface temperatures at night for the southwest and east exposures. Because of the different orientations and wall constructions, it is difficult to explain such anomalies.

The heat fluxes in Figs. 4 and 5 are even more difficult to interpret than the outside surface temperatures. The fluctuation in the heat flux for the southwest-facing IR wall in Fig. 4 and the fluctuation for the southeast-facing Non wall in Fig. 5 are similar. Both are presumably a response to the air conditioning system in the office. The peak heat flux is lower for the southwest-facing IR wall than for the southeast-facing Non wall. The east wing with the exercise room was served by a separate air conditioning system, which did not appear to cause as severe fluctuations for the heat fluxes through the east and south walls. The relatively short delay that is seen between the peak temperature and the peak heat flux for the east wall in Fig. 4 is consistent with the small thermal mass of the east wall. The relatively high peak heat flux for the east wall relative

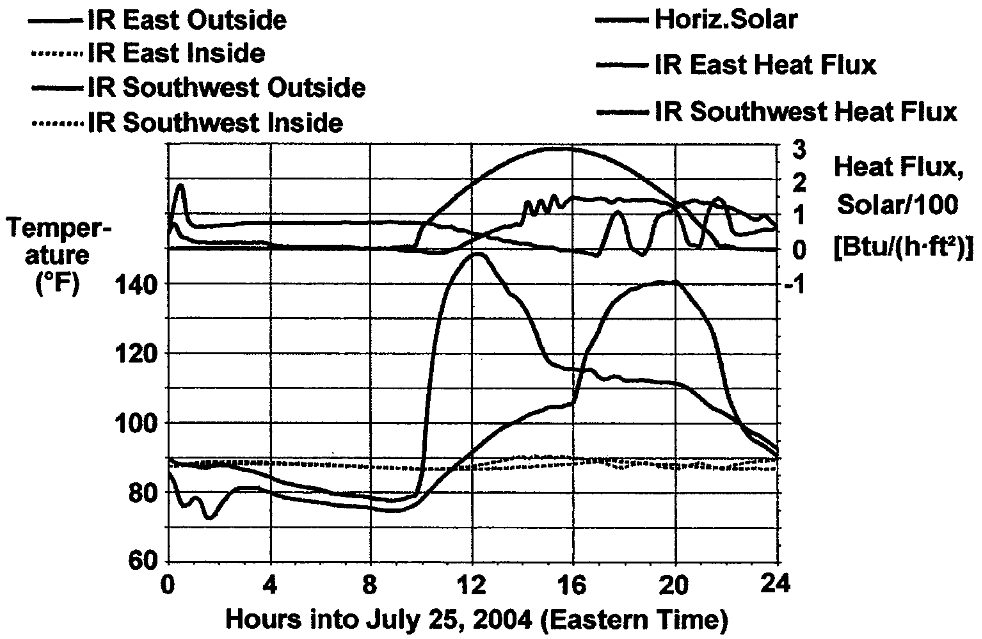

Fig. 4 Comparison of Temperatures and Heat Fluxes with IrBPs (IR) on the East and Southwest Exposures in Phoenix

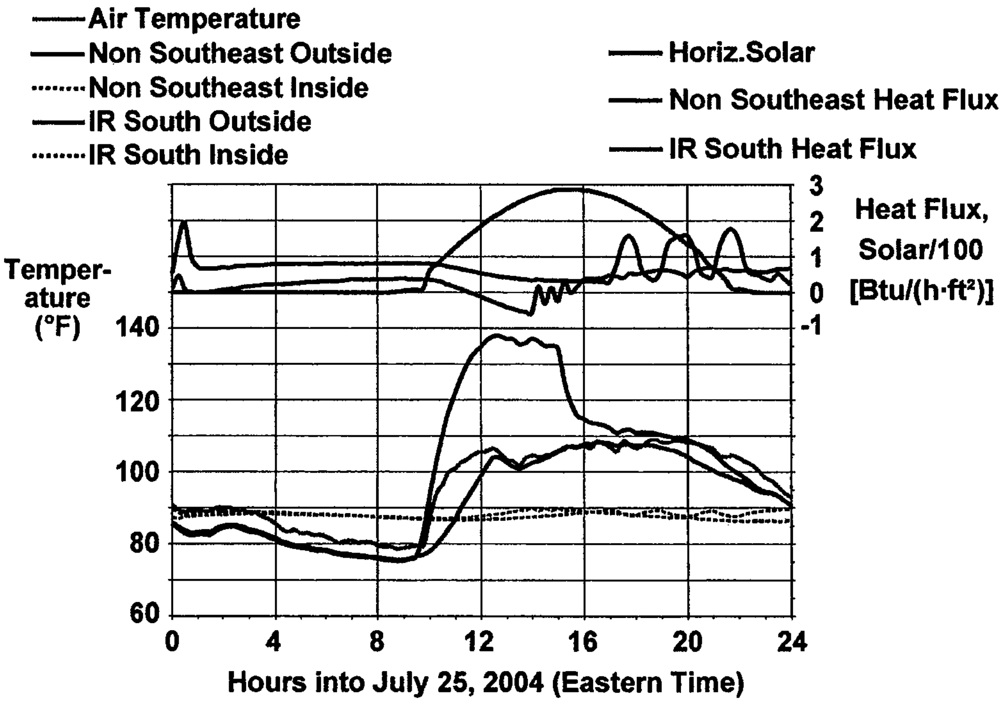

Fig. 5 Comparison of Temperatures and Heat Fluxes without IrBPs (Non) on the Southeast Exposure and with IrBPs (IR) on the South Exposure in Phoenix

to that for the south wall is consistent with the lower thermal mass of the east wall. These two IR walls had approximately equal insulation levels.

The heat flux transducers for the southeast-facing Non wall and the south-facing IR wall were high sensitivity instruments from our limited supply of these special transducers. They were about five times more sensitive than the transducers for the southwest-facing IR wall and the east-facing IR wall. Thus, both a high and low sensitivity heat flux transducer were used in each room. If sensitivity were an issue, the responses of the heat flux transducers in each room would not be so similar.

Consistency of data

Other example days could be presented but the instrument responses for them were similar to those for the one selected. Each presents anomalies of its own. In an effort to obtain an overall assessment of the consistency of the Phoenix data as it evolved, hourly averages of the measured temperatures and heat fluxes for each exposure were compiled for each four-week period ("month") and input to PROPOR.

Figure 6 shows the best estimates of R-value and volumetric heat capacity for the test sections from month to month of data collection in Phoenix. Months 6 and 7 (most of October and November 2004) yielded R-values and thermal mass that are different for each test section from the estimates for months 1 through 5. This is attributed to the smaller temperature differences across the walls and heat fluxes becoming essentially zero through the walls as the climate moderated in Phoenix.

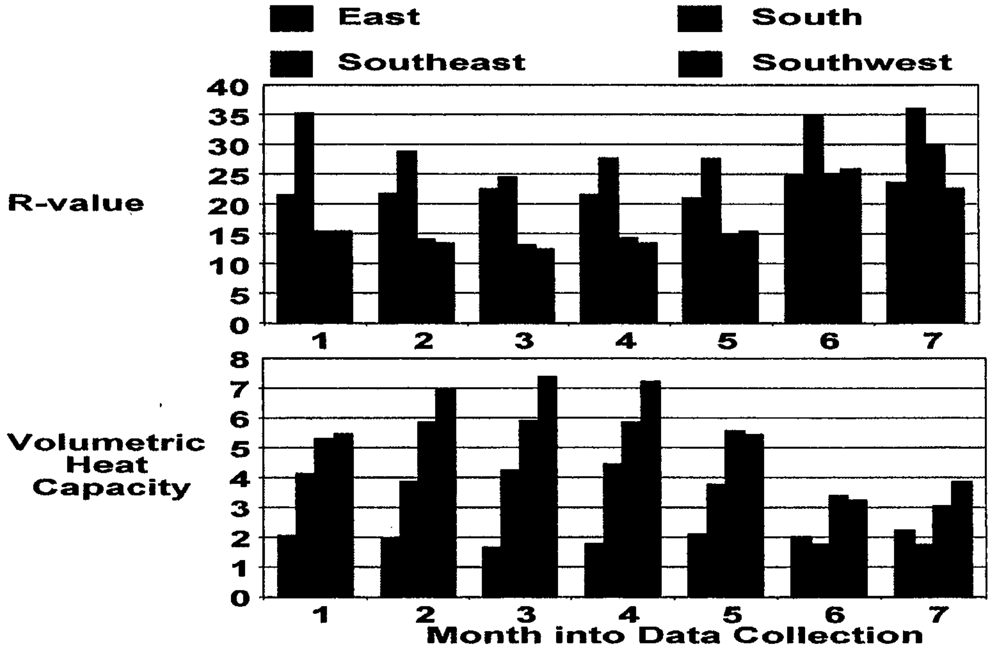

Fig. 6 Best Estimates of R-value and Volumetric Heat Capacity for the Test Sections in Phoenix

Besides the behavior in months 6 and 7, other anomalies are apparent but no simple explanation is offered. No attempt was made to monitor or affect the thermostat settings or other choices by the residents of the Phoenix house that might have led to better data. The southwest and southeast walls should have the same R-value and thermal mass. This is true except for the thermal mass in months 2, 3 and 4. The south and east walls should have about the same R-value. This is true only for months 2, 3 and 4. The R-value for the southwest and southeast walls should be smaller than that for the south and east walls. This is generally true. The south wall should have the same or slightly more thermal mass than the southwest and southeast walls. It has less. The east wall should have the least thermal mass. This is generally true.

The Phoenix data, even if restricted to months 1 through 5, are not consistent with all the construction features of the walls. The data are not suitable for validation of a model of the thermal behavior of walls coated with and without IrBPs. The Phoenix data are valuable for qualitatively showing the effect of heat flux transducer sensitivity, wall orientation and construction features, including shadowing effects, during the most severe part of the Phoenix cooling season.

Jacksonville Test Site

Installation and instrumentation

The Jacksonville residence used for a test site is a two-story wood-sided house on Ponte Vedra Beach. The deck on the east side of the house faces the Atlantic Ocean. The left half of Fig. 7 shows the ocean side of the house before the whole house was coated with Texcote coating in Undersea color. The right half of Fig. 7, with the arrow and boxes added to the picture, shows the south side in Undersea color while the side-by-side test sections were being prepared above the steps leading to the ocean-side deck. The test sections followed the slope of the steps.

Fig. 7 Residence on Ponte Vedra Beach near Jacksonville, Florida Used as Test Site for the Project (Left: East Side; Right: South Side with Side-by-Side Test Sections)

Two thermocouples for each test section were attached with staples and caulk to the outside of the wall so that their measuring junctions straddled the center of the test section. The caulk was allowed to cure before the coatings were applied. The coatings on the test sections were drying when the photograph was taken so they are slightly more glossy than the rest of the wall. A pyranometer for measuring solar radiation flux to the vertical wall was located between the test sections.

Figure 8 is a photograph of the gypsum panels added inside the family room behind a large television in the southeast corner of the room. The gypsum panels were placed so that the heat flux transducer in the middle of each was in the middle of the corresponding recoated area on the south wall. The wall was 7¼ in. thick, as determined by drilling from outside to inside through a 2x6 stud. Stud spaces were insulated with nominal R-19 insulation. Wood siding over sheathing outside and gypsum wallboard inside completed the wall construction.

Fig. 8 Gypsum Panels Added to Family Room Walls Inside the Test Sections at the Test Site near Jacksonville

A Campbell Scientific 21X data logger was placed on the floor behind the television. Leads from the outside surface thermocouples and the pyranometer were brought through the hole drilled in the wall. These leads, along with those from the inside thermocouples and the heat flux transducers, were attached to the data logger. The data logger was connected to a modem. The owners agreed to connect the modem to their personal telephone line as needed for downloading the data to a computer at Oak Ridge.

The data were collected at one minute intervals and fifteen minute averages were stored. There was enough storage capacity in the data logger so that the owners did not have to be bothered more than once a month for downloading. Data were obtained from May 5, 2004 through December 3, 2004. Analysis of the first month's data revealed no significant difference between results for the two test sections. At that point, there was sufficient uncertainty about the exact formulation of the coatings applied on May 5 that it was decided to recoat the test sections. This was accomplished on July 9, 2004. The sensors and data logger were removed on December 8, 2004.

Typical data

Figure 9 is an example of the daily variation in observed temperatures and heat fluxes from the side-by-side test sections on the house near Jacksonville. The day chosen is August 19, 2004. Wall solar heat flux peaks at about 1300 Eastern Daylight Time. The outside surface temperatures peak at the same time. Due to the recoating that was done on

July 9, several coats of colored coatings comprised the substrate for both test sections. On the IR test section, the last appeared to be a coating without IrBPs. The peak Non surface temperature in Fig. 9 is only slightly warmer than that of the IR surface. Such a small difference is evidence that the IR coating was not put over a white primer.

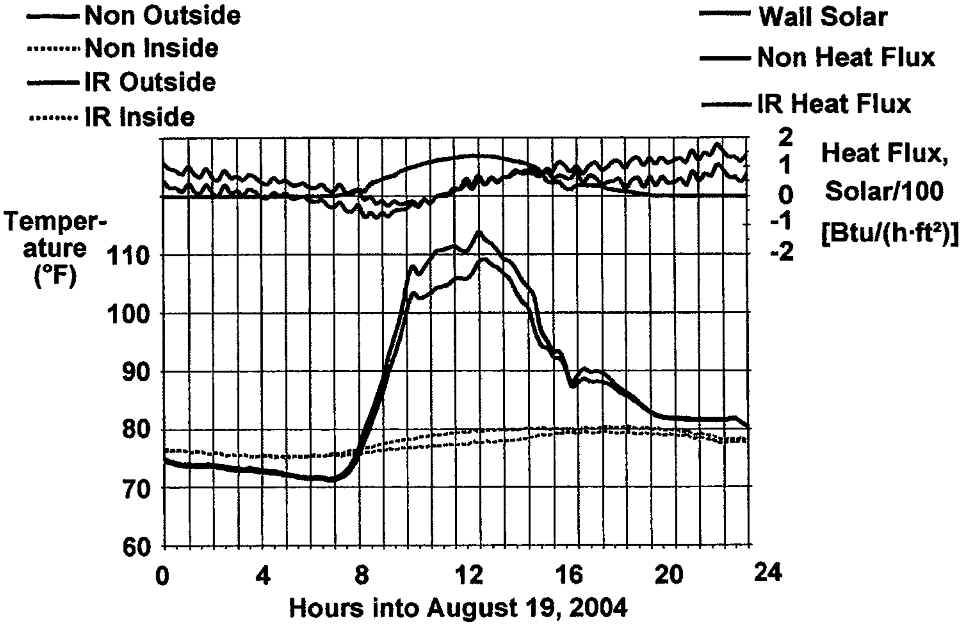

Fig. 9 Comparison of Temperatures and Heat Fluxes with IrBPs (IR) and without IrBPs (Non) near Jacksonville

The outside surface temperatures behave as expected at night. The inside temperatures are slightly different during midday. Figure 8 showed that the gypsum panels were not at the same level because the test sections followed the slope of the steps on the outside. The dead air behind the television likely experiences some stratification of temperatures. Figure 9 shows that the inside temperature for the Non test section is cooler than the inside temperature for the IR test section even though the Non exposure is slightly warmer. This is consistent with the lower placement of the Non test section on the wall.

The heat fluxes peak about ten hours after the outside surface temperatures. This is much too long for walls that have relatively little thermal mass. The four hour delay observed for the east wall in Phoenix was expected. The heat flux transducers used here were not highly sensitive units, but that did not seem to matter in Phoenix. The Non and IR heat fluxes are equal at midday as a consequence of the equal nighttime temperatures. Because the outside surface temperatures are lower than the inside surface temperatures for several hours, it is reasonable that the heat fluxes become slightly negative.

Consistency of data

Figure 10 presents the PROPOR results for the test sections near Jacksonville from hourly averages of the evolving data for each four-week period ("month") into the testing. Months 1 and 2 (most of May and June 2004) occurred before the test sections were recoated. The uncertainty in the pigmentation of the coatings on the test sections for these months should not affect the PROPOR results. Regardless, the R-value is high and the thermal mass is low for the IR test section in months 1 and 2 relative to months 3 through 7. Only month 1 for the Non test section is different than the other months for it. However, in months 3 through 7, the R-values are lower than the expected R-20 for both test sections. The thermal mass for the Non test section is unexpectedly high for months 2 through 7. Values of 5 to 6 were obtained for the massive walls in Phoenix. The value of 2 for the IR test section agrees well with the values for the lightweight east test section in Phoenix.

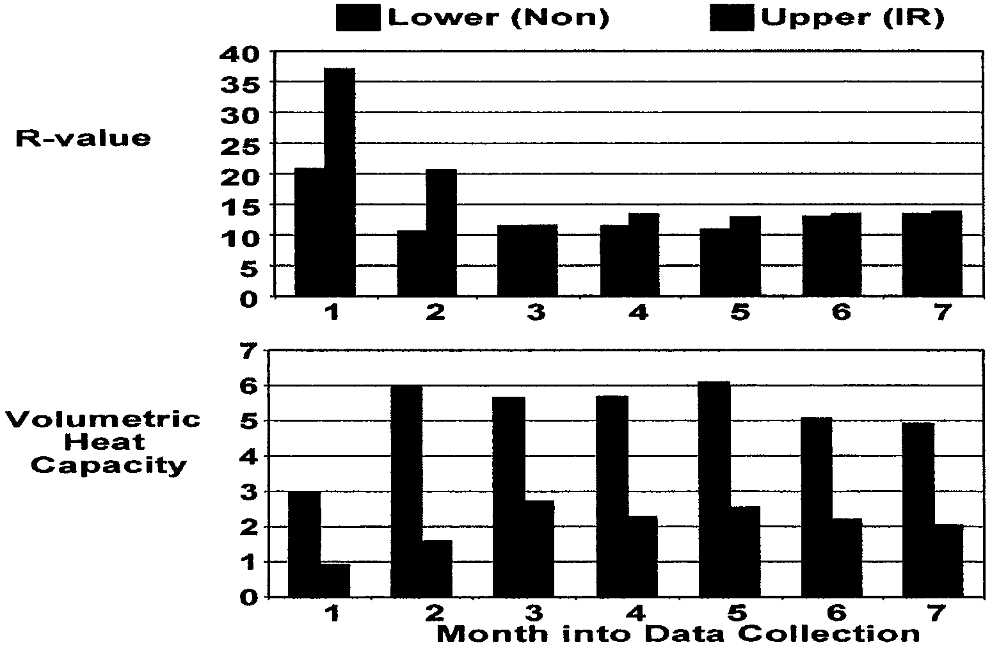

Fig. 10 Best Estimates of R-value and Volumetric Heat Capacity for the Test Sections near Jacksonville

The Jacksonville data, even if restricted to months 3 through 7, are not consistent with the known simple construction features of the walls. The data are not suitable for validation of a model of the thermal behavior of walls with and without IrBPs. It was useful, however, to gather field data in the harsh coastal environment on the Atlantic Ocean side of Florida. The thermal performance of these test sections was quite different from that of the Phoenix test sections due to the more frequent periods of cloudiness and rain, including minor effects of the downgraded Hurricanes Frances and Jeanne as they passed by the Jacksonville area during the test period.

Test Site at the Oak Ridge National Laboratory

Installation and instrumentation

The Envelope Systems Research Apparatus (ESRA) in the Buildings Technology Center (BTC) at the Oak Ridge National Laboratory was constructed especially to provide large roof and wall areas for field tests of building envelope components in the mixed climate of East Tennessee. A mixed climate is one with significant heating and cooling requirements. The ESRA served initially as a test site for side-by-side comparison of the thermal performance of foam insulations as they aged in low-slope roofs. In recent years it has been used for side-by-side comparisons of cool membranes for low-slope roofs and bare and coated metal roofs, both low-slope and steep-slope. Currently, various steep-slope tile and metal roofs with cool surfaces are being tested on the ESRA. They are seen on its roof in Fig. 11. A 4 ft x 4 ft exposure on the south wall of the ESRA, seen in Fig. 11 toward the east end of the south wall, was covered several years before this project with a 1-in.-thick coat of stucco over a ¾ in. vented air space. The moisture transport experiment for which it was built ended in 2003.

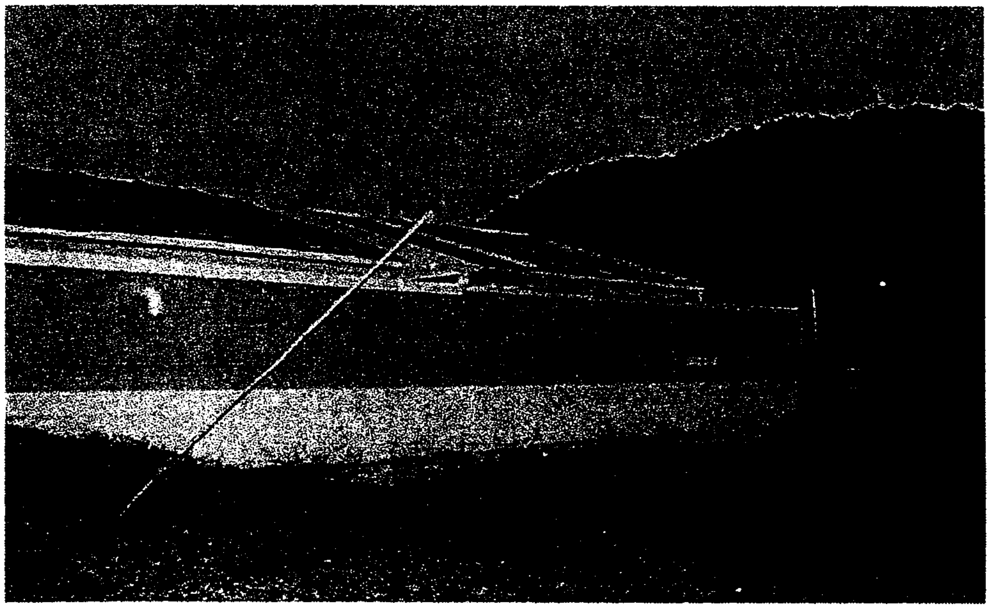

Fig. 11 South Wall of the Envelopes Systems Research Apparatus at the Oak Ridge National Laboratory

The left half of Fig. 12 shows the adaptation of the stucco-coated wall for this project. The inlet vents for the air space at the bottom of the wall were covered with metal tape. A pyranometer was added to the wall to complement the horizontal solar pyranometer and infrared pyrgeometer that are part of a complete local weather station on a building within 100 yards of the ESRA. The thermocouples on the exposures for the test sections were each attached with caulk that was allowed to cure before the coating was done. The 4-ft width of the test section comprises three stud spaces in the wall of the ESRA. The original experiment had instrumentation in the center space. It was left intact and includes relative humidity sensors and thermocouples at several locations through the wall. Two high sensitivity heat flux transducers remained in place between the gypsum at the interior and the R-11 fiberglass batt insulation in the stud spaces. They are spaced ±1 ft vertically from the midheight of the test section.

The right half of Fig. 12 shows the gypsum panels added at the inside of the test sections. They have high sensitivity heat flux transducers in the middle of their areas, flush with the surface against the existing wall. The heat flux transducers are positioned vertically half way between the pairs of thermocouples seen on the east and west stud spaces in the left picture. Pairs of thermocouple measuring junctions, at the same height as those that measure outside surface temperature, are in place on both surfaces of the added gypsum panels. The use of the added gypsum panels for the ORNL test sections made them similar to the test sections in Phoenix and Jacksonville.

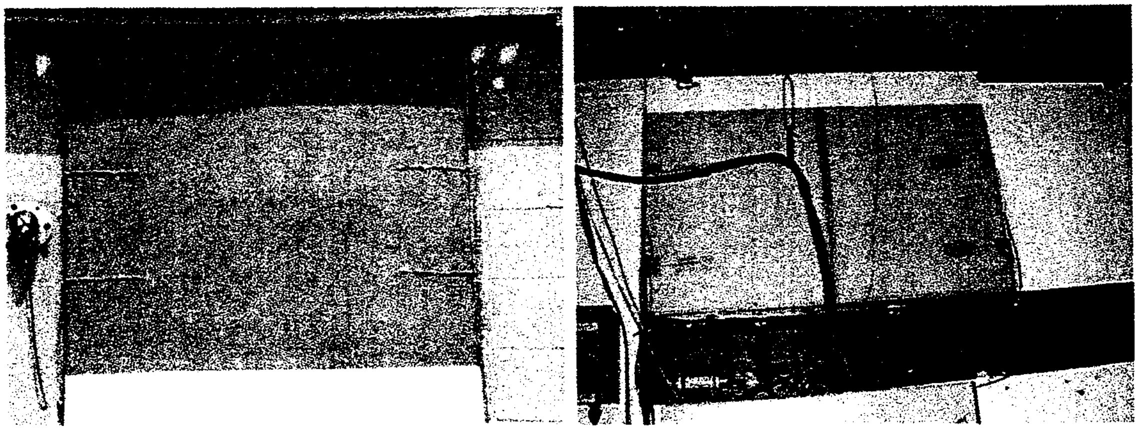

Fig. 12 Coated Areas on the Stucco-Coated Test Section (Left) and Inside View of the Test Section (Right) at the Oak Ridge National Laboratory Test Site

The entire stucco-coated area was primed with Texcote Classic white primer. A small strip of the primer was left exposed. After the primer had dried thoroughly, the area outside the east stud space and the upper half of the center stud space were coated with Texcote Supercote Platinum in Undersea color (IR test section). The area outside the west stud space and the lower half of the center stud space were coated with Texcote Supercote in Undersea color (Non test section). This pattern is difficult to see in the left half of Fig. 12 because the colors of the two coatings are the same to the human eye. The pattern was chosen to allow the existing heat flux transducers to give additional insight to the measurement of heat flux by the east and west heat flux transducers in the added gypsum panels.

The leads from the thermocouples and heat flux transducers that were added to the stucco test section were plugged into available jacks for the data acquisition system that serves the ESRA. This system has a dedicated computer to run software for continuous acquisition and storage of data. The list of active channels for experiments in the ESRA is scanned every minute. For the test of the IR and Non coatings on the wall, averages of all temperatures and heat fluxes were computed every 15 minutes and reported weekly in a spreadsheet. Data at the same frequency from the nearby weather station for the Buildings Technology Center were added to the weekly spreadsheet for the coatings. The spreadsheets were used for further analysis and plotting of the data. Data acquisition began on July 30, 2004 when the primer was applied. The coatings were applied on August 3, 2004. Data acquisition continued uninterrupted through September 1, 2005.

Typical data

Figure 13 is an example of the side-by-side behavior of the IR and Non coatings during the year of monitoring. Two clear days are shown: a spring day (April 16, 2005) and a summer day (July 25, 2005). The peak solar radiation incident on the wall is higher for the spring day because the Sun has a lower altitude angle (higher zenith angle) than it does for the summer day. The outside air temperature goes from 40°F at night to 75°F at midday for the typical spring day. It goes from 70°F to 95°F for the hot summer day. The spring day is an example of a day when solar heat gain through the wall would be desirable. The summer day is an example of a typical cooling day when it is desirable to use solar radiation control to decrease the solar heat gain.

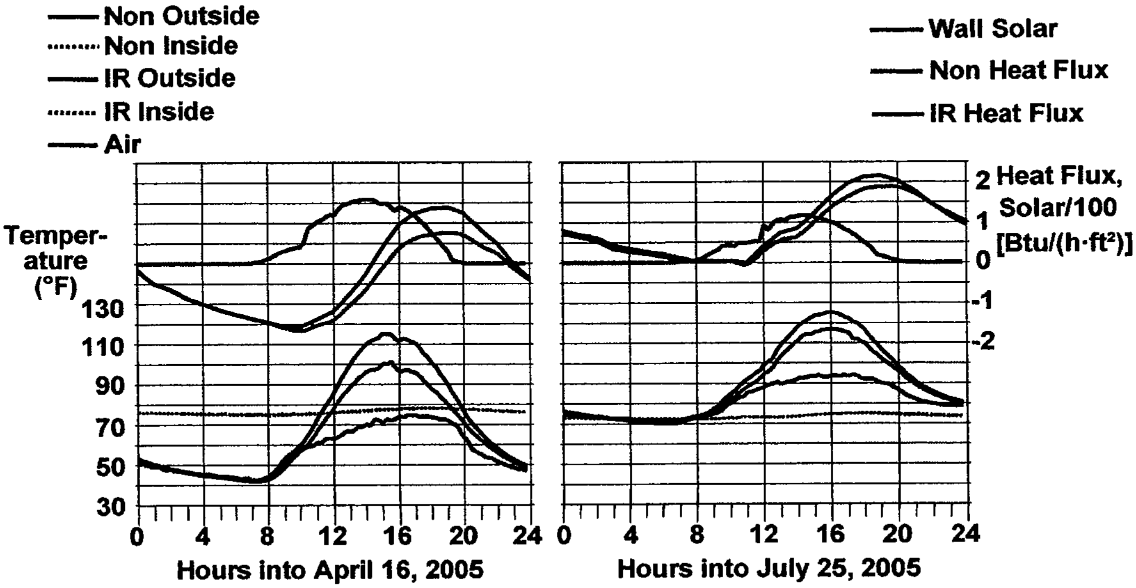

Fig. 13 Comparison of Temperatures and Heat Fluxes with IrBPs (IR) and without IrBPs (Non) for a Spring and Summer Day at the Oak Ridge National Laboratory

The temperature inside the ESRA is maintained between 70°F and 75°F year round for storage of materials and for the comfort of researchers. The ESRA houses the Hygrothermal Properties Laboratory for measurement of the moisture properties of building materials. The inside surface temperatures on both days behave as expected. They are the same for the IR and Non test sections and about the same as the air temperature maintained in the ESRA.

The outside surface temperatures also behave as expected. At nighttime, in the absence of solar effects, they are the same under the IR and Non coatings. They become equal to the air temperature when daytime solar effects damp out. During the daytime the peak outside surface temperature of the Non coating is higher than that of the IR coating because of the lower solar reflectance of the Non coating. In response to the higher wall solar heat flux for the spring day, the difference between peak outside surface temperatures for the Non and IR coatings is slightly larger for the spring day than for the summer day. Note that it is about 15°F larger for the spring day, an indication that the IR coating over the white primer is performing as expected.

As Fig. 13 shows, the heat fluxes between the gypsum surfaces also behave as expected. The nighttime heat fluxes become equal for both the Non and IR 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. Peaks for both the Non and IR test sections occur about four hours after peaks in the outside surface temperature. This is an indication that the stucco coating adds thermal mass to the otherwise lightweight wall. This amount of delay is what is observed in Fig. 4 for the east exposure in Phoenix. The difference between the peak heat fluxes for the Non and IR coatings is larger for the spring day than for the summer day. This is a response to the larger solar flux incident on the wall for the spring day.

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 could supply some of this heat, are less for the IR wall than the Non wall. This is an example of the heating penalty associated with solar radiation control. The behavior of the temperatures and heat fluxes for the Non and IR test sections for other example days during the year of testing was consistent with that on the days shown.

Consistency of data

Hourly averages of the temperatures and heat fluxes during 13 four-week periods ("months") were prepared as input to PROPOR. Figure 14 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 Fig. 14 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 Oak Ridge. There seems to be a slight seasonal variation in the R-values and thermal mass estimated by PROPOR. 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 for the IR test section and 20.3 h·ft^2·°F/Btu for the Non test section. The confidence

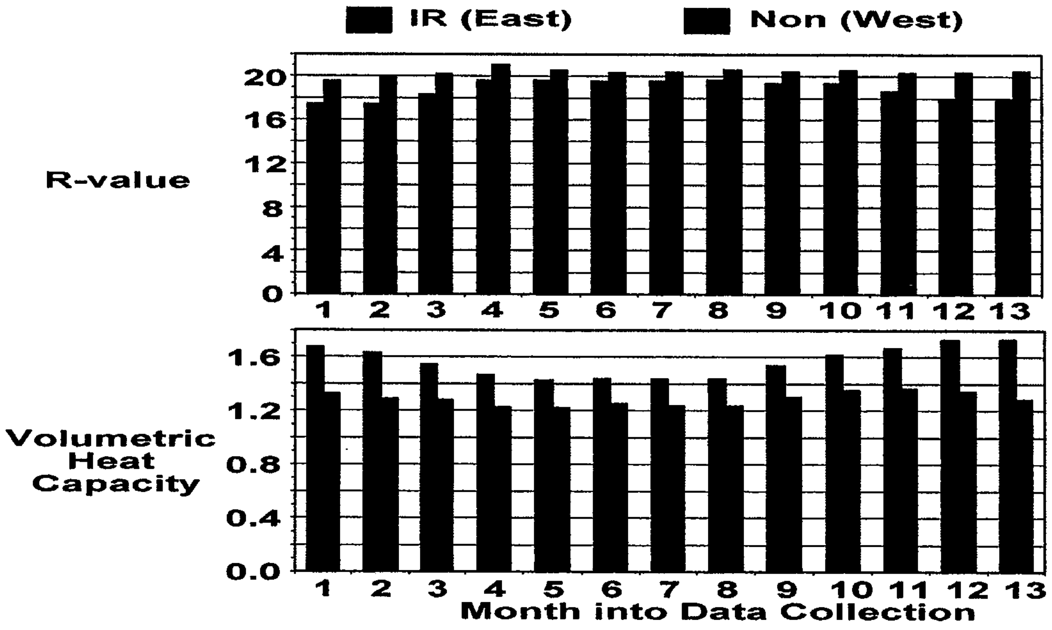

Fig. 14 Best Estimates of R-value and Volumetric Heat Capacity for the Test Sections at the Oak Ridge National Laboratory

intervals for both test sections are less than ±1.5% of the best estimates, indicating good confidence. The average volumetric heat capacity is 1.6 Btu/(ft^3·°F) for the IR test section and 1.3 Btu/(ft^3·°F) for the Non test section. Confidence intervals are less than ±3.0%, which is also good.

Table 2 lists the wall components through the insulation in the stud spaces, thicknesses of the components, and handbook values of their properties at room temperature. Average outside surface temperature for the year is 65°F under the IR coating and 68°F under the Non coating. Inside surface temperature averages about 72°F for both test sections. Properties at room temperature are appropriate for comparison. The last row of the table gives properties 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 because they are 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.-thick vertical air space at room conditions bounded by non-metallic surfaces is 0.9 h·ft^2·°F/Btu (ASHRAE 2005a). Total R-value of the test section from the properties of its components is 14.1 to 17.3 h·ft^2·°F/Btu. This range should correspond to the total thickness divided by the thermal conductivity that PROPOR estimates. The value of 18.8 h·ft^2·°F/Btu for the IR test section is closer to this range than the value of 20.3 h·ft^2·°F/Btu for the Non test section but both are too high.

Table 2. Details of the test wall at the Oak Ridge National Laboratory

Component	Thickness [in.]	R-value [h·ft^2·°F/Btu]	ρc [Btu/(ft^3·°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)

The higher value of total volumetric heat capacity in the last row of Table 2 is estimated as the volume weighted average over all the components: the sum over components of the product of thickness and volumetric heat capacity for each component, divided by total thickness. This assumes that the thermal mass is equally effective wherever it occurs in the test section. The most effective thermal mass is that which sees a significant temperature fluctuation. By this criterion, the volumetric heat capacity would be lower and approximately that of the stucco. Thus, the volumetric heat capacity of both test sections is 3.8 to 6.2 Btu/(ft^3·°F). This range should correspond to the values estimated directly by PROPOR. The value of 1.6 Btu/(ft^3·°F) for the IR test section is closer to the lower end of this range than the value of 1.2 Btu/(ft^3·°F) for the Non test section but both are too low.

The ORNL data yield consistent PROPOR estimates of R-value and volumetric heat capacity from month to month. The estimates agree reasonably well with expected R-value and volumetric heat capacity for the test sections. The estimates for the IR test section are closer to expected values. The ORNL data are considered suitable for validation of a model for the thermal behavior of walls with IrBPs and without IrBPs in their coatings.

MODELING THE THERMAL BEHAVIOR OF WALLS

Confidence in Measurements

Measured and accepted properties of the ORNL test sections are used for validation of the proposed model of the thermal behavior of walls. Agreement between measured and predicted outside surface temperatures and agreement between measured and predicted heat fluxes at the location of the heat flux transducers are the criteria for deciding if the model is valid. Since the measurements for the two test sections are independent, the model for the IR test section is validated independently from the model for the Non test section. The models for validation differ only in the solar reflectance of the coating, but uncertainties in the measured solar reflectance, outside surface temperatures and heat fluxes all affect the validation.

The uncertainty of the solar reflectance was assigned the value ±0.008 in the discussion accompanying Table 1. The measurements of temperature and heat flux also have inherent uncertainty. Here, automated data acquisition and averaging of many data guarantee equal and small imprecision. However, uncertainty is the square root of the sum of the squares of imprecision and inaccuracy, in the same units (ASHRAE 2005b). Therefore, uncertainty is also affected by accuracy.

As Fig. 13 from the ORNL data shows, the Non test section has generally higher surface temperatures and larger positive (inward) heat fluxes than the IR test section. In general, larger responses, within the range of allowable responses from calibrated instruments with fixed inaccuracy, have smaller percentage inaccuracy. The Non responses are not so much larger than those of the IR test section to significantly affect the RSS estimate of uncertainty. The fact that PROPOR estimates of thermal resistance and volumetric heat capacity for the IR test section are closer to expectations than those for the Non test section is considered significant. According to PROPOR the annual averages of measurements for the IR test section are more accurate. As a consequence the IR measurements are considered more certain than the Non measurements.

Selection of Model

The goal of the modeling task is a model that can be generalized to give results for whole buildings in various climates with typical wall configurations. Buildings usually have four walls that face in different directions. Overhangs and other architectural features, as well as landscaping and nearby buildings, create shadows that affect the amount of solar insolation that strikes the walls. The primary requirement for a wall model is its ability to accurately account for solar insolation on each wall and include its effects on the building load. Walls receive solar radiation directly from the Sun and by reflection from the ground and the sky.

The programs we used to model low-slope and steep-slope roofs cannot be easily adapted to walls. For low-slope roofs, the program Simplified Transient Analysis of Roofs (STAR) (Wilkes 1989) does finite-difference calculation of transient one-dimensional conduction in multilayer assemblies in response to boundary conditions. The detailed structure and properties of each layer are input. If desired, ambient weather conditions provide one type of external boundary condition. Total horizontal solar flux, including effects of clouds, is assumed in STAR to uniformly irradiate the low-slope surface. There is no provision for shading. Input solar absorptance determines how the incident solar flux impacts the roof surface temperature. Measured infrared flux (with a pyrgeometer) or estimated sky cover determines the effective sky temperature for exchange of infrared radiation. Input infrared emittance determines how much the sky temperature affects the roof surface temperature. Some low-slope roof surfaces, such as bare metal or metal capsheets, can have low infrared emitance causing them to retain energy compared to common surfaces with high infrared emittance. Low-slope roofs do not see the ground so STAR has no provision for radiation exchange with the ground.

STAR cannot account for the complex radiation exchange for walls. For this project, STAR is useful for prediction of internal heat fluxes once the outside surface temperature is determined by a suitable wall model. If STAR is used with specified temperatures as the boundary conditions on the inside and outside surfaces of an assembly, then the orientation, surface properties and radiation exchange are irrelevant.

Because STAR is not adequate for steep-slope roofs with an unconditioned attic space under them, K.E. Wilkes developed another model for the thermal performance of residential attics (Wilkes 1991). It is a nodal model that assigns a single temperature to each of the various components of a residential attic, including two roof sections, two gables, two vertical eave sections, a ceiling and an attic air space. Temperatures are assigned to the various nodes as a result of energy balances. Algebraic equations are used. Transient conduction across structural or insulating elements, including the ceiling, typically with mass insulation on top of it, is handled with conduction transfer functions. No temperatures or heat fluxes are available inside the elements. Radiation heat transfer exchange is done separately from convection-conduction heat transfer inside the attic. Latent heat effects can also be included and trusses or joists and rafters can be specified to include their effects on the moisture balance.

When ambient weather conditions are used for external boundary conditions, the treatment of radiation for the roof is quite simple. Infrared radiation is neglected. Total horizontal solar radiation is corrected for roof slope and orientation. The energy balances for the gables and vertical eave sections do not account for any incident solar radiation, directly or from the sky or the ground. Therefore, gables and vertical eave sections in the Wilkes attic model would not be reasonable models of walls in buildings.

The public domain program DOE 2.2 (http://www.doe2.com/) is selected as the model for the thermal behavior of walls coated with and without IrBPs because it can accurately account for solar insolation on walls from the Sun, sky and ground. In the form used herein, it is a command line-launched program and requires input files created using a text editor. Building descriptions must be done in DOE 2.2's Building Description Language. Use of this form of DOE 2.2 is convenient for this project because of the extensive validation we have done of a DOE 2.2 model of a single-story, 1100 ft^2 residence in previous projects in cooperation with the Lenoir City, TN and Chattanooga, TN Habitat for Humanity chapters (Petrie *et al.* 2002, Petrie *et al.* 2005). The non-wall specific features of the house will be given later in the section that describes how the model is applied in different climates with different wall constructions.

DOE 2.2 Input for Validation of the Wall Model

Wall details

The walls in the previous model of a single-story residence were vinyl-sided and wood-framed, with a single layer of gypsum on the inside. They were modified to accommodate the features of the ORNL test sections. Stucco and an air layer were substituted for the vinyl siding on the outside of the exterior walls and an extra gypsum layer was added to the inside. The properties and dimensions of the wall materials are those presented in Table 2. The air layer is assigned an R-value of 1 h·ft²·°F/Btu, giving it no thermal mass in DOE 2.2. The approach for solid materials to account for thermal mass is to assign thickness, thermal conductivity, density and specific heat in a material definition or by reference to a material in the DOE2 libraries.

Radiation properties of walls and ground

The radiation properties of the surfaces are very important for validation of a model of thermal performance of walls with and without IrBPs in their coatings. DOE 2.2 assumes that wall surfaces have the infrared emittance of common non-metallic materials and infrared radiation exchange is not done separately. Measurement of the infrared emittance for a few samples of the coatings on aluminum strips verified that the infrared emittance was 0.9 as expected. A substrate with high thermal conductivity is best for the technique that was used, namely, ASTM C 1371, Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers. DOE 2.2 requires an estimate of the solar absorptance (1 - solar reflectance) of all exterior wall and roof surfaces and assumes that they are opaque. Overall annual average values of solar reflectance for the ORNL test surfaces were used, namely, 0.238 without IrBPs and 0.495 with them, as listed in Table 1.

In addition to the solar absorptance of exterior walls, the solar reflectance of the ground seen by each exposure is required input to DOE 2.2. The range suggested in the DOE2 support documentation is 0.08 for dark soil or asphalt to 0.24 for dry grass. As seen in Fig. 13, the ground in the immediate neighborhood of the south wall of the ESRA is covered with gravel. Beyond the gravel are weeds, which invade the gravel as the growing season progresses. DOE 2.2 was run for ground reflectance of 0.08 and 0.24.

Climatic conditions, including cloud amount, precipitation and wind

To allow comparable predicted and measured results in the validation effort, the weather and solar conditions to DOE 2.2 should be as identical as possible with hourly averages of the measured climatic conditions. DOE2 utilities can take user-generated weather files in proper format and pack them for use by DOE 2.2. The task here was to convert and supplement the data from the Buildings Technology Center weather station during the year of testing. Table 3 lists what DOE 2.2 requires, its units or values, and how it was obtained. The source for four of the weather file entries is listed as a utility fragment. This is a fragment of code supplied in the DOE2 weather utilities that was compiled into a small executable program. It uses horizontal solar, dry bulb temperature, atmospheric pressure and relative humidity directly from the BTC weather station records to produce the listed data for the weather file.

The estimation of cloud amount, a number between 0 for a clear sky to 10 for a completely cloudy sky, is obtained in a spreadsheet from a fragment of code in STAR. The preferred input to STAR for estimating sky temperature is the infrared flux from a pyrgeometer, such as is present in the BTC weather station. Given infrared flux q_{IR}, STAR uses $q_{IR} = \sigma T_{sky}^4$ to calculate absolute sky temperature, T_{sky}, where σ is the Stefan-Boltzmann constant. Given cloud amount, which is commonly available in compilations of weather data such as typical meteorological years (TMY2) (NREL 1995), STAR contains a series of equations to estimate sky temperature. The sequence of these

Table 3. 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	--	BTC weather station record
Day	--	BTC weather station record
Hour	--	BTC weather station record
Wet Bulb Temperature	°F	Utility fragment
Dry Bulb Temperature	°F	BTC weather station outside temperature
Atmospheric Pressure	in.-Hg	BTC weather station outside pressure
Cloud Amount	0 to 10	From BTC weather station pyrgeometer
Snow Flag	0,1	Set to 0
Rain Flag	0,1	1 if BTC weather station Δrain > .01 in.
Wind Direction	0 to 15	BTC weather station, ranges of ° to #
Humidity Ratio	--	Utility fragment
Moist Air Density	lb/ft^3	Calculate from P, T, humidity ratio
Moist Air Enthalpy	Btu/lb	Utility fragment
Horizontal Solar	$Btu/(h \cdot ft^2)$	BTC weather station pyranometer
Direct Solar	$Btu/(h \cdot ft^2)$	Utility fragment
Cloud Type	0,1,2	Set to 1
Wind Speed	knots	BTC weather station, mph to knots

equations was reversed in a spreadsheet to start with sky temperature from the infrared flux in a BTC weather station record and calculate a raw cloud amount. The raw cloud amounts for the year were offset and normalized to the range from 0 to 10 and rounded off to the required integer in the DOE 2.2 weather file.

The BTC weather station includes a rain gauge. Infrequent snow that entered the rain gauge melted under direct sunlight and was counted as rain. Hence, the snow flag was set to 0 for the whole year. The difference between the cumulative rainfall from hour to hour was formed. If the difference was greater than 0.01 in., the rain flag was set to 1. If not, it was set to 0. Once the utility fragment produced the humidity ratio for the moist air at measured absolute temperature, T, and pressure, P, the ideal gas equation was used for density: $\rho=P/RT$, where the ideal gas constant R included the effect of the water vapor.

Records from the BTC weather station from August 5, 2004 through August 4, 2005 and the procedures in Table 3 yielded 8760 entries for a DOE 2.2 weather file. The entries were rearranged from January 1 through December 31 and checked for consistency at the end of August 4. The required formatting was done in a text editor to produce the input file that the DOE2 weather utility required to produce a packed weather file. Statistics for the year of Oak Ridge weather that the utility produced were compared to the statistics for the TMY2 weather for Knoxville. A typical meteorological year in the TMY2 compilation combines actual records from what are considered typical months for the location.

Table 4 is a comparison of some annual averages from the two weather files. The only significant difference in Table 4 between the actual weather of Oak Ridge and the typical weather of Knoxville is in the annual average wind speed. The Oak Ridge average of 1.9 mph rather than the Knoxville TMY2 average of 6.7 mph is a reasonable difference. The anemometer on the BTC weather station is less than 5 meters above the roof of a small test building that is sheltered by nearby buildings. The Knoxville TMY2 wind speed is presumably from a 30 m tower out in the open, which is the usual source of meteorological wind data. To do accurate estimates of infiltration DOE 2.2 has site parameters to handle wind speed properly, but wind has little effect on the thermal performance of walls.

Table 4. Comparison of annual averages for
Oak Ridge test year vs. Knoxville TMY2

Weather statistic	Oak Ridge test year	Knoxville TMY2
Dry bulb temperature, °F	58.6	58.3
Web bulb temperature, °F	54.5	52.9
Daily maximum temperature, °F	69.7	68.1
Daily minimum temperature, °F	49.6	49.3
Heating degree days, base 65°F	3356	3662
Cooling degree days, base 65°F	1408	1366
Wind speed, mph	1.9	6.7
Avg. daily direct normal solar, Btu/(h·ft^2)	1164	1152
Avg. daily total horizontal solar, Btu/(h·ft^2)	1227	1334

Validation Results

DOE 2.2 execution and output selections

Within DOE 2.2, the LOADS subprogram first operates with a fixed inside air temperature to produce the loads from the building components on the HVAC system. DOE 2.2 reckons solar position hour by hour and does calculations for shading of exterior surfaces by architectural and landscaping features. LOADS responds to input weather and solar conditions, infiltration, schedules of people, lighting and equipment, heat transfer through walls, roofs and windows and effects of building shades on incident solar radiation. Then, if desired, the HVAC subprogram corrects the loads for effects of outside air requirements, hours of equipment operation, equipment control strategies and thermostat setpoints. The HVAC subprogram weights the various loads to account for delays due to thermal mass. The user can request pre-designed output reports or can specify custom-designed hourly reports. Hourly report generation is a feature of DOE 2.2 that allows a user to output hourly values used within the program. Both the LOADS and HVAC subprograms were run for the validation task but only the LOADS output was used for comparison to the measurements.

Hourly reports of the total solar radiation on the wall after shading, the fraction of the wall that is shaded, intensity of direct solar radiation before shading, intensity of diffuse solar radiation from the sky and ground after shading, and the outside surface temperature were requested for the south-facing wall. The outside surface temperature is of direct interest for comparison to the measured outside surface temperature. When compared to measured wall solar, the total solar radiation, in particular, and the other solar parameters serve to verify that DOE 2.2 correctly interprets input solar radiation. DOE 2.2 uses the total horizontal and direct solar radiation in its weather file to compute wall solar from Sun, sky and ground sources.

DOE 2.2 was run with wall construction like that of the test wall and with the weather from the year of ORNL tests. To cover the range of ground reflectance given in the DOE2 support documentation, separate runs were made with ground reflectance of 0.08 and 0.24 at every set of conditions. The values of interest from the DOE 2.2 hourly reports were pasted into a summary spreadsheet that contained a compilation of the hourly average measurements. Hourly average measurements were generated by averaging the data in the weekly reports from 45 min., 30 min., 15 min. and 0 min. previous to a particular hour. The data in the weekly reports were averages from data acquired at 1-minute intervals.

Typical temperature predictions

The summary spreadsheet permitted plotting of comparisons for selected days during the year of testing. Figure 15 is an example comparison for the spring day (April 16, 2005) and summer day (July 25, 2005) that were used for Fig. 13. The measured and predicted outside surface temperatures and the outside air temperatures are shown on a common scale. The measured temperatures have already been discussed. As expected, the predictions by DOE 2.2 for both values of ground reflectance are equal at night and essentially equal to the air temperature and the measured temperatures. The nighttime agreement is better for the summer day than for the spring day. However, the peak behavior is more regular for the spring day than for the summer day. During the spring day, the predictions peak at the same time as the measurements and the peak values for a ground reflectance of 0.08 are closer to the measured values. During the summer day, the predictions appear to peak about an hour earlier than the measurements and the peak values for a ground reflectance of 0.24 are better, at least for the IR surface.

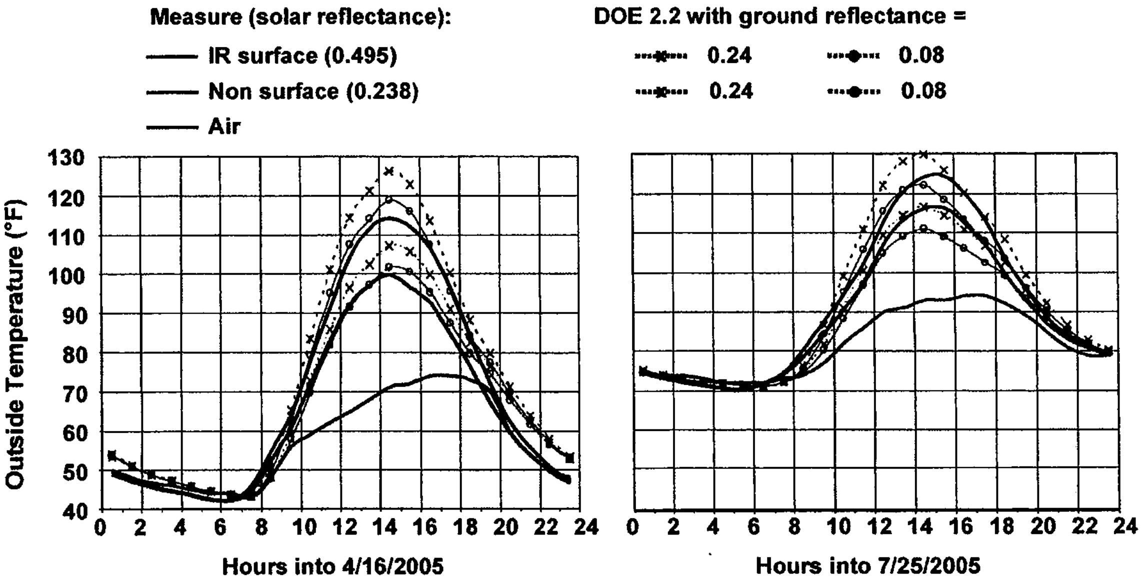

Fig. 15 Comparison of Measured and Predicted Outside Surface Temperatures with IrBPs (IR) and without IrBPs (Non) for a Spring and Summer Day at the Oak Ridge National Laboratory

There are more weeds growing in the gravel near the south wall of the ESRA in summer than in early spring. This could explain the tendency toward better agreement with predictions for ground reflectance of 0.24 in summer, but does not address the other anomalies. More graphs like Fig. 15 but for other days during the year were prepared. They did not help to convey a general sense of how well DOE 2.2 predicts the temperatures of the IR and Non outside surfaces.

Annual averages of temperatures

The summary spreadsheet, with a list of measurements and predictions for all 8760 hours in the test year, made it possible to generate annual averages. Annual averages are proposed as a general measure of how well the predictions agree with the measurements. Table 5 has the results for the average outside surface temperatures. Temperatures are generally measured with an uncertainty of ±0.5°F but averaging over multiple sensors and multiple measurements is taken to improve this to ±0.05°F.

Table 5. Comparison of annual averages for
measured and predicted outside surface temperatures

Annual average outside surface temperature, °F	Δ	**IR**	Δ	**Non**	Δ
Measurements		65.3	2.7	68.0	
	0.5				1.8
DOE 2.2 with ground reflectance of 0.08		65.8	4.0	69.8	
	1.1				1.5
DOE 2.2 with ground reflectance of 0.24		66.9	4.4	71.3	

To aid in seeing how consistent the averages are, the differences between adjacent entries, both down and across, have been added to the table. The predictions for both surfaces and the two values of ground reflectance are consistent. Annual average temperature increases 1.1 to 1.5°F as ground reflectance increases from 0.08 to 0.24 for either surface. Annual average temperature increases 4.0 to 4.4°F as surface changes from IR to Non for either ground reflectance. The measured value for Non seems inconsistent, about 1.0°F low. Recall that the PROPOR results for these test sections indicated that the IR measurements were closer to the expected thermal properties than the Non measurements.

The solar reflectance used for the predictions is 0.495 for the IR surface and 0.238 for the Non surface. Uncertainty of ±0.008 is expected. Additional DOE 2.2 trials for the Non wall were made to decrease predicted surface temperatures by 1°F rather than increase the Non measurement to achieve consistency. DOE 2.2 needed solar reflectance of 0.300 to predict an annual average outside surface temperature of 68.8°F for ground reflectance of 0.08 and 70.3°F for ground reflectance of 0.24. This reflectance is too different from the measured 0.238 to be within the confidence limits for the reflectance of the Non surface.

Typical heat flux predictions

To obtain heat fluxes at the location of the heat flux transducers in the IR wall, the program STAR was used. The inside boundary condition was the temperatures measured at the inside surface of the IR test section. Three different outside surface temperatures were used for the outside boundary condition: the measured outside surface temperature; the outside surface temperature predicted by DOE 2.2 for ground reflectance of 0.08; and, the outside surface temperature predicted by DOE 2.2 for ground reflectance of 0.24. The same procedure was followed for the Non wall. Both sets of results were added to the summary spreadsheet.

Graphs were created to compare these predictions to their respective measured heat fluxes. Figure 16 shows the comparisons for the spring day (April 16, 2005) and summer day (July 25, 2005) that were used for Figs. 13 and 15. It is more complicated than Fig. 15 for two reasons. There are extra data for heat fluxes from STAR using measured outside surface temperature, which do not exactly coincide with the measured heat fluxes. The solar flux incident on the wall estimated by DOE 2.2 is different for each ground reflectance and both are different from the measured wall solar flux. The DOE 2.2 estimates of wall solar for ground reflectance of 0.24 are, as expected, slightly higher than for 0.08. Both have a smoother shape compared to the measured wall solar.

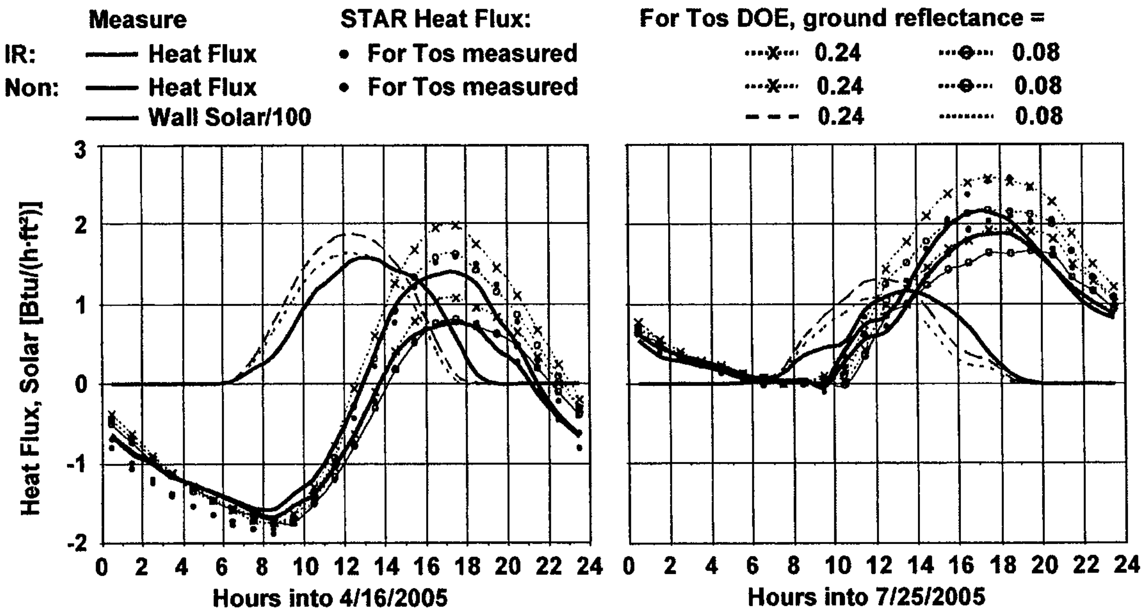

Fig. 16 Comparison of Measured and Predicted Heat Fluxes with IrBPs (IR) and without IrBPs (Non) for a Spring and Summer Day at the Oak Ridge National Laboratory

The wall solar measured with the pyranometer seen in Fig. 12 is sensitive to the shadows and microclimate at the ESRA. The DOE 2.2 estimates use the horizontal solar measured with a pyranometer mounted about 4 ft above the roof of a nearby building. The horizontal solar data are further used in the routine from the DOE2 weather utilities to estimate the direct solar for the weather file. Together they are used in DOE 2.2 itself to estimate wall solar. The more irregular shape of the measured wall solar compared to the DOE 2.2 curves makes it difficult to judge actual area under the curves, that is, the total solar incident on the test section for each of the two days. Adding the hourly values for the two days in the spreadsheet yields the following:

Total daily wall solar, Btu/ft²	Spring Day	Summer Day
Measurements with wall pyranometer	1136	792
DOE 2.2 for ground reflectance of 0.24	1265	867
DOE 2.2 for ground reflectance of 0.08	1086	697

The measured wall solar is between the DOE 2.2 values for both days. It is closer to the value for ground reflectance of 0.08 on the spring day and closer to the value for ground reflectance of 0.24 on the summer day. Ground reflectance of 0.08 is better for the spring day and 0.24 is better for the summer day. This is consistent with what was observed for the DOE 2.2 predictions of outside surface temperatures in Fig. 13.

The measured and predicted heat fluxes and the incident wall solar radiation are shown on a common scale, which emphasizes the differences between the spring day and summer day. The measured heat fluxes have already been discussed relative to the measured outside surface temperatures. The predictions by STAR using the measured outside surface temperatures agree with the measured heat fluxes better for the IR test section than the Non test section, but not significantly better than the predictions by STAR using DOE 2.2 outside surface temperatures. As expected, all heat fluxes are equal at night in the absence of solar effects. The expected nighttime agreement is better for the summer day than for the spring day as is the agreement at peak conditions. The decreased peak solar flux for the summer day due to the higher solar altitude is a likely reason. During the spring day, the predictions match the shape of the measured heat fluxes better than they do during the summer day. For the summer day, the peaks are broader and extend longer into the evening for the predictions compared to the measurements.

Annual averages of heat fluxes

More graphs were prepared like Fig. 16, but for other clear days during the year. As with the additional graphs for surface temperatures, they did not help to convey a general sense of how well DOE 2.2 via STAR predicts the heat fluxes inside the IR and Non test sections. Annual averages are proposed for heat fluxes, too, as a general measure of how well the predictions agree with the measurements.

The spreadsheet that listed the hourly measurements was used to generate annual averages. Outward and inward heat fluxes were treated separately. Two more columns were formed next to each heat flux. One listed only outward heat fluxes, that is, heat fluxes less than zero with the sign convention adopted for the project. The other listed only inward or positive heat fluxes.

This separation of heat fluxes seeks to extract common behavior in order to focus better on the differences due to the higher solar reflectance of the IR surface. For the mixed climate of Oak Ridge, outward heat fluxes occur more often than inward heat fluxes. Outward heat fluxes for the Non wall occurred for about 5540 out of 8760 hours. For the IR wall the number was about 5950. Therefore, the number of inward heat fluxes for both walls is about 3000, sufficient for meaningful annual averages.

Table 6 presents the annual averages of the inward and outward heat fluxes. The measured Non outward heat fluxes average 0.03 Btu/(h·ft^2) less than the IR outward heat fluxes. The opposite is true for all the STAR predictions of Non and IR outward heat fluxes. Measured heat fluxes are considered uncertain to at least ±5%, or ±0.05 Btu/(h·ft^2) for the level of outward heat fluxes in Table 6. The same uncertainty is assumed for comparisons between the predicted heat fluxes for the two walls. Thus, not much significance can be attributed to the observed differences among the outward heat fluxes for the two walls. Since they occur mostly at night, when no difference is expected in the thermal behavior of the two test sections, this is reasonable.

The measured heat fluxes appear low relative to all the STAR predictions, including those that use the measured outside surface temperatures. Average measured outward heat flux for the IR wall is 0.14 Btu/(h·ft^2) less than the IR STAR...measured prediction. For the Non wall, average measured heat flux is 0.19 Btu/(h·ft^2) less than the Non STAR...measured predictions. Prediction of the absolute level of the heat fluxes in each wall with a program such as STAR is more uncertain than prediction of differences between the behaviors of the two walls. The PROPOR results with the measured temperatures and heat fluxes as input indicated higher R-values for the test sections than expected from handbook properties. If R-values were indeed higher than used in STAR, its predictions would indicate higher heat fluxes than measurements.

Table 6. Comparison of annual averages for
measured and predicted heat fluxes at the gypsum interface

Annual average heat flux, Btu/(h·ft^2)	**IR Outward**	**Non Outward**	**IR Inward**	**Non Inward**
Measurements of heat flux at gypsum interface	-0.959	-0.933	+0.621	+0.753
STAR from measured outside surface temperatures	-1.101	-1.127	+0.662	+0.879
STAR from DOE 2.2, ground reflectance of 0.08	-1.095	-1.118	+0.623	+0.953
STAR from DOE 2.2, ground reflectance of 0.24	-1.098	-1.119	+0.717	+1.087

The annual averages of the inward heat fluxes in Table 6 are, as expected, smaller for the IR walls than the corresponding Non walls. The differences between Non and IR values are significantly larger than the expected uncertainty of about ±5% or ±0.03 to ±0.05 Btu/(h·ft^2) for them. From PROPOR, the average measured heat flux is considered more accurate for the IR wall than the Non wall. For the IR wall, the average inward heat flux from STAR...ground reflectance of 0.08 is closer to the measurements (only 0.002 difference) than the average from STAR...measured (0.041 difference). This difference is about the same as the expected uncertainty. The annual averages clearly indicate that ground reflectance of 0.08 is better than 0.24 for the ORNL tests.

Neither the outward nor the inward average heat fluxes deal with the expected heating penalty for solar radiation control. The heating penalty arises on cold sunny days when the building requires heating. Outward heat fluxes are not very sensitive to solar effects. The higher solar reflectance of the IR coating makes the inward directed heat flux less for the IR wall than the Non wall. However, the average inward heat fluxes do not have information about when the building requires heating. Therefore, they have no information about the heating penalty either. Averaging would need to be done only over hours when the building required heating.

Overview of annual average temperature and heat flux predictions

Figure 17 addresses the consistency of the heat fluxes and supports the claim that the measured heat flux for the Non wall seems low, like the measured outside surface temperature for the Non wall. The annual average outside surface temperatures from Table 5 and the annual average inward heat fluxes from the right half of Table 6 are plotted side-by-side with scales that emphasis their similar behavior. The annual averages of the heat fluxes from STAR using the measured outside surface temperatures are moved to the right in the heat flux chart. Thus, the first three sets of bars in this chart are for the same constraints as the three sets in the temperature chart.

Dashed lines are shown on the DOE 2.2 bars to indicate outside surface temperatures and internal heat fluxes for a surface with a solar reflectance of 0.300. They

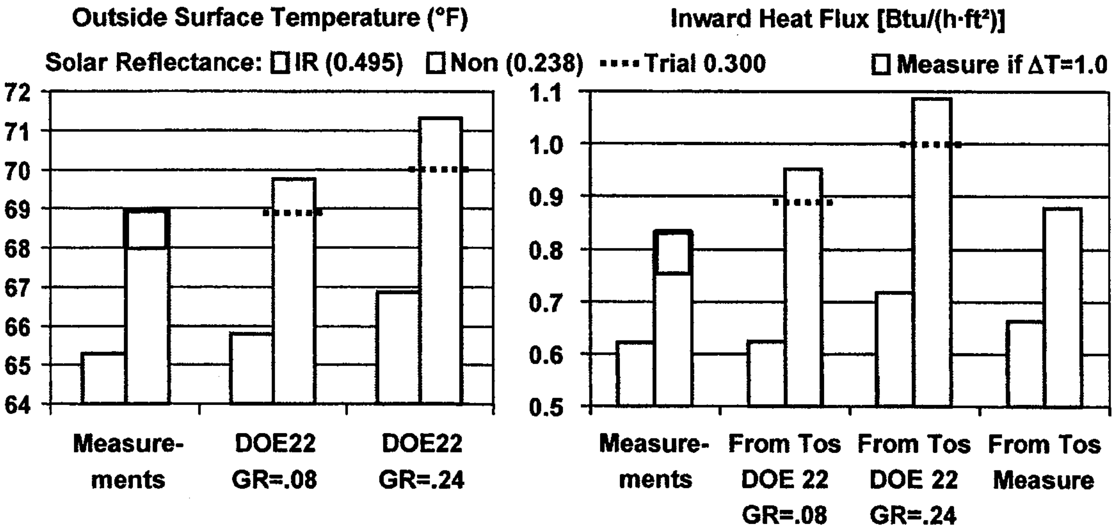

Fig. 17 Annual Averages of Outside Surface Temperature and Inward Heat Flux from Measurements and Predictions for the Test Sections at the Oak Ridge National Laboratory

are associated with the Non bars only because the measured inside surface temperatures for the Non test section were used for them. In terms of changes from case to case, if 0.300 were a reasonable solar reflectance for the Non surface, it would serve to make the heat fluxes for the Non wall consistent with those for the IR wall in Fig. 17. As the discussion of Table 5 stated, 0.300 reflectance causes 1.0°F decrease in outside surface temperatures for the Non wall for both values of ground reflectance and would serve to make outside surface temperatures consistent between the Non and IR walls.

Expected uncertainty in solar reflectance measurements dictates that such a change in solar reflectance is not reasonable for the Non wall. However, the dashed lines can be used to determine the sensitivity of the heat flux to outside surface temperature. Since measured inside surface temperatures for the Non wall are used, this sensitivity should apply to the Non measurements. For ground reflectance of 0.08, an increase of 1.0°F in outside surface temperature yields a 0.076 Btu/(h·ft^2) increase in heat flux. For ground reflectance of 0.24, an increase of 1.0°F in outside surface temperature yields a 0.088 Btu/(h·ft^2) increase in heat flux. The average of 0.082 Btu/(h·ft^2) is shown on top of the measured heat flux for the Non wall. The speculated 1°F change in outside surface temperature for the measured Non wall is shown on top of its measured outside temperature.

It is claimed that these changes are possible in light of the PROPOR results for the ORNL test sections. They make results for the Non wall more consistent with those for the IR wall. The fact remains that outside surface temperatures were measured independently of the heat fluxes. The temperature and heat flux changes would both have to occur, which is unlikely in light of their respective ±0.05°F and ±0.03 to ±0.05 Btu/(h·ft^2) uncertainties. The practical consequence of the changes is that it makes differences between the two walls from the measurements closer to those from the predictions, which helps to validate the model. Annual average difference between measured Non and IR outside surface temperatures becomes 3.7 (not 2.7) °F, compared to 4.0°F for STAR...ground reflectance of 0.08. Annual average difference between measured Non and IR gypsum heat fluxes becomes 0.214 (not 0.132) Btu/(h·ft^2), compared to 0.330 Btu/(h·ft^2) for STAR...ground reflectance of 0.08. Regardless, predicted temperature differences are still 8% higher than measured differences. Predicted heat flux differences are 54% higher.

Conclusions About Model Validation

A model of the test sections at ORNL was substituted for the exterior walls in a model of a small residence in the program DOE 2.2. The small residence had been monitored continuously for a year of energy use and its model validated. The south-facing wall was singled out in DOE 2.2 to produce hourly reports of its outside surface temperature and solar radiation incident upon it. The solar and weather data from the year of testing at ORNL were put into a weather file for DOE 2.2. The program was run with walls having the solar reflectance of the IR wall and, separately, ground reflectance of 0.08 and 0.24. The same runs were done with walls having the solar reflectance of the Non wall. The outside surface temperatures predicted by DOE 2.2 and those measured for the year of testing were used by the program STAR to predict the heat fluxes through the interface between two layers of gypsum at the inside of the walls where the heat flux transducers were located in both test sections.

Detailed comparisons of predictions and measurements were made on selected clear days during the year of testing. They showed, in general, that predictions met expectations from the measurements regarding nighttime behavior, effect of ground reflectance, and some daytime behavior. The shape of daytime temperature and heat flux predictions and the delay between them generally matched the measurements. Too many anomalies occurred in the measurements from day to day, however, to judge from several typical days the overall goodness of agreement between measurements and predictions.

Annual averages of hourly outside surface temperatures and internal heat fluxes were generated to quantify the overall agreement between measurements and predictions. The heat fluxes were separated into outward and inward heat fluxes to focus on the effects of the different values of solar reflectance for the walls. The measured outward heat fluxes, generally occurring in the absence of solar effects, were not different for the two walls. The predictions also showed no significant differences between the two walls in nighttime behavior. Significance was judged in light of the expected uncertainty of the heat fluxes, no less than ±5% or ±0.03 to ±0.05 Btu/(h·ft^2).

The measured outside surface temperatures and inward heat fluxes were significantly different for the IR and Non walls. Predictions for the IR wall and ground reflectance of 0.08 matched very well the measured outside surface temperature and inward gypsum heat flux. The predictions for the ground reflectance of 0.24 were reasonably higher than the predictions for the ground reflectance of 0.08 for both walls. To achieve the same consistency between predictions and measurements for the Non wall required either an increase in reflectance of the Non wall from the measured 0.238 to about 0.300 or an increase in the measured annual average outside surface temperature from 68°F to 69°F. The change that would need to occur in measured gypsum heat flux was an increase from 0.753 Btu/(h·ft^2) to 0.835 Btu/(h·ft^2). The change in reflectance is not reasonable. Such simultaneous large changes in both the average measured outside surface temperature and internal heat flux are also unlikely.

Even if the higher annual averages of measurements for the Non wall are accepted and justified by the more uncertain PROPOR results for this wall, an important fact remains. The annual average difference between outside surface temperatures for the two walls is 8% larger for the predictions than for the measurements. The annual average difference between inward heat fluxes for the two walls is 54% larger for the predictions compared to the measurements. Using the DOE 2.2 model to quantify the difference in thermal performance of walls coated with and without IrBPs 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 is not necessarily the case for this project.

APPLICATION OF MODEL IN COOLING AND MIXED CLIMATES

Whole House Model

DOE 2.2 estimates hourly energy use for a whole building given hourly weather information and a description of the building, its occupants, its equipment and how the building is operated. Estimates of use up to a year at a time are possible with appropriate weather information and schedules for occupancy and equipment operation. DOE 2.2 can be used to determine the choice of building parameters that improve energy efficiency and cost effectiveness. The purpose of the program is to aid in the analysis of energy use in buildings (LBNL 2004). It is especially useful to look at the effect of a single change, holding all other parameters constant.

To put into proper perspective the effect of using a wall coating with infrared blocking pigments instead of one without them, a carefully chosen base is important. 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 model was modified as described above to validate the procedures for handling 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. As configured by the Lenoir City, TN chapter, the single-story, 3-bedroom house has 1094 ft^2 of floor space. The floor is insulated with batt insulation having R-value of 19 $h{\cdot}ft^2{\cdot}{}^\circ F/Btu$. The crawlspace under the floor has concrete masonry unit or similar walls. All ductwork is in the crawlspace. The attic over the living space has blown-in insulation with R-value of 26 $h{\cdot}ft^2{\cdot}{}^\circ F/Btu$, including the effect of the joists and less insulation at the eaves. There are 1045 ft^2 of opaque wall area with double-pane windows in vinyl-clad frames. The total window area is 77 ft^2, 7½% of the wall area.

Two different configurations of walls were specified for the application of the model to different climates. The walls for one configuration were standard 2x4 wood-framed walls with studs 16 in. oc and R-11 batt insulation between the studs. Like the validation configuration, a coating of 1-in.-thick concrete stucco and a ¾-in.-thick unvented air layer were placed on the outside over the sheathing in order to present a typical case for use of coatings with and without IrBPs. The inside wall covering was ½-in.-thick gypsum and only a single layer of it, unlike the validation configuration with an extra gypsum layer to hold a heat flux transducer. The other configuration of walls was considered more typical of houses in severe cooling climates. Concrete masonry units, 8-in.-thick, were covered with 1-in. of concrete stucco on the outside. They were covered by R-5 foam and ½-in.-thick gypsum on the inside.

For the validation task, the shading of the south wall of the ORNL test building was imposed. It was minimal shading from a gutter that extended only 3¾-in. beyond the plane of the test wall. For application to different climates the effect was included of more typical eave overhangs that extended 2 ft out from the walls. For typical residential applications, dry grass is considered more typical of the ground cover near the walls than gravel. Hence, a ground reflectance of 0.24 was specified in all climates.

The occupants and their energy use are very important for determining the energy consumption of a house. The Building America Performance Analysis Resources (http://www.eere.energy.gov/buildings/ building_america/pa_resources.html) were used to obtain the energy use profile for the default number of three occupants for a 3-bedroom home.

These resources are especially convenient for use of DOE 2.2, with fragments prewritten in the Building Description Language (BDL) that DOE 2.2 requires. The detail is extensive, to the point of providing location specific inlet water temperatures for the domestic hot water heater. Also provided are daily schedules for occupancy, lighting, domestic hot water use, appliance loads and plug loads. Separate schedules were used for weekdays and for weekends and holidays.

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 a typical house to walls coated with and without IrBPs. The forced-air HVAC system chosen as typical for such climates used an air-to-air heat pump. Typical peak efficiencies were input corresponding to a seasonal energy efficiency ratio (SEER) of 12 for cooling and a seasonal heating performance factor (SHPF) of 7, both in units of Btu/(watt-h). Supplemental and emergency heating capacity was specified as 10 kW of electric resistance heat in all climates. DOE 2.2 defaults were used for heat pump heating capacity (56.2% of cooling capacity) and for all part load curves. After using the DOE 2.2 procedure for autosizing the cooling capacity, it was rounded up to the next commercial size. This yielded 3 T (36,000 Btu/h) for all locations except Miami for which it was 3½T (40,000 Btu/h).

Appendix A lists the BDL files for the wood-framed and the concrete masonry unit-walled houses in Knoxville, TN for the coatings without IrBPs. A note gives the only change necessary to model coatings with IrBPs, *i.e.*, the solar absorptance in the exterior wall construction needs to be changed from ABS = 0.762 to ABS = 0.505. In studying the files it is useful to note that comments are made by beginning a line with a $ sign or, within a line, putting the comment between $ signs. A command continues, from line to line if necessary, until it is ended with "..". Since these files were adapted for this project from previous research, there are many materials and constructions listed that are not used for the house as it was modeled for this project.

Whole House Results

Total energy needs

Figure 18 gives some insight to the nature of the climates at the seven locations that were chosen. Each location is included in the Typical Meteorological Year (TMY2) data set (NREL 1995). TMY2 data are convenient because they can be converted to DOE 2.2 weather files with a converter in the DOE2 weather utilities. The locations are arranged in Fig. 18 by decreasing cooling degree-days, which also arranges them more or less by increasing heating degree-days. Both characteristics depend on dry bulb temperature alone. Cooling and heating degree-days do not measure potential latent cooling and heating needs. Characterizing Richmond, VA, Knoxville, TN and Sacramento as locations with mixed climates (significant heating and cooling) is rather arbitrary. Fig. 18 displays the average daily horizontal solar that all the locations receive. It is relatively constant. All locations in the contiguous United States receive about the same amount of solar radiation. Variation in amount depends more on altitude and average cloudiness at a location than on latitude and longitude.

The top half of Table 7 presents the cooling, heating and total energy needs of the single-story house with wood-framed walls. The walls are coated with coatings that do not contain IrBPs. The bottom half of Table 7 shows the same needs for the house with

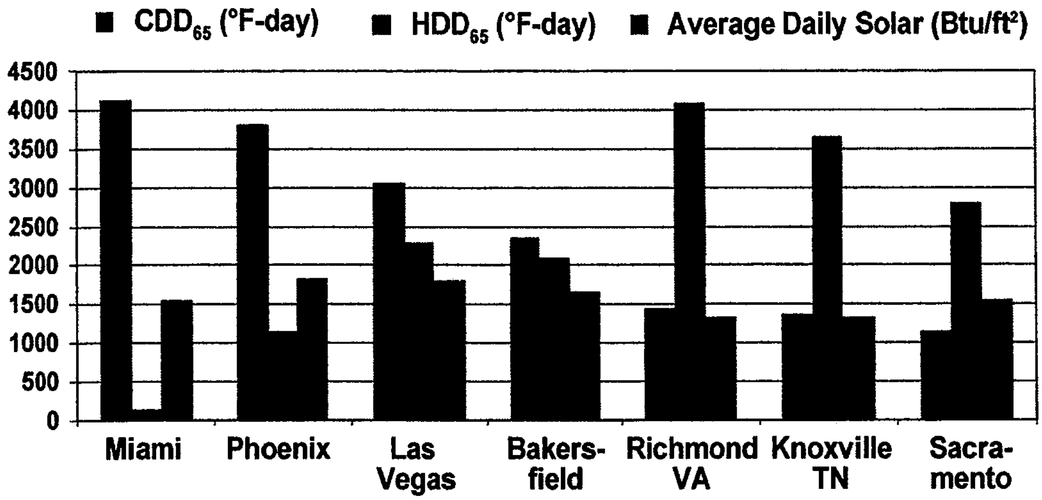

Fig. 18 Cooling Degree Days (Base 65°F), Heating Degree Days (Base 65°F) and Average Daily Solar (Btu/ft²) for Seven Climates of Interest

concrete masonry unit (CMU) walls. The data in Table 7 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 is only slightly higher for the CMU-walled house. The total use compared to the wood-framed house is 370 kWh more for Miami to 850 kWh more for Richmond, VA.

Table 7. Annual electricity needs (kWh) in various climates with typical occupant energy use for single-story residences without IrBPs in the wall coating

Annual electricity needs, kWh	**Cooling**	**Heating**	**Total**
Walls: Wood Studs + R-11 Batts			
Miami	5172	8	12958
Phoenix	4794	245	12996
Las Vegas	3483	851	12602
Bakersfield	2729	863	11961
Richmond, VA	1501	4300	14608
Knoxville, TN	1610	3804	14219
Sacramento	1387	1650	11679
Walls: Concrete Masonry Units + R-5 Foam			
Miami	5540	10	13328
Phoenix	5185	339	13481
Las Vegas	3739	1124	13131
Bakersfield	2915	1152	12436
Richmond, VA	1568	5085	15460
Knoxville, TN	1693	4549	15047
Sacramento	1388	2133	12163

As the houses are configured, heating and cooling needs are about a quarter to a half of the total use. For the wood-framed walls, the heating and cooling is 26% (Sacramento) to 40% (Richmond, VA) of total use in each climate. For the CMU walls, the percentages are 29% (Sacramento) to 43% (Richmond, VA). DOE 2.2 reports heating energy for heat pumps in two categories: heat pump heat and supplemental heat. They are added to comprise most of the heating. DOE 2.2 also reports ventilation fan energy as a separate category without regard to heating or cooling. In both houses as modeled the fans cycled with load. Fan energy was assigned according to the percentages of total heating and cooling energy that each mode represented. Fixed annual energy uses for both houses include 1330 kWh for lights and 4250 kWh for appliance and plug loads. Energy for domestic hot water varies with location because of the climate-dependent inlet water temperature, shown for Knoxville, TN in Appendix A. The variation is from 2200 kWh in Miami to 3230 kWh in Richmond, VA.

Cooling energy savings

Figures 19 and 20 present savings in cooling energy from use of coatings with IrBPs. This is the benefit of IrBPs that this project sought to quantify. The annual maximum in the solar altitude during the cooling season and the shading from the overhang on the south walls impact the cooling savings for walls. Less solar energy is available for the wall coatings to block. For the wood-framed walls, the walls with IrBPs save 4% to 9% (4% to 6% in the cooling climates) compared to the walls without them. Percentages are higher in the mixed climates relative to the cooling climates because the cooling energy use decreases faster than savings relative to the Non wall. Amounts of savings range from 240 kWh in Phoenix to 110 kWh in Richmond, VA. 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. Larger percentages for these low R-value walls are consistent with the general observation that solar radiation control is more effective on low R-value

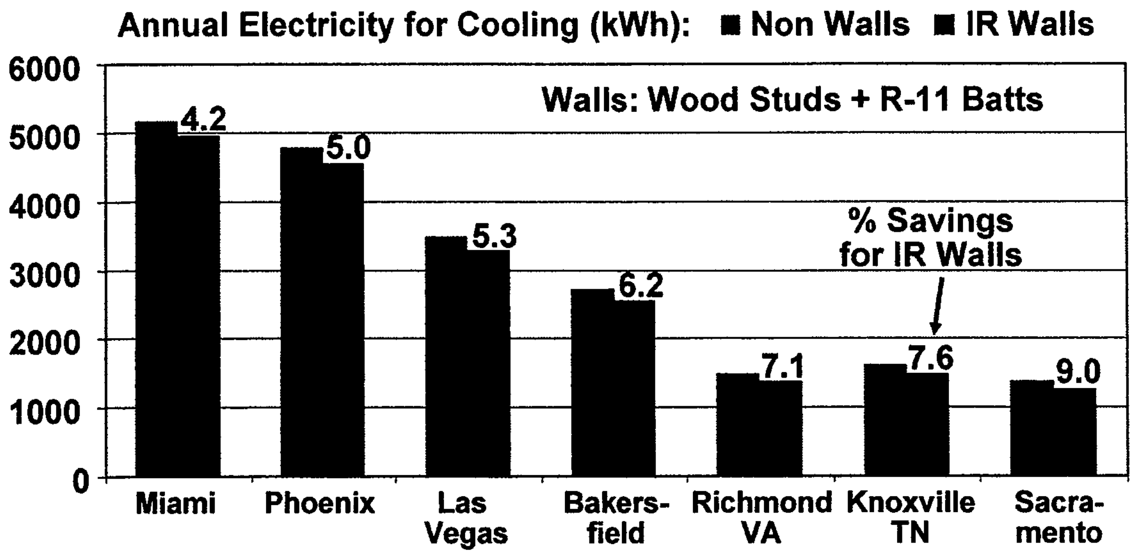

Fig. 19 Annual Electricity Use for Cooling in the Single-Story House with and without IrBPs in the Coating on its Wood-Framed Walls

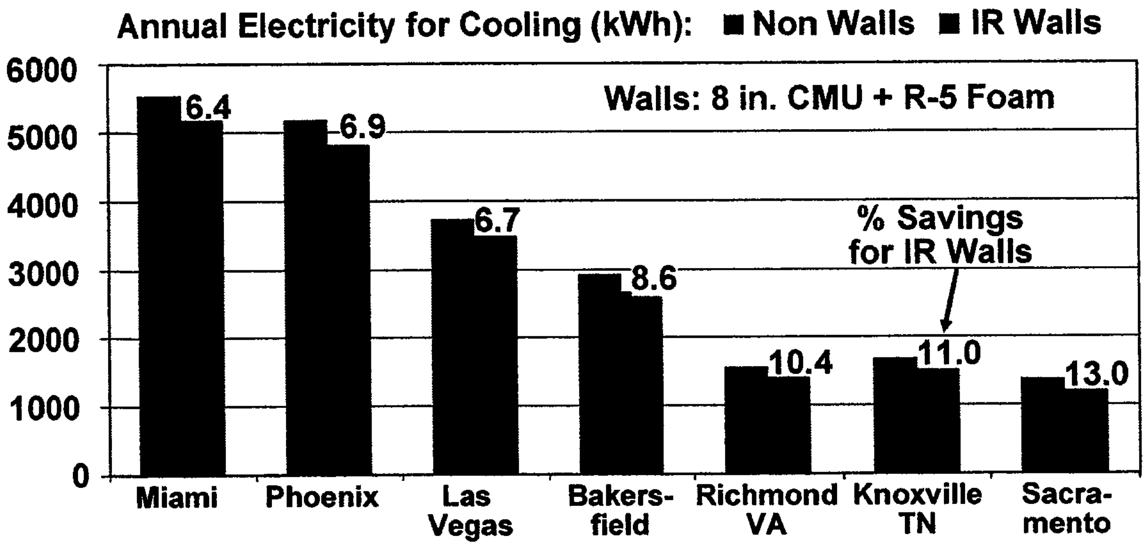

Fig. 20 Annual Electricity Use for Cooling in the Single-Story House with and without IrBPs in the Coating on its CMU Walls

assemblies. The absolute amounts of savings also bear out this observation, ranging from 360 kWh in Phoenix to 160 kWh in Richmond, VA. The model validation concluded that the savings cannot be viewed as conservative.

Heating energy penalty

Figures 21 and 22 quantify the penalty in heating energy from use of coatings with IrBPs. The natural decrease of the solar altitude from the peak value during the cooling season makes for significant heating penalties for walls. More solar energy impinges despite the overhang and is blocked by the IrBPs when it is needed. For the

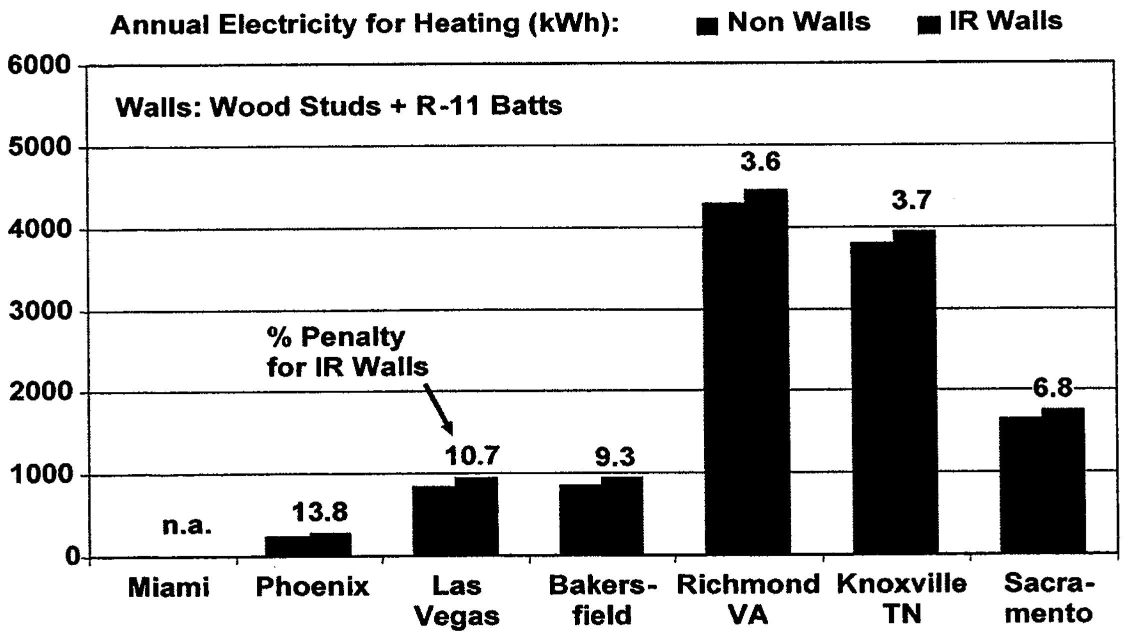

Fig. 21 Annual Electricity Use for Heating in the Single-Story House with and without IrBPs in the Coating on its Wood-Framed Walls

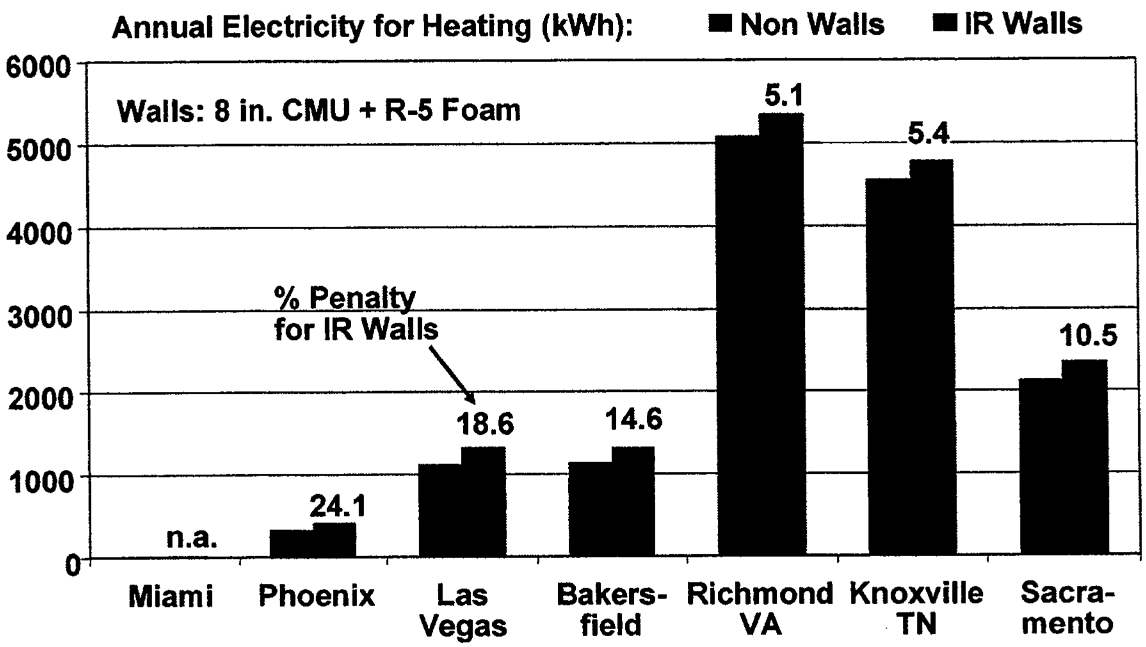

Fig. 22 Annual Electricity Use for Heating in the Single-Story House with and without IrBPs in the Coating on its CMU Walls

wood-framed walls, the walls with IrBPs require 4% to 14% (4% to 7% in the mixed climates) more heating energy than walls without them. Percentages are higher in the cooling climates relative to the mixed climates because the heating energy decreases faster than the increase in heating energy relative to the Non wall. Amounts of increases range from 160 kWh in Richmond, VA to 30 kWh in Phoenix. Miami has so little heating need that heating parameters are considered not applicable. For the CMU walls, the walls with IrBPs require 5% to 24% (5% to 11% in the mixed climates) more heating energy compared to the walls without them. Amounts of increases range from 260 kWh in Richmond, VA to 80 kWh in Phoenix. Larger percentages and larger absolute increases compared to the wood-framed walls follow from the smaller R-value of the CMU walls.

Net energy savings

Figures 23 and 24 present the total annual electricity use for the houses whose walls are coated with and without IrBPs. These figures show, in terms of total energy use, the net effect of the cooling savings and the heating penalty. For this particular situation Figs. 23 and 24 imply a breakeven situation for use of solar radiation control that occurs when the cost of less cooling energy is exactly offset by the cost of more heating energy. As the houses are configured, they use electricity for all energy needs. Unit cost of the electricity is assumed to be constant year round. A highly efficient heat pump is used to convert the electricity to cooling and heating. With these constraints, the total electricity use increases slightly with the application of IrBPs in the two climates with the most heating needs. Total electricity use follows cooling energy use and decreases in the cooling climates with the application of IrBPs.

Relative to annual use of 12000 to 14000 kWh, the increases and decreases are small. For the wood-framed walls, 20 kWh more annual use occurs due to IrBPs in Knoxville, TN and 50 kWh more occurs in Richmond, VA. This contrasts to 200 kWh

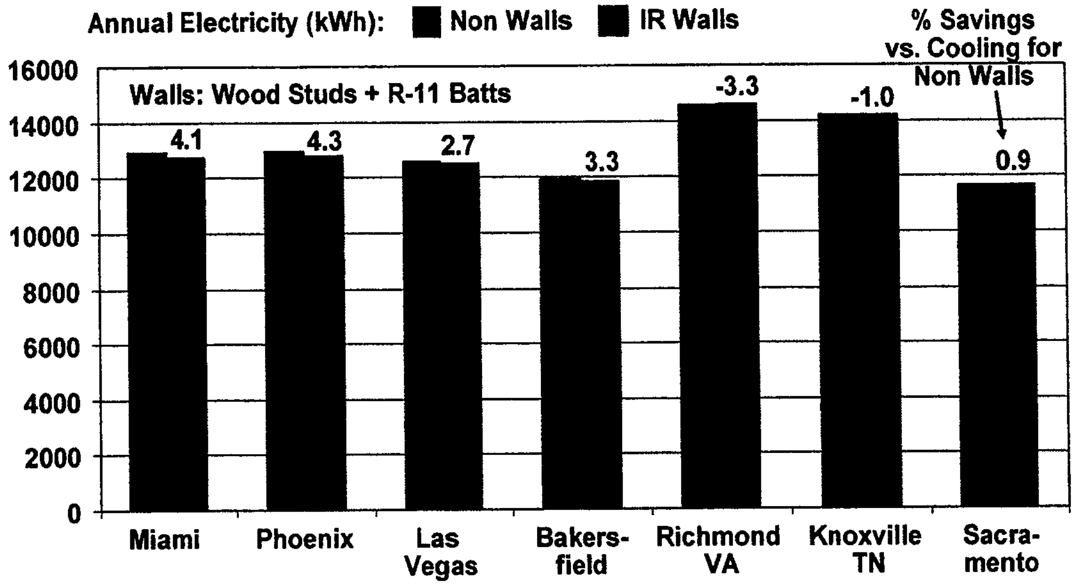

Fig. 23 Total Annual Electricity Use in the Single-Story House with and without IrBPs in the Coating on its Wood-Framed Walls

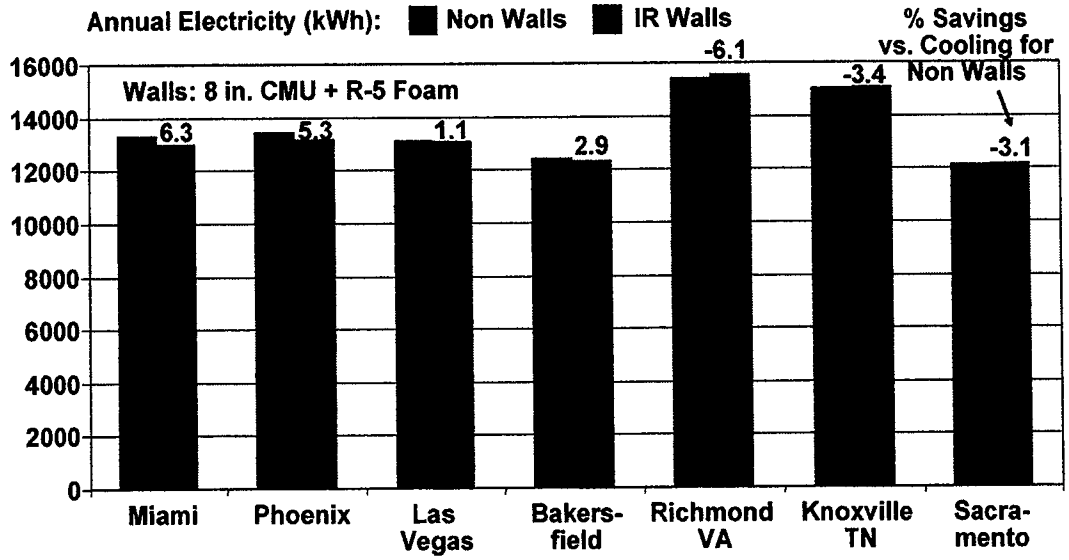

Fig. 24 Total Annual Electricity Use in the Single-Story House with and without IrBPs in the Coating on its CMU Walls

less annual use in Phoenix and 220 less in Miami. For the CMU walls, the numbers are larger. Increases of 60 kWh in Knoxville, TN and 100 kWh in Richmond, VA are contrasted to decreases of 270 kWh in Phoenix and 350 kWh in Miami. The numbers above the total energy for the IR walls in each location put these decreases and increases in perspective. They represent the percentage of the net annual savings relative to the cooling energy in each location for the house with Non walls. Relative to the percentages on the same basis for cooling energy savings alone in Figs. 21 and 22, the percentages for net savings decrease significantly. They vary from -3% to 4% (3% to 4% in the cooling climates) for the houses with wood-framed walls and from -6% to 6% (1% to 6% in the cooling climates) for the houses with CMU walls.

Breakeven Criterion for IrBPs on Walls

Cooling savings and heating penalty in Knoxville and Richmond

Total electricity use in Figs. 23 and 24 increases slightly due to use of cool colors on walls in the mixed climates of Richmond, VA and Knoxville, TN. This is somewhat surprising based on our experience with low-slope roofs, for which these mixed climates remain favorable for solar radiation control. The details of this observation are presented in Table 8 from the output of DOE 2.2 that led to Figs. 19 to 24. Details are added from additional trials with DOE 2.2 in which, for the house with wood-framed walls coated without IrBPs, the roof was coated with and without IrBPs. In addition, trials were done with the low-slope calculator (http://www.ornl.gov/sci/roofs+walls/facts/CoolCalcEnergy.htm) and steep-slope calculator (http://www.ornl.gov/sci/roofs+walls/SteepSlopeCalc/index.htm) for the roof alone. To magnify trends, all numbers in Table 8 are rounded off to the nearest integer, which is the precision in the output building utility performance report from which the DOE 2.2 numbers were obtained. In discussion of Figs. 19 to 24, round off to ±10 kWh was made. Practically, with electricity costing about $0.10 per kWh to residential customers, annual differences of ±100 kWh are not significant.

Table 8. Trials with DOE 2.2 and the Low- and Steep-Slope Calculators to explore the cooling savings and heating penalty with IrBPs in Knoxville, TN and Richmond, VA

	Knoxville, TN			**Richmond, VA**		
Annual effect of coatings with IrBPs, kWh	**Cooling Savings**	**Heating Penalty**	***Net Benefit**	**Cooling Savings**	**Heating Penalty**	***Net Benefit**
Wood-framed walls, DOE 2.2	123	139	-16	107	157	-50
CMU Walls, DOE 2.2	187	245	-58	164	260	-96
R-25.9 Roof, DOE 2.2	118	89	+29	100	99	+1
R-11.0 Roof, DOE 2.2	234	172	+62	200	188	+12
R-25.9 Roof only, Low-slope	83	62	+21	81	68	+13
R-11.0 Roof only, Low-slope	187	137	+50	182	150	+32
R-25.9 Roof only, Steep-slope	38	53	-15	37	56	-19
R-11.0 Roof only, Steep-slope	85	108	-23	82	114	-32

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

The details for the wood-framed and CMU walls in Table 8 bear out the slight increase in total electricity use for use of IrBPs seen in Figs. 23 and 24 for these climates. The heating penalty that is inherent to solar radiation control exceeds the cooling savings that are the primary reason why solar radiation control is implemented. The slightly larger number of heating degree days in Richmond, VA compared to Knoxville, TN, as seen in Fig. 18, makes the penalty slightly larger in Richmond, VA.

The cases in the last six rows of the table explore the effect of coating the roof with and without IrBPs. The first of these cases shows that, according to DOE 2.2, roofs of this house are less sensitive to the effect of the heating penalty than its walls. The roof has the same R-26 insulation and other features that were used for all the figures. For exploration of the effect of coating the roof, it is assumed that the same solar reflectance of the wall coatings with and without IrBPs can be obtained on a steep-slope roof surface, for example, by use of coated metal. In the house with wood-framed walls coated without IrBPs, roof absorptance was changed to 0.762 (solar reflectance of 0.238) then 0.505 (solar reflectance of 0.495) instead of the absorptance of 0.85 used for all the figures.

With the typically insulated R-26 ceiling, neither location yields a net penalty for coating the roof with IrBPs, although Richmond, VA is near the breakeven point. To verify that solar radiation control is more effective for lower R-value components, regardless of whether they are roofs or walls, the results of another case with DOE 2.2 are shown in the second roof case. A roof identical in all respects to the R-26 version is stripped of enough insulation to yield R-11 for the ceiling insulation, which is the same amount of insulation in the wood-framed wall. Compared to the R-26 case, DOE 2.2 yields more net savings in both locations but the increase is more in Knoxville, TN than in Richmond, VA, consistent with fewer HDD_{65} in Knoxville.

Differences between cool walls and cool roofs

The attic and roof are modeled in DOE 2.2 with a horizontal ceiling that has mass insulation on top of it. The roof is two tilted surfaces having little R-value. The ridge at the junction of the tilted surfaces runs east-west. The attic is an unventilated air space with no detail other than description in the DOE2 library as a sloped air space greater than 4-in. thick. In structure and behavior the attic and roof are like a horizontal exterior wall. Regardless, the rest of the model is the same as it was for the wall cases, including the effects of occupants and their activities. A complete load calculation for the building was done every hour to determine whether or not the building needed heating or cooling. The shift from a net penalty with walls to net savings with roofs is significant.

The steep-slope and low-slope calculators on our website deal only with the roof. There is no information included in the calculators about how the building is operated. It is assumed that the building needs heating from the HVAC system when the outside air dry bulb temperature drops below 60°F and it needs cooling from the HVAC system when the outside air dry bulb temperature rises above 75°F. Any heat flow outward through the ceiling when the temperature is below 60°F is counted as part of the heating load due to the roof. Any heat flow inward through the ceiling when the temperature is above 75°F is counted as part of the cooling load due to the roof. Annual heating and cooling need due to the roof are the sums of the contributions meeting the respective criteria.

The low-slope and steep-slope calculators were run with the roof parameters in the DOE 2.2 roof simulations. Solar reflectance of the exterior roof surface was set to 23.8% then 49.5% for each R-value. The calculators do estimates relative to a roof surface with a solar reflectance of 5%. To see the effect of changing from 23.8% to 49.5%, two runs were done in each calculator at each location. Annual cooling and heating loads in Btu/ft^2 were entered in a spreadsheet. Values were multiplied by the 1094 ft^2 of ceiling area for this house and divided by the appropriate coefficient of performance (COP). Differences were taken and units converted to yield kWh of electricity annually. Fixed seasonal efficiencies for the HVAC system components were used in the calculators. Seasonal COP for cooling of 3.5 (SEER of 12) was used in DOE

2.2 and the calculators. The air-to-air heat pump in DOE 2.2 has a seasonal COP for heating of 2.05 (SHPF of 7) but also uses supplemental electric resistance heat (COP of 1.0). To compensate for supplemental heat use in the calculators a seasonal COP for heating of 1.55 was used.

In Table 8 the cooling savings, heating penalty and net savings from the low-slope calculator for both R-values and both locations are very similar to the corresponding estimates for the roof with DOE 2.2. Neither climate causes severe enough heating penalties to rule out economic use of radiation control coatings on roofs. For this building, all of the detailed load calculations in DOE 2.2, including effects of occupants and their activities, do not strongly affect the annual energy differences due to the presence or absence of IrBPs in the roof coating. For this building, the focus on the roof only, with loads determined by the simple scheme explained above, does just as well.

According to the steep-slope calculator for both roofs and both locations, there is a net annual energy penalty. The cooling savings are noticeably less for both roofs and both locations relative to the corresponding DOE 2.2 and low-slope calculator estimates for the roofs. The heating penalties are only slightly less than the corresponding DOE 2.2 and low-slope calculator estimates for the roofs. The results for the steep-slope calculator are most similar to those from the house with wood-framed walls in DOE 2.2. For both the cooling savings are not large enough to offset the heating penalty.

Different reasons lead to relatively small cooling savings for walls with DOE 2.2 and for roofs with the steep-slope calculator. Unlike roofs, south-facing walls do not experience annual peak solar load at the peak of the cooling season when the Sun is at its highest altitude, especially with typical overhangs. For west-facing and east-facing walls, peak solar load always occurs early or late in the day when the Sun is at relatively low altitude. For north-facing walls, there is little solar load. For this house, total wall area is 1045 ft^2 compared to ceiling area of 1094 ft^2. The north-facing and south-facing walls each have area of about 330 ft^2. The east-facing and west-facing walls each have area of about 190 ft^2. Therefore, the total benefit of solar radiation control on the walls of this house is diminished, especially during the cooling season, relative to its roof.

The steep-slope calculator represents generalization of a database obtained from exercising the attic model of Wilkes (1991) discussed earlier. It includes an algorithm to ventilate the attic from eave to ridge with outside air as a result of wind and buoyancy forces. The higher the solar reflectance of the roof surface, the lower the roof surface temperature. Lower roof surface temperature generates less buoyancy force. There is sufficient buoyancy force to significantly affect ventilation only during summer. Coating the roof surface with and without IrBPs leads to a difference in ventilation that diminishes the cooling savings over what would happen with no ventilation. The estimates for roofs with DOE 2.2 and the low-slope calculator do not include effects of ventilation.

Breakeven energy savings for walls vs. heating degree-days

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 have not been addressed. To quantify better than Table 8 where the breakeven energy savings occur, Fig. 25 was prepared from DOE 2.2 results for all climates in Fig. 18 except Miami and Phoenix. Two additional mixed climates, Atlanta and Memphis, were included on Fig. 25 because they each have about

3100 HDD_{65} and show net annual energy savings near zero. In addition to the data, a best-fit straight line is shown for each wall configuration. Sacramento yields the most deviation from the line for each wall. Breakeven is 3300 to 3400 HDD_{65} for the wood-framed wall and 2800 to 2900 HDD_{65} for the CMU wall. If the choice of coating walls with or without IrBPs is to be based solely on potential energy savings for this house, then a wood-framed wall should not be coated with IrBPs unless HDD_{65} are less than about 3300. For the CMU wall, coating with IrBPs should not be done unless HDD_{65} are less than about 2800.

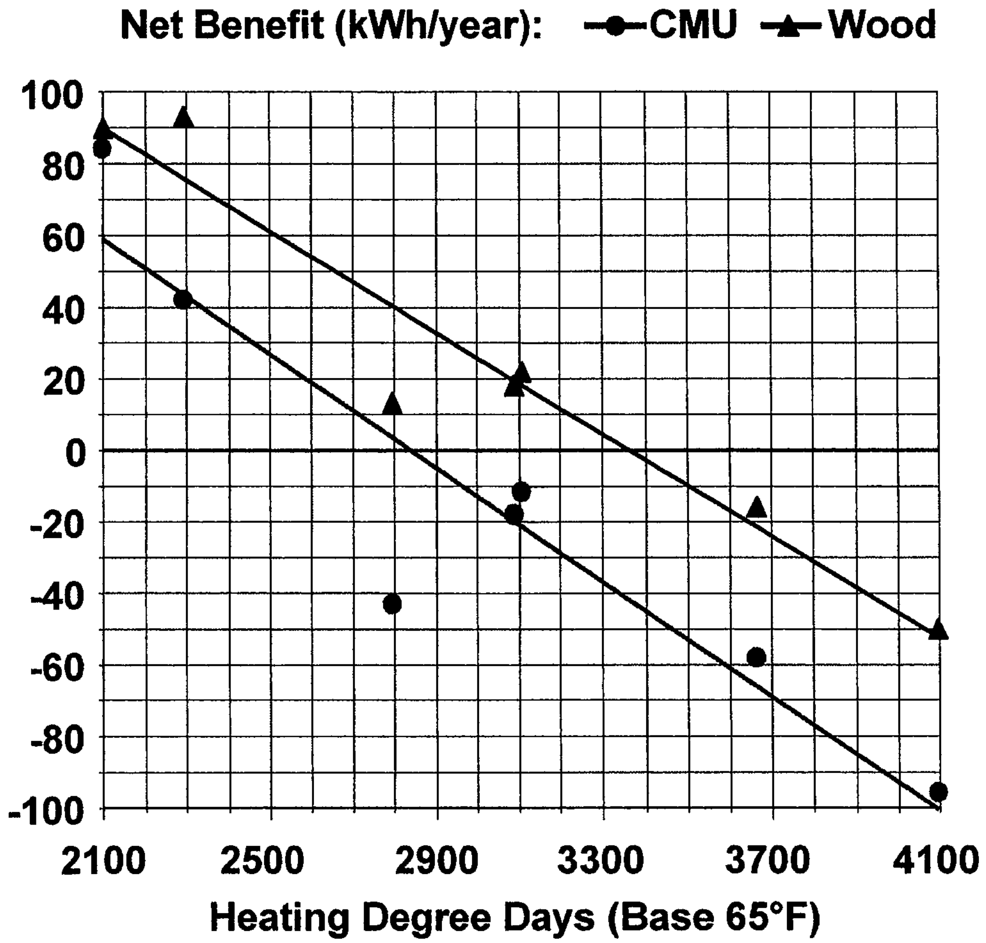

Fig. 25 Breakeven Annual Energy Savings with IrBPs in the Coatings on the Wood-Framed and CMU Walls

DOE 2.2 can be expected to do better than the low-slope and steep-slope roof calculators in judging what is cooling load and what is heating load for the specific building being modeled. This would be very important for buildings with high internal loads, possibly to the extent of never having a heating load. For such cases Fig. 25 would not apply. Unfortunately, DOE 2.2 is not suitable for use as a web-based tool because of the detailed input that it requires. Since the detailed input was available as listed in Appendix A, extra runs of DOE 2.2 were easily done here.

The DOE 2.2 results herein are for one simple house with an all-electric heating and cooling system most suitable for cooling climates. According to Fig. 25, the heating penalty for walls offsets the cooling savings for most mixed climates so cooling climates are of most interest. Making the results more general, for example, in the form of a companion to the cool roof calculators, would require effort far beyond the scope of this project to generate and access a database that includes the range of parameters of interest for walls. Parameters not addressed in this project include many other wall constructions, varying wall height and overhangs (including single-story vs. multistory), wall colors, house aspect ratios and orientations, *etc.* The DOE 2.2 model for the simple house used in this project is not conservative yet it indicates at most 6% net benefit in cooling climates for use of wall coatings with IrBPs compared to cooling energy without IrBPs. The effort to produce and access a comprehensive database would not likely be worth it.

CONCLUSIONS

A project, begun in May 2004, sought to gather field data and validate a model for the thermal performance of walls with and without infrared blocking pigments in their coatings. The field test sites included residences in Phoenix, AZ and near Jacksonville, FL. The Phoenix site had three test sections coated with a coating containing infrared blocking pigments (IrBPs) (called IR test sections) and one coated with a coating without IrBPs (called a Non test section), but they varied in construction features and orientation. They produced data over the peak Phoenix cooling season that qualitatively showed the effect of heat flux transducer sensitivity, wall orientation and wall construction features, including shadowing effects. The Jacksonville site had side-by-side IR and Non test sections on a south-facing wood-sided wall. The data obtained there were not consistent with the construction features of the light weight walls but showed how a coating with IrBPs behaved when it was not applied over a white primer. Priming with a white coating then color coating is the application sequence recommended by the manufacturer of the coatings. It was proved to be necessary for maximum energy savings with IrBPs.

IR and Non test sections in a south-facing wall at the Oak Ridge National Laboratory provided data for validation of the desired model. The public domain whole building energy use program DOE 2.2 was selected for the modeling task because it is able to accurately account for solar radiation incident on walls from the Sun, sky and ground and is sensitive to the solar reflectance of the walls and the ground in front of the walls. The solar reflectance of the wall coatings was measured *in-situ* at four times during the year of testing within ±0.008 uncertainty. The solar reflectance of the IR and Non 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 a solar reflectance between 0.08 and 0.24 during the project.

DOE 2.2 predictions of outside surface temperature for ground reflectance of 0.08 and 0.24 were compared to the measurements. The predicted annual average outside surface temperature of the IR wall for ground reflectance of 0.08 agreed with that for the measurements within 0.5°F. Annual averages of temperatures are judged uncertain to ±0.05°F. Looking for consistency among the predictions for 0.08 and 0.24 and the measurements led to speculation that the average for the Non wall was about 1.0°F low.

Heat fluxes were separated into outward and inward directed values to focus on solar effects. There were no significant differences among the annual averages for the outward directed heat fluxes because of lack of solar effects for them. The annual average inward heat flux from the outside surface temperatures generated by DOE 2.2 agreed within 0.002 Btu/(h·ft^2) with the measurements for the IR wall. Measured annual average heat fluxes are uncertain to about ±0.03 to ±0.05 Btu/(h·ft^2). The annual average of the measurements for the Non wall seemed more consistent with all the other heat flux averages if 0.082 Btu/(h·ft^2) was added to it. This addition was consistent with the speculated 1.0°F addition to the average measured outside surface temperature for the Non wall.

The goodness of agreement of predictions with measurements for the IR wall supports the conclusion that the DOE 2.2 model is valid. The speculations about the Non measurements reflect less confidence in the Non measurements than in the IR measurements. As a result less satisfactory agreement of predictions with measurements for the Non wall does not rule out that the model is valid.

Although the validation process did not prove the model conservative, the model was used to show the energy effects of coating walls with and without IrBPs for different wall constructions in various climates. The single-story residence whose south wall was used for validation was configured to have typical stucco-coated walls. The total energy use of the houses without IrBPs was consistent with location and wall construction. The most encouraging results for the use of IrBPs on walls were the cooling energy savings compared to cooling energy without IrBPs. When using IrBPs on stucco over wood-framed walls, they varied from 4% to 9% (4% to 6% in the cooling climates). When using IrBPs on stucco over concrete masonry units, cooling savings varied from 6% to 13% (6% to 9% in cooling climates).

A heating penalty is intrinsic to use of passive solar radiation control, here in the form of IrBPs on walls. The percentages compared to heating energy without IrBPs for houses with wood-framed walls varied from 4% to 14% (4% to 7% in the mixed climates). The percentages for CMU-walled houses varied from 5% to 24% (5% to 10% in the mixed climates). Net savings, defined as cooling savings less heating penalty, compared to cooling energy without IrBPs varied from -3% to 4% (3% to 4% in the cooling climates) for the houses with wood-framed walls and from -6% to 6% (1% to 6% in the cooling climates) for the houses with CMU walls.

The most significant conclusion from this project is that the heating penalty for walls offsets the cooling savings in climates with relatively few heating degree days. Net annual energy savings were determined as a function of HDD_{65} for the houses with wood-framed and CMU walls. The results indicate that zero net savings occur between 3300 and 3400 HDD_{65} for the wood-framed wall and between 2800 and 2900 HDD_{65} for the CMU wall. If the choice of coating walls with or without IrBPs is to be based solely on potential energy savings for this house, then the wood-framed wall should not be coated with IrBPs unless HDD_{65} are less than about 3300. For a CMU wall, HDD_{65} should be less than about 2800. Positive potential energy savings do not appear possible for locations with heating needs that are more severe than those of Atlanta.

RECOMMENDATION

The DOE 2.2 results for this project are for one simple house with an all-electric heating and cooling system most suitable for cooling climates. Making the results more general, for example, in the form of a companion to the cool roof calculators on our website, would require effort far beyond the scope of the project to generate and access a database that includes results over the wide range of parameters for walls. The DOE 2.2 model used herein is not conservative yet it indicates at most 6% net benefit in cooling climates for use of wall coatings with IrBPs compared to cooling energy without IrBPs. The effort to produce the database and a tool to access it would not likely be worth it.

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APPENDIX A. INPUT FILES FOR DOE 2.2 MODEL OF WOOD-FRAMED AND CMU-WALLED HOUSES IN KNOXVILLE, TN

Wood-framed house without IrBPs on walls (Change ABS = 0.762 to 0.505 for IrBPs):

```
INPUT .. $DOE2.2 input file$
TITLE  LINE-1  *Conv Habitat House+Stucco (fix size HP) *
       LINE-2  *229 Bethel Road, Lenoir City, Tennessee *
       LINE-3  *Vented Crawlspace with Band Joist Top   *
       LINE-4  *Occupied(3 people + Bldg Amer load)     *
       LINE-5  *Detailed Hourly Reports for Profile     * ..
$ House is 27'4" x 45'4" outside with 8' x 10'8" notched out for corner porch.
$ House is 26'6" x 44'6" less porch inside.
$ Yield 1094 net sq ft living area. Exterior walls R-11, 2x4 16 in. oc + stucco
$ Total glazing area 67.5 sq ft + 4.5 sq ft in kitchen door - 6.6% of living area.
$ Crawl space floor model uses updated analytical procedure described in
$ Winkelmann, F.C. 1998. "Underground Surfaces, How to Get a Better
$ Underground Heat Transfer Calculation in DOE-2.1E," pp 6-13,
$ Building Simulation User News, 19(1). Modified Ueff to match Tcrawl
DIAGNOSTIC  WARNINGS ..
ABORT ERRORS ..
PARAMETER
    AREALESSPORCH=1093.9  IWALLAREA=687
    DUCTLOSS=0.15 DUCTUA=120. ACEFF=0.274
    $INFILT=.00032  - 5/31/01 BLOWER DOOR TEST: 49.6 in² @ 4 Pa $
    $INFILT=.00042  - 3/1/01 BLOWER DOOR TEST: 65.9 in² @ 4 Pa $
    INFILT=.00042   $ 3/1/01 BLOWER DOOR TEST: 65.9 in² @ 4 Pa  $
    WINDOWGT=WINDOW-2grey $ GLASS TYPE $
    CFMPER=0.10 .. $Trial-and-error for crawlspace temperature$
RUN-PERIOD      JAN 1 2000  THRU  DEC 31 2000  ..
SITE-PARAMETERS   LAT=35.82  LON=83.98  T-Z=5  ALT=981 $ Knoxville, TN $
     WS-HEIGHT=33 SHIELDING-COEF=0.24  $ Some obstruction $
     TERRAIN-PAR1=.85 TERRAIN-PAR2=.20
     WS-TERRAIN-PAR1=1  WS-TERRAIN-PAR2=0.15 ..
BUILD-PARAMETERS   AZIMUTH=0 .. $Back faces North; Living room faces South$
$ LOADS SCHEDULES ADDED 10/19/04
$ FOR COMPARISON TO MEASUREMENTS NO LOADS SCHEDULES ARE NEEDED $
$ Internal loads are available from Building America Performance Analysis
$ Resources at http://www.eere.energy.gov/buildings/building_america/
$ pa_resources.html. Spreadsheets give profiles to use: hot water use
$ profile from ASHRAE; lighting equipment and use profile documented
$ for DOE by Navigant; appliance and other plug loads by NREL from
$ Navigant analysis; occupancy schedule assumes number of occupants equals
$ number of bedrooms and profiles developed by NREL from ASHRAE schedule
$ and engineering judgment.
$ For occupancy use single zone Occ L1-WD workbook data in ccupancy_schedules_multilevel_04_03.xls
$ Occupancy Schedule, average for all WEEKDAYS of the year, all spaces
Occ-WD-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,0.8300,
     0.2899,0.1247,0.1247,0.1247,0.1247,0.1247,0.1247,0.1247,
     0.1247,0.5000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000) ..
$ Occupancy Schedule, average for all WEEKENDS and HOLIDAYS of the year, all spaces
Occ-WE-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,
     0.6700,0.5000,0.5000,0.5000,0.5000,0.5000,0.5000,0.5000,
     0.6700,0.6700,0.6700,0.6700,0.6700,1.0000,1.0000,1.0000) ..
```

```
Occupancy-SCH =SCHEDULE TYPE = FRACTION
      THRU DEC 31 (WD)  Occ-WD-DS   (WEH)  Occ-WE-DS  ..
$ For lighting use corresponding Ltg L1-WD workbook in lighting_042004.xls
$ Lighting Schedule, average for all WEEKDAYS of the year, all spaces
Ltg-WD-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0085,0.0085,0.0085,0.0085,0.0237,0.0499,0.0561,0.0498,
      0.0203,0.0135,0.0135,0.0135,0.0135,0.0135,0.0135,0.0257,
      0.0561,0.0807,0.1053,0.1244,0.1270,0.0847,0.0440,0.0203)  ..
$ Lighting Schedule, average for all WEEKENDS and HOLIDAYS of the year, all spaces
Ltg-WE-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0085,0.0085,0.0085,0.0085,0.0237,0.0502,0.0553,0.0501,
      0.0254,0.0186,0.0186,0.0186,0.0186,0.0186,0.0186,0.0271,
      0.0549,0.0729,0.1051,0.1269,0.1270,0.0948,0.0590,0.0203)  ..
Lighting-SCH =SCHEDULE TYPE = FRACTION
      THRU DEC 31 (WD)  Ltg-WD-DS   (WEH)  Ltg-WE-DS  ..
$ Appliance & Plug Load Schedule, average for all days of the year, all spaces
$ Daily sum = 1.0,  Peak schedule value = 0.0588
ApplPlug-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0335,0.0288,0.0288,0.0270,0.0270,0.0335,0.0447,0.0523,
      0.0523,0.0482,0.0417,0.0417,0.0376,0.0341,0.0341,0.0341,
      0.0429,0.0347,0.0588,0.0588,0.0564,0.0564,0.0506,0.0417)  ..
ApplPlug-SCH =SCHEDULE TYPE = FRACTION THRU DEC 31 (ALL)  ApplPlug-DS  ..
$ Schedule for Hourly Reports all hours to get detailed wall loads
HR-SCH-L=SCHEDULE  TYPE=ON/OFF THRU DEC 31 (ALL) (1,24) (1) ..
$ GLASS TYPES $
WINDOW-2alt   GLASS-TYPE TYPE=GLASS-TYPE-CODE
        GLASS-TYPE-CODE=2000 ..  $ Same as Window-2 in old code $
WINDOW-2grey  GLASS-TYPE TYPE=GLASS-TYPE-CODE $U=.49 SHGC=.61 Tvis=.55$
        GLASS-TYPE-CODE=2213 .. $Close to TVA's U=.50 SHGC=.54 Tvis=.55$
WINDOW-2LOWe  GLASS-TYPE TYPE=GLASS-TYPE-CODE GLASS-TYPE-CODE=2612 ..
 $ MATERIALS $
R11BATINS=MAT TYPE=PROPERTIES TH=.2917  COND=.02652
   DENS=.6  S-H=.19  .. $ R-11 batts for wall$
R13BATINS=MAT TYPE=PROPERTIES TH=.2917  COND=.02244
   DENS=.8  S-H=.19  .. $ R-13 batts for wall$
R15BATINS=MAT TYPE=PROPERTIES TH=.3666  COND=.02412
   DENS=.6  S-H=.19  .. $ 'R-15.2' batts for flr$
R17BATINS=MAT TYPE=PROPERTIES TH=.4125  COND=.02412
   DENS=.6  S-H=.19  .. $ 'R-17.1' batts for flr$
R19BATINS=MAT TYPE=PROPERTIES TH=.4583  COND=.02412
   DENS=.6  S-H=.19  .. $ R-19 batts for flr $
REQUIV=MAT    TYPE=PROPERTIES TH=.9917  COND=.03832
   DENS=.6  S-H=.19  .. $ Ins.for Equiv.Roof$
R19INS=MAT    TYPE=PROPERTIES TH=.6878  COND=.0362
   DENS=.5  S-H=.19  .. $ 8.25" blown FG $
R19INSJ=MAT   TYPE=PROPERTIES TH=.2295  COND=.0362
   DENS=.5  S-H=.19  .. $ 2.75" FG above 2x6 $
R25INS=MAT    TYPE=PROPERTIES TH=.9208  COND=.0362
   DENS=.5  S-H=.19  .. $ 11.05" avg FG R-25.4$
R25INSJ=MAT   TYPE=PROPERTIES TH=.6292  COND=.0362
   DENS=.5  S-H=.19  .. $ 7.55" FGovr2x4 R1-17.4$
R28INS=MAT    TYPE=PROPERTIES TH=1.000  COND=.0362
   DENS=.5  S-H=.19  .. $ 12" blown FG R-27.62 $
R28INSJ=MAT   TYPE=PROPERTIES TH=.7083  COND=.0362
   DENS=.5  S-H=.19  .. $ 8.5" FG above 2x4 R19.57 $
R38INS=MAT    TYPE=PROPERTIES TH=1.3756 COND=.0362
```

```
   DENS=.5  S-H=.19  .. $ 16.5" Blown FG $
R38INSJ=MAT   TYPE=PROPERTIES TH=1.0839 COND=.0362
   DENS=.5  S-H=.19  .. $ 13" FG above 2x4 $
FRAM=MAT     TYPE=PROPERTIES TH=.2917  COND=.0833
   DENS=28  S-H=.39  .. $ 3.5 in.2x4 wall,clg$
RJST=MAT     TYPE=PROPERTIES TH=.7917  COND=.0833
   DENS=28  S-H=.39  .. $ 9.5 in.2x10 flr jst$
JSTS=MAT     TYPE=PROPERTIES TH=1.    COND=.0833
   DENS=28  S-H=.39  .. $ 12 IN.  $
BANDJST=MAT   TYPE=PROPERTIES TH=.125   COND=.0833
   DENS=28  S-H=.39  .. $ 1.5 IN. $
GYPBD=MAT    TYPE=PROPERTIES TH=.04167 COND=.0926
   DENS=50  S-H=.26  .. $ 0.5" wall,clg gyp $
STUCCO=MAT   TYPE=PROPERTIES TH=.0833 COND=0.8083
         DENS=120. S-H=.20 .. $ 1.0 in. concrete stucco $
AIRGAP=MAT   TYPE=RESISTANCE RES=1.0 ..
   $ 3/4 in. unvented air space under stucco$
CONFILL=MAT   TYPE=PROPERTIES TH=.25    COND=1.06
   DENS=140 S-H=.22   .. $ Heavyweight concrete$
SHEATH=MAT   TYPE=PROPERTIES TH=.04167 COND=.0783
   DENS=50  S-H=.31  .. $1/2 in. OSB under stucco$
SOIL=MAT     TYPE=PROPERTIES TH=.95    COND=.75
   DENS=115 S-H=.20  .. $ Rec 1 ft. too thick$
EARTH=MAT    TYPE=PROPERTIES TH=2.5    COND=.5
   DENS=120 S-H=.20  ..
FIC-DIRT-FLR=MAT  TYPE=RESISTANCE RES=1000.  ..
   $ No steady ht through crawlspc flr; OK 1 ft soil$
$  LAYERS $
CONVINS=LA   MAT=(STUCCO,AIRGAP,SHEATH,R11BATINS,GYPBD) ..
CONVSTUD=LA   MAT=(STUCCO,AIRGAP,SHEATH,FRAM,GYPBD) ..
INTWALLC=LA   MAT=(GYPBD,"Air Lay <4in Vert (AL21)",GYPBD) ..
   $Through center cavity interior walls$
INTWALLS=LA   MAT=(GYPBD,FRAM,GYPBD) .. $Through stud interior walls$
ROOFJST=LA   MAT=("Asph Siding (AR02)","Bldg Paper Felt (BP01)",
   "Plywd 1/2in (PW03)","Air Lay >4in Slope (AL32)",R25INSJ,FRAM,GYPBD) ..
ROOFINS=LA   MAT=("Asph Siding (AR02)","Bldg Paper Felt (BP01)",
   "Plywd 1/2in (PW03)","Air Lay >4in Slope (AL32)",R25INS,GYPBD) ..
ROOFEQUIV=LA  MAT=("Asph Siding (AR02)","Bldg Paper Felt (BP01)",
   "Plywd 1/2in (PW03)","Air Lay >4in Slope (AL32)",REQUIV,GYPBD) ..
FLRINS=LA     MAT=(R17BATINS,"Plywd 1/2in (PW03)","PartBd Underlay 5/8in (PB04)",
   "Carpet & Rubber Pad (CP02)") I-F-R=.92 ..
FLRJST=LA     MAT=(RJST,"Plywd 1/2in (PW03)","PartBd Underlay 5/8in (PB04)",
   "Carpet & Rubber Pad (CP02)") I-F-R=.92 ..
BANDJ=LA     MAT=(STUCCO,SHEATH,BANDJST) ..
CMUWALL=LA   MAT=("CMU HW 8in ConcFill (CB12)") .. $Concrete filled cement block$
UNDGWALLC=LA  MAT=(SOIL,"CMU HW 8in ConcFill (CB12)") ..
    $Conventional crawlspace wall below grade$
DIRTFLR=LA   MAT=(FIC-DIRT-FLR,SOIL) I-F-R=0.92  .. $Updated procedure$
$ CONSTRUCTION $
$ 12.7% of conv. external walls is 2 x 4 wood framing (to get Rwall=10.6 not 9.8)
$ 10% of framed internal walls is 2 x 4 wood framing
$ 11.2% of framed floors is 2 x 10 floor joists; with R-'15.2'batts, Rflr=16.45
$ Handle by using 'AREA TIMES Fraction' for center cavity+framing in parallel
$ Ceiling insulation depth adjusted for eaves, Rceil=28.35 with equivalent FG
CONV-INS     CONS   TYPE=LAYERS LAYERS=CONVINS ABS=.762  ..
      $Conv wall insul path$
```

```
CONV-STUD    CONS   TYPE=LAYERS LAYERS=CONVSTUD ABS=.762  ..
        $Conv wall framing path$
ROOF-JST     CONS   TYPE=LAYERS LAYERS=ROOFJST  ABS=.85  ..
        $Roof equiv through trusses$
ROOF-INS     CONS   TYPE=LAYERS LAYERS=ROOFINS  ABS=.85  ..
        $Roof equiv through insulation$
ROOF-EQUIV   CONS   TYPE=LAYERS LAYERS=ROOFEQUIV ABS=.85 ..
        $Overall equivalent roof$
IWALLCAV     CONS   TYPE=LAYERS LAYERS=INTWALLC  .. $Interior walls through cavity$
IWALLSTD     CONS   TYPE=LAYERS LAYERS=INTWALLS  .. $Interior walls through studs$
DOORFRONT    CONS   TYPE=U-VALUE U-VALUE=.37  .. $Solid foam core steel door$
DOORBACK     CONS   TYPE=U-VALUE U-VALUE=.48  .. $2 pane glass in foam core steel door$
FLRICONS     CONS   TYPE=LAYERS LAYERS=FLRINS  ..  $Floor over crawlspc through insulation$
FLRJCONS     CONS   TYPE=LAYERS LAYERS=FLRJST  ..  $Floor over crawlspace through joist$
CRWLSPWALLC  CONS   TYPE=LAYERS LAYERS=UNDGWALLC  ..
        $Conventional below grade wall$
CRWLSPEXWALLC CONS  TYPE=LAYERS LAYERS=CMUWALL  ..
        $Conv above grade crawlspc walls$
CRWLSPBAND   CONS   TYPE=LAYERS LAYERS=BANDJ  ..
        $Band jst atop conv crawlspace walls$
CRWLSPFLR    CONS   TYPE=LAYERS LAYERS=DIRTFLR  ..  $Dirt crawlspace floor$
$ Porch Shade $
B-S  X=34.67  Y=0     Z=8 AZ=180 W=10.67 H=8 TILT=0  ..
$ Gable and Eave Shading: Gables at 4 in 12 pitch (tan TILT=4/12) $
B-S  X=-2     Y=-2    Z=8 AZ=180 W=49.33 H=2   TILT=0  .. $Front overhang$
B-S  X=47.33  Y=29.33 Z=8 AZ=0   W=49.33 H=2   TILT=0  .. $Back overhang$
B-S  X=0      Y=-2    Z=8 AZ=90  W=16.51 H=2   TILT=18.43  .. $Down gable$
B-S  X=-2     Y=29.33 Z=8 AZ=270 W=16.51 H=2   TILT=18.43  .. $Down gable$
B-S  X=45.33  Y=29.33 Z=8 AZ=270 W=16.51 H=2   TILT=18.43  .. $Upside gable$
B-S  X=47.33  Y=-2    Z=8 AZ=90  W=16.51 H=2   TILT=18.43  .. $Upside gable$
$ Space Conditions $
ALLFLR=FLOOR  SHAPE=NO-SHAPE AREA=1304 ..
HOUSE=SPACE   SHAPE=NO-SHAPE
          AREA=AREALESSPORCH  VOLUME=AREALESSPORCH TIMES 8
          TEMPERATURE=(72) NUMBER-OF-PEOPLE=3 $BA Profiles$
          PEOPLE-SCHEDULE=Occupancy-SCH $N-O-P=#bedrooms$
          PEOPLE-HG-LAT=166.1 PEOPLE-HG-SENS=219.7
          LIGHTING-W/AREA=3.331 $BA formulas for lights;plug$
          LIGHTING-SCHEDULE=Lighting-SCH LIGHTING-TYPE=INCAND
          EQUIPMENT-W/AREA=10.64 EQUIP-SCHEDULE=ApplPlug-SCH
          EQUIP-SENSIBLE=.697 EQUIP-LATENT=.103 $No latent refrig.;washer$
          INF-METHOD=S-G  FRAC-LEAK-AREA=INFILT  FLOOR-WEIGHT=0
          FURNITURE-TYPE=LIGHT FURN-FRACTION=0.4 FURN-WEIGHT=8.0 ..
    IWALL-CAV=INTERIOR-WALL
          INT-WALL-TYPE=INTERNAL AREA=IWALLAREA TIMES 0.9
          CONSTRUCTION=IWALLCAV ..
    IWALL-STUD=INTERIOR-WALL
          INT-WALL-TYPE=INTERNAL AREA=IWALLAREA TIMES 0.1
          CONSTRUCTION=IWALLSTD ..
    NWALL-INS=EXTERIOR-WALL   $N is back of house$
          WIDTH=39.57  CONSTRUCTION=CONV-INS  GND-REFLECTANCE=0.24
          X=45.33  Y=27.33  HEIGHT=8  AZIMUTH=0 ..
          BACKDOOR=DOOR
          WIDTH=3 CONSTRUCTION=DOORBACK
          X=15.2  Y=0  HEIGHT=6.75 ..
    NWIND=WINDOW  GLASS-TYPE=WINDOWGT
```

```
    X=28.0  Y=4  W=1.92  H=2.92 .. $Bathroom window$
NWALL-STUD=EXTERIOR-WALL
    WIDTH=5.76  CONSTRUCTION=CONV-STUD  GND-REFLECTANCE=0.24
    X=5.76  Y=27.33  HEIGHT=8  AZIMUTH=0 ..
SWALL-INS=EXTERIOR-WALL  $S is front of house$
    WIDTH=30.27  CONSTRUCTION=CONV-INS  GND-REFLECTANCE=0.24
    X=0     Y=0 AZIMUTH=180 HEIGHT=8 ..
SWIND1=WINDOW  GLASS-TYPE=WINDOWGT
    X=19.0  Y=2.5  W=2.92  H=4.92  .. $One of living room windows$
SWIND2=WINDOW  GLASS-TYPE=WINDOWGT
    X=22.5  Y=2.5  W=2.92  H=4.92  .. $Other living room window$
SWIND3=WINDOW  GLASS-TYPE=WINDOWGT
    X=5.8   Y=2.5  W=2.92  H=4.92  .. $Bedroom 2 window$
SWALL-STUD=EXTERIOR-WALL
    WIDTH=4.40  CONSTRUCTION=CONV-STUD  GND-REFLECTANCE=0.24
    X=30.27  Y=0  AZIMUTH=180 HEIGHT=8 ..
EWALL-INS=EXTERIOR-WALL  $E is right of house facing front$
    WIDTH=16.88  CONSTRUCTION=CONV-INS  GND-REFLECTANCE=0.24
    X=45.33  Y=8  AZIMUTH=90 HEIGHT=8 ..
EWALL-STUD=EXTERIOR-WALL
    WIDTH=2.45  CONSTRUCTION=CONV-STUD  GND-REFLECTANCE=0.24
    X=45.33  Y=24.88  AZIMUTH=90 HEIGHT=8 ..
WWALL-INS=EXTERIOR-WALL  $W is left of house facing front$
    WIDTH=23.86  CONSTRUCTION=CONV-INS  GND-REFLECTANCE=0.24
    X=0  Y=27.33  AZIMUTH=270 HEIGHT=8 ..
WWIND=WINDOW  GLASS-TYPE=WINDOWGT
    X=5  Y=2.5  W=2.92  H=4.92  .. $Bedroom 3 window$
WWALL-STUD=EXTERIOR-WALL
    WIDTH=3.47  CONSTRUCTION=CONV-STUD  GND-REFLECTANCE=0.24
    X=0  Y=3.47  AZIMUTH=270 HEIGHT=8 ..
SWALL-POR-INS=EXTERIOR-WALL
    WIDTH=9.31  CONSTRUCTION=CONV-INS  GND-REFLECTANCE=0.24
    X=34.67 Y=8 AZIMUTH=180  HEIGHT=8 ..
SWIND1P=WINDOW  GLASS-TYPE=WINDOWGT
    X=3 Y=2.5  W=2.92  H=4.92  .. $Bedroom 1 window$
SWALL-POR-STUD=EXTERIOR-WALL
    WIDTH=1.36  CONSTRUCTION=CONV-STUD  GND-REFLECTANCE=0.24
    X=43.98 Y=8 AZIMUTH=180  HEIGHT=8 ..
EWALL-POR-INS=EXTERIOR-WALL
    WIDTH=6.98  CONSTRUCTION=CONV-INS  GND-REFLECTANCE=0.24
    X=34.67 Y=0 AZIMUTH=90  HEIGHT=8  ..
FRONTDOOR=DOOR
    WIDTH=3  CONSTRUCTION=DOORFRONT
    X=2  Y=0 HEIGHT=6.667 ..
EWALL-POR-STUD=EXTERIOR-WALL
    WIDTH=1.02  CONSTRUCTION=CONV-STUD  GND-REFLECTANCE=0.24
    X=34.67 Y=6.98 AZIMUTH=270  HEIGHT=8    ..
BACKROOF=ROOF $Tilted for solar; OK back,front not meeting at ridge$
    X=44.92  Y=26.92  Z=8  AZ=0  W=44.50
    H=13.25  CONS=ROOF-EQUIV  TILT=18.43  ..
FRONTROOF=ROOF $W adjusted on front portion to not include porch$
    X=.42  Y=.42  Z=8  AZ=180  W=38.06
    H=13.25  CONS=ROOF-EQUIV  TILT=18.43  ..
INSFLR=INTERIOR-WALL  $ Floor above crawlspace $
    TILT=180  CONSTRUCTION=FLRICONS
    AREA=AREALESSPORCH TIMES .888  NEXT-TO=CRAWL ..
```

Strategic Approach

***<u>Objective</u>*: To counter the negative perception of distressed debt investors and mitigate the potential harm that could be caused to this market by new regulations.**

- ***Establish a platform to confront misperceptions on solutions to poverty in the developing world.***

- ***Promote the importance of the secondary market to create a context for education efforts in Washington.***

Two Messaging Tracks

Role of Secondary Market

- Preserves global liquidity by ensuring that money continually flows between debtors and creditors.
- Allows developing countries to continue to borrow on favorable, affordable terms.
- Finance important institutional projects in the areas of healthcare, education and other social welfare programs.

Role of Institutional Corruption/ Lack of Transparency

- Confront misperceptions on solutions to poverty in the developing world.
- Corruption and the lack of transparency perpetuate poverty, not distressed debt investors.
- Debt forgiveness in countries with corrupt rulers does not aid the intended recipients.

Global Platform

World Growth Transparency Initiative

Mission: to Expose and Confront Institutional Corruption as the Major Perpetuator of Poverty in the World

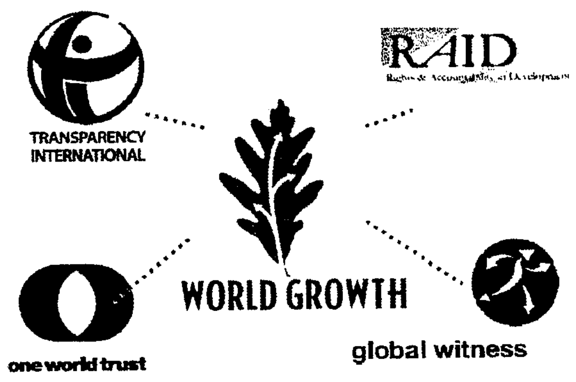
Provides Counter-Argument to Debt-Forgiveness Movement with Policy-Makers and the media.

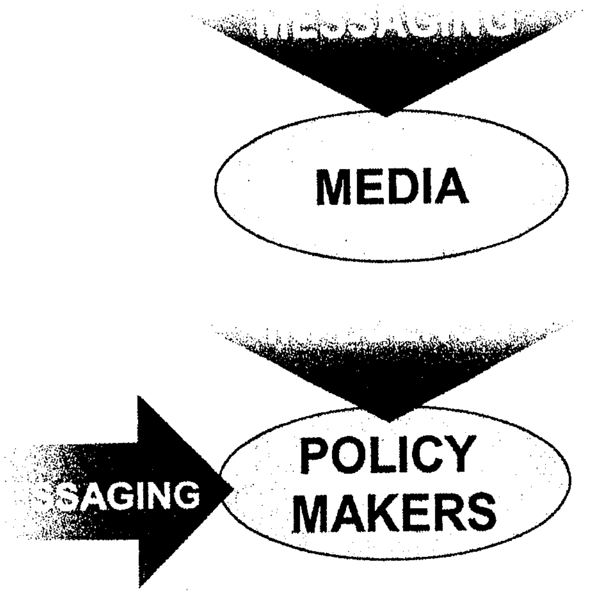
Generates Content

- *Opinion Pieces*
- *Research Papers*
- *Forums*
- *Speeches*

This Content will also be used in:

- *Capitol Hill / Administration Education Effo*
- *Additional Media Outreach*





Sample Function #1: Analyze the Value of Debt Relief

A joint-analysis by World Growth and the MIT Poverty Lab on the role of debt-forgiveness versus that of new capital through the secondary market.

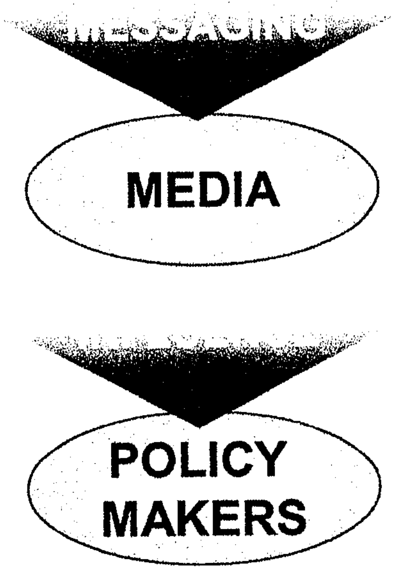
This landmark report would reveal the successes associated with post-settlement improvements in developing countries, including improved:

- Governance
- Financial Systems
- Transparency
- Foreign Direct Investment

WORLD GROWTH

Massachusetts Institute of Technology

ABDUL LATIF JAMEEL Poverty Action Lab



MESSAGING

MEDIA

POLICY MAKERS

Washington Strategy

Target Audiences

1. ***Pro-Growth Democrats, including in Congressional Black Caucus***
2. ***Moderate Republicans***
3. ***Administration, particularly international economic types***
4. ***Multilateral Organizations (World Bank, IMF)***

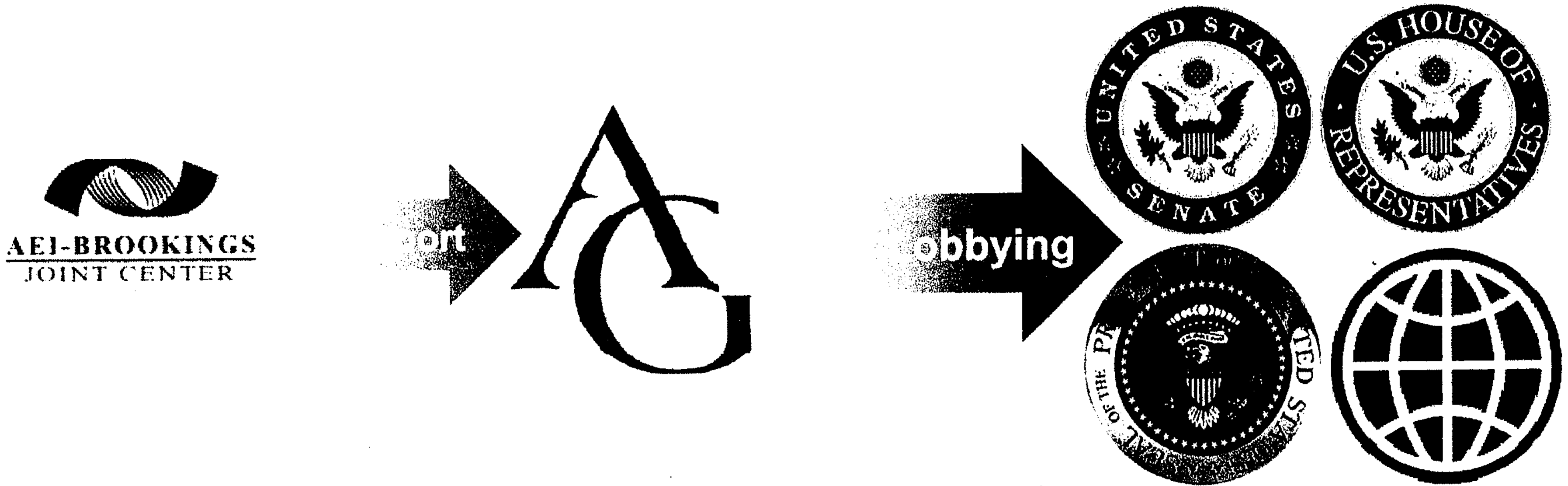
Key Messages

1. ***Secondary markets are critical to U.S. economy and to developing economies***
2. ***Explain Elliott's corporate philosophy***
3. ***Corruption perpetuates poverty, and the secondary market can help reduce this impact***
4. ***Rule of law and sanctity of contract are critical to developing economies***

Sample Function #2: Value of Secondary Market

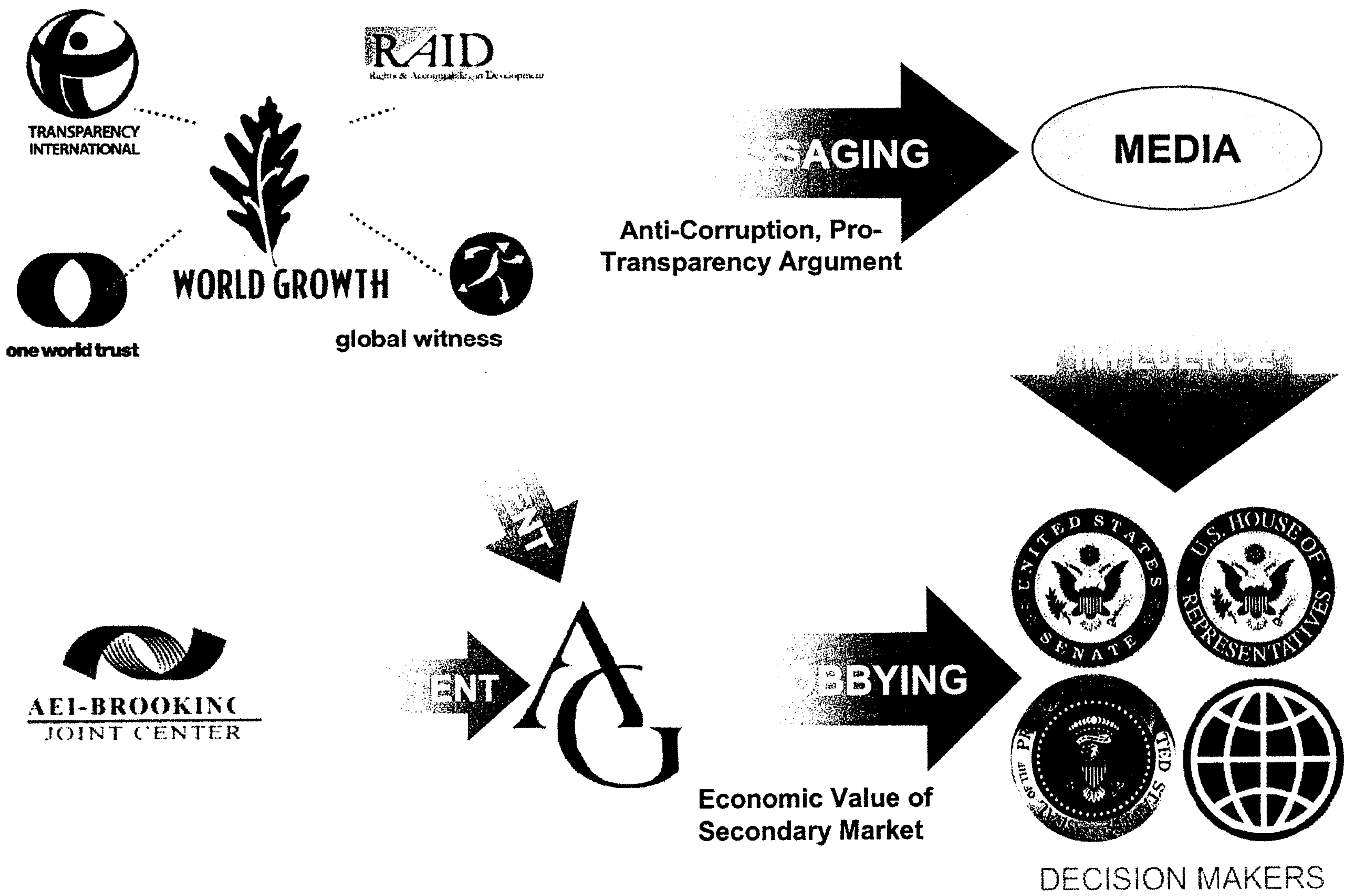
Need: To Highlight the Importance of the Secondary Market to Banks, Financial Institutions and Global Liquidity to Policymakers and the Media

Solution: A report co-authored by key opinion leaders published by the AEI-Brookings Joint Center for Regulatory Studies



Ray: Please add photos of Glenn Hubbard and Roger Ferguson before the AEI-Brookings logo

Campaign Diagram



Anti-Corruption, Pro-Transparency Argument

Economic Value of Secondary Market

DECISION MAKERS

```
   JSTFLR=INTERIOR-WALL
         TILT=180  CONSTRUCTION=FLRJCONS
         AREA=AREALESSPORCH TIMES .112  NEXT-TO=CRAWL ..
$ Crawlspace walls above ground are treated as exterior walls except at
$ the porch.  Walls for support of porch are ignored.
CRAWL=SPACE  SHAPE=NO-SHAPE
        AREA=AREALESSPORCH  VOLUME=AREALESSPORCH TIMES 4.
        TEMPERATURE=(63)  FLOOR-WEIGHT=0 I-M=AIR-CHANGE  F-WGT=0.
        I-CFM=CFMPER Z-TYPE=UNCONDITIONED F-F=0.  F-TYPE=LIGHT ..
   NCRWLBAND=E-W  H=1.0 W=45.33  $North band joist$
        X=45.33 Y=27.33 Z=-1.0 AZ=0   CONS=CRWLSPBAND ..
   ECRWLBAND=E-W  H=1.0 W=19.33  $East band joist without porch wall$
        X=45.33 Y=8     Z=-1.0 AZ=90  CONS=CRWLSPBAND ..
   SCRWLBAND=E-W  H=1.0 W=34.67  $South band joist without porch wall$
        X=0     Y=0     Z=-1.0 AZ=180 CONS=CRWLSPBAND ..
   WCRWLBAND=E-W  H=1.0 W=27.33  $West band joist$
        X=0     Y=27.33 Z=-1.0 AZ=270 CONS=CRWLSPBAND ..
   NCRWLEXP=E-W  H=1.5  W=45.33  $North exposed wall$
        X=45.33 Y=27.33 Z=-2.5 AZ=0   CONS=CRWLSPEXWALLC ..
   ECRWLEXP=E-W  H=1.5  W=19.33  $East exposed wall without porch wall$
        X=45.33 Y=8     Z=-2.5 AZ=90  CONS=CRWLSPEXWALLC ..
   SCRWLEXP=E-W  H=1.5  W=34.67  $South exposed wall without porch wall$
        X=0     Y=0     Z=-2.5 AZ=180 CONS=CRWLSPEXWALLC ..
   WCRWLEXP=E-W  H=1.5  W=27.33  $West exposed wall$
        X=0     Y=27.33 Z=-2.5 AZ=270 CONS=CRWLSPEXWALLC ..
   NCRWLUG=U-W  H=1.5  W=45.33  $North underground wall$
        X=45.33 Y=27.33 Z=-4.0 AZ=0   CONS=CRWLSPWALLC ..
   ECRWLUG=U-W  H=1.5  W=19.33  $East underground wall without porch wall$
        X=45.33 Y=8     Z=-4.0 AZ=90  CONS=CRWLSPWALLC ..
   SCRWLUG=U-W  H=1.5  W=34.67  $South underground wall without porch wall$
        X=0     Y=0     Z=-4.0 AZ=180 CONS=CRWLSPWALLC ..
   WCRWLUG=U-W  H=1.5  W=27.33  $West underground wall$
        X=0     Y=27.33 Z=-4.0 AZ=270 CONS=CRWLSPWALLC ..
   CRWLFLR=U-F  A=AREALESSPORCH  CONS=CRWLSPFLR  U-EFF=0.5  TILT=180 ..
      $After trial-and-error for U-EFF to get crawlspace temperature
$ Electric and Fuel Meters
"EM1" = ELEC-METER TYPE = UTILITY ..
"FM1" = FUEL-METER TYPE = NATURAL-GAS ..
MASTER-METERS
  MSTR-ELEC-METER  = "EM1"  MSTR-FUEL-METER  = "FM1" ..
$  SYSTEM SCHEDULES WITH CONSTANT THERMOSTAT 68 HEAT 76 COOL$
HTSCH=SCHEDULE    TYPE=TEMPERATURE THRU DEC 31 (ALL)(1,24) (68) ..
CLSCH=SCHEDULE    TYPE=TEMPERATURE THRU DEC 31 (ALL)(1,24) (76)..
FNSCH=SCHEDULE    TYPE=ON/OFF THRU DEC 31 (ALL)(1,24)(1)  ..
$ Schedule for Hourly Reports for detailed profiles of electricity use
HR-SCH-S=SCHEDULE TYPE=ON/OFF  THRU DEC 31 (ALL) (1,24) (1) ..
$  SYSTEMS AND ZONES SERVED $
MAIN=SYSTEM       TYPE=RESYS2 CONTROL-ZONE=HOUSEZONE DUCT-ZONE=CRAWLZONE
             DUCT-AIR-LOSS=DUCTLOSS DUCT-AIR-LOSS-OA=0.0 DUCT-UA=DUCTUA
             SUPPLY-FLOW=980. SUPPLY-KW/FLOW=0.000254 SUPPLY-DELTA-T=0.8
             INDOOR-FAN-MODE=INTERMITTENT  FAN-CONTROL=CONSTANT-VOLUME
             FAN-PLACEMENT=BLOW-THROUGH
             MAX-SUPPLY-T=105.  MIN-SUPPLY-T=55. $Same as defaults$
             FAN-SCHEDULE=FNSCH  COOLING-CAPACITY=36000. $30046 autosize$
             COOLING-EIR=ACEFF $COOL-SH-CAP=18000.  autosize$
             $SEER=12(assume 14 during peak); Use default part load curve$
```

```
          HEAT-SOURCE=HEAT-PUMP  HP-SUPP-HT-CAP=-34120. $default HP size$
          $Use 10 kW max strip heat only thru MIN-HP-T,MAX-HP-SUPP-T$
          HEATING-EIR=.487 $Rated SHPF=7; use default part load curve$
          MIN-HP-T=10.  MAX-HP-SUPP-T=17. $Default 10, 17; Max 70 both$
          CRANKCASE-HEAT=0.  $Disabled$ ..
HOUSEZONE=ZONE    TYPE=CONDITIONED SPACE=HOUSE D-H-T=72  D-C-T=72
          HEAT-TEMP-SCH=HTSCH  COOL-TEMP-SCH=CLSCH ASSIGNED-FLOW=980.
          THERMOSTAT-TYPE=TWO-POSITION  ..
          $Note: No throttling range allowed$
CRAWLZONE=ZONE    TYPE=UNCONDITIONED SPACE=CRAWL D-H-T=52  D-C-T=75 ..
$ DHW Use Schedule, average for all days of the year
$ Daily sum = 1.0,  Peak schedule value = 0.0921
DHW-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0126,0.0042,0.0042,0.0000,0.0000,0.0042,0.0167,0.0711,
      0.0753,0.0921,0.0711,0.0586,0.0544,0.0502,0.0377,0.0335,
      0.0377,0.0418,0.0544,0.0753,0.0628,0.0544,0.0460,0.0418)  ..
DHW-SCH =SCHEDULE TYPE = FRACTION
      THRU DEC 31 (ALL)  DHW-DS  ..
$ DHW Monthly Inlet temperatures for Knoxville, TN
MAINS-T-SCH = SCHEDULE  TYPE=TEMPERATURE
        THRU JAN 31 (ALL) (1,24) (53.5)    THRU FEB 28 (ALL) (1,24) (52.8)
        THRU MAR 31 (ALL) (1,24) (55.0)  THRU APR 30 (ALL) (1,24) (59.4)
        THRU MAY 31 (ALL) (1,24) (64.9)  THRU JUN 30 (ALL) (1,24) (70.0)
        THRU JUL 31 (ALL) (1,24) (73.5)     THRU AUG 31 (ALL) (1,24) (74.4)
        THRU SEP 30 (ALL) (1,24) (72.5)     THRU OCT 31 (ALL) (1,24) (68.3)
        THRU NOV 30 (ALL) (1,24) (62.8)   THRU DEC 31 (ALL) (1,24) (57.6)  ..
DHWLOOP = CIRCULATION-LOOP
        TYPE = DHW
        PROCESS-FLOW = 0.915
        PROCESS-SCH = DHW-SCH
        HEAT-SETPT-T = 120.
        DHW-INLET-T-SCH = MAINS-T-SCH ..
DHWHTR = DW-HEATER
        TYPE = ELEC
        DHW-LOOP = DHWLOOP ..
LOADS-REPORT            REPORT-FREQUENCY=HOURLY $For hourly reports$
           VERIFICATION=(LV-K) SUMMARY=(LS-A,LS-B,LS-C,LS-D,LS-F)
           HOURLY-DATA-SAVE=FORMATTED  ..
SYSTEMS-REPORT    VERIFICATION (SV-A,SV-C)  SUMMARY=(SS-A,SS-H)
           REPORT-FREQUENCY=HOURLY  HOURLY-DATA-SAVE=FORMATTED  ..
PLANT-REPORT     SUMMARY(BEPS,BEPU,PS-B) ..
$HOURLY REPORTS
LHR-0=REPORT-BLOCK  V-T=GLOBAL  V-L=(4,15) ..
$Variables: 4=DBT;15=SOLRAD
LHR-1=REPORT-BLOCK V-T=BUILDING-LOADS V-L=(3,21) ..
$Variables: 3=Heating from wall conduction;21=Cooling from wall conduction
LHR-N=REPORT-BLOCK  V-T=NWALL-INS V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after

LHR-S=REPORT-BLOCK  V-T=SWALL-INS V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
LHR-E=REPORT-BLOCK  V-T=EWALL-INS V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
```

```
LHR-W=REPORT-BLOCK  V-T=WWALL-INS V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
SHR-1=REPORT-BLOCK  V-T=HOUSEZONE  V-L=(6) ..
$Variables: 6=TzoneF
SHR-2=REPORT-BLOCK V-T="EM1" V-L= (1,3,4,5,8,10,20) ..
$1=lights;3=equip;4=heat;5=cool;8=fans;10=suppl;20=total
SYS-REP=HOURLY-REPORT  REPORT-SCHEDULE=HR-SCH-S
REPORT-BLOCK=(LHR-0,LHR-S) ..
END ..
COMPUTE ..
STOP ..
```

CMU-walled house without IrBPs on walls (Change ABS = 0.762 to 0.505 for IrBPs):

```
INPUT .. $DOE2.2 input file$
TITLE   LINE-1  *Conv Habitat House+Stucco (fixsize HP) *
     LINE-2  *229 Bethel Road, Lenoir City, Tennessee *
     LINE-3  *Vented Crawlspace with Band Joist Top   *
     LINE-4  *Occupied(3 people + Bldg Amer load)     *
     LINE-5  *Detailed Hourly Reports for Profile     * ..
$ House is 27'4" x 45'4" outside with 8' x 10'8" notched out for corner porch.
$ House is 26'6" x 44'6" less porch inside.
$ Yield 1094 net sq ft living area. Exterior walls R-11, 2x4 16 in. oc + stucco
$ Total glazing area 67.5 sq ft + 4.5 sq ft in kitchen door - 6.6% of living area.
$ Crawl space floor model uses updated analytical procedure described in
$  Winkelmann, F.C. 1998. "Underground Surfaces, How to Get a Better
$  Underground Heat Transfer Calculation in DOE-2.1E," pp 6-13,
$  Building Simulation User News, 19(1). Modified Ueff to match Tcrawl
DIAGNOSTIC  WARNINGS ..
ABORT ERRORS  ..
PARAMETER
     AREALESSPORCH=1093.9  IWALLAREA=687
     DUCTLOSS=0.15 DUCTUA=120. ACEFF=0.274
     $INFILT=.00032  - 5/31/01 BLOWER DOOR TEST: 49.6 in² @ 4 Pa $
     $INFILT=.00042  - 3/1/01 BLOWER DOOR TEST: 65.9 in² @ 4 Pa $
     INFILT=.00042   $ 3/1/01 BLOWER DOOR TEST: 65.9 in² @ 4 Pa  $
     WINDOWGT=WINDOW-2grey $ GLASS TYPE $
     CFMPER=0.10 .. $Trial-and-error for crawlspace temperature$
RUN-PERIOD       JAN 1 2000  THRU  DEC 31 2000  ..
SITE-PARAMETERS   LAT=35.82  LON=83.98  T-Z=5  ALT=981 $ Knoxville, TN $
          WS-HEIGHT=33 SHIELDING-COEF=0.24  $ Some obstruction $
          TERRAIN-PAR1=.85 TERRAIN-PAR2=.20
          WS-TERRAIN-PAR1=1  WS-TERRAIN-PAR2=0.15 ..
BUILD-PARAMETERS   AZIMUTH=0 .. $Back faces North; Living room faces South$
$ LOADS SCHEDULES ADDED 10/19/04
$ FOR COMPARISON TO MEASUREMENTS NO LOADS SCHEDULES ARE NEEDED $
$ Internal loads are available from Building America Performance Analysis
$ Resources at http://www.eere.energy.gov/buildings/building_america/
$ pa_resources.html. Spreadsheets give profiles to use: hot water use
$ profile from ASHRAE; lighting equipment and use profile documented
$ for DOE by Navigant; appliance and other plug loads by NREL from
$ Navigant analysis; occupancy schedule assumes number of occupants equals
$ number of bedrooms and profiles developed by NREL from ASHRAE schedule
$ and engineering judgment.
```

```
$ For occupancy use single zone Occ L1-WD workbook data in
occupancy_schedules_multilevel_04_03.xls
$ Occupancy Schedule, average for all WEEKDAYS of the year, all spaces
Occ-WD-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,0.8300,
        0.2899,0.1247,0.1247,0.1247,0.1247,0.1247,0.1247,0.1247,
        0.1247,0.5000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000) ..
$ Occupancy Schedule, average for all WEEKENDS and HOLIDAYS of the year, all spaces
Occ-WE-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,1.0000,
        0.6700,0.5000,0.5000,0.5000,0.5000,0.5000,0.5000,0.5000,
        0.6700,0.6700,0.6700,0.6700,0.6700,1.0000,1.0000,1.0000) ..
Occupancy-SCH =SCHEDULE TYPE = FRACTION
        THRU DEC 31 (WD)  Occ-WD-DS  (WEH)  Occ-WE-DS ..
$ For lighting use corresponding Ltg L1-WD workbook in lighting_042004.xls
$ Lighting Schedule, average for all WEEKDAYS of the year, all spaces
Ltg-WD-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0085,0.0085,0.0085,0.0085,0.0237,0.0499,0.0561,0.0498,
        0.0203,0.0135,0.0135,0.0135,0.0135,0.0135,0.0135,0.0257,
        0.0561,0.0807,0.1053,0.1244,0.1270,0.0847,0.0440,0.0203) ..
$ Lighting Schedule, average for all WEEKENDS and HOLIDAYS of the year, all spaces
Ltg-WE-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0085,0.0085,0.0085,0.0085,0.0237,0.0502,0.0553,0.0501,
        0.0254,0.0186,0.0186,0.0186,0.0186,0.0186,0.0186,0.0271,
        0.0549,0.0729,0.1051,0.1269,0.1270,0.0948,0.0590,0.0203) ..
Lighting-SCH =SCHEDULE TYPE = FRACTION
        THRU DEC 31 (WD)  Ltg-WD-DS  (WEH)  Ltg-WE-DS ..
$ Appliance & Plug Load Schedule, average for all days of the year, all spaces
$ Daily sum = 1.0,  Peak schedule value = 0.0588
ApplPlug-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0335,0.0288,0.0288,0.0270,0.0270,0.0335,0.0447,0.0523,
        0.0523,0.0482,0.0417,0.0417,0.0376,0.0341,0.0341,0.0341,
        0.0429,0.0347,0.0588,0.0588,0.0564,0.0564,0.0506,0.0417) ..
ApplPlug-SCH =SCHEDULE TYPE = FRACTION
        THRU DEC 31 (ALL)  ApplPlug-DS ..
$ Schedule for Hourly Reports all hours to get detailed wall loads
HR-SCH-L=SCHEDULE  TYPE=ON/OFF THRU DEC 31 (ALL) (1,24) (1) ..
$ GLASS TYPES $
WINDOW-2alt   GLASS-TYPE TYPE=GLASS-TYPE-CODE
           GLASS-TYPE-CODE=2000 ..  $ Same as Window-2 in old code $
WINDOW-2grey  GLASS-TYPE TYPE=GLASS-TYPE-CODE $U=.49 SHGC=.61 Tvis=.55$
           GLASS-TYPE-CODE=2213 .. $Close to TVA's U=.50 SHGC=.54 Tvis=.55$
WINDOW-2LOWe  GLASS-TYPE TYPE=GLASS-TYPE-CODE GLASS-TYPE-CODE=2612 ..
$  MATERIALS $
R11BATINS=MAT TYPE=PROPERTIES TH=.2917  COND=.02652
    DENS=.6  S-H=.19  .. $ R-11 batts for wall$
R13BATINS=MAT TYPE=PROPERTIES TH=.2917  COND=.02244
    DENS=.8  S-H=.19  .. $ R-13 batts for wall$
R15BATINS=MAT TYPE=PROPERTIES TH=.3666  COND=.02412
    DENS=.6  S-H=.19  .. $ 'R-15.2' batts for flr$
R17BATINS=MAT TYPE=PROPERTIES TH=.4125  COND=.02412
    DENS=.6  S-H=.19  .. $ 'R-17.1' batts for flr$
R19BATINS=MAT TYPE=PROPERTIES TH=.4583  COND=.02412
    DENS=.6  S-H=.19  .. $ R-19 batts for flr $
REQUIV=MAT    TYPE=PROPERTIES TH=.9917  COND=.03832
    DENS=.6  S-H=.19  .. $ Ins.for Equiv.Roof$
```

```
R19INS=MAT   TYPE=PROPERTIES TH=.6878  COND=.0362
   DENS=.5  S-H=.19  .. $ 8.25" blown FG $
R19INSJ=MAT   TYPE=PROPERTIES TH=.2295  COND=.0362
   DENS=.5  S-H=.19  .. $ 2.75" FG above 2x6 $
R25INS=MAT   TYPE=PROPERTIES TH=.9208  COND=.0362
   DENS=.5  S-H=.19  .. $ 11.05" avg FG R-25.4$
R25INSJ=MAT   TYPE=PROPERTIES TH=.6292  COND=.0362
   DENS=.5  S-H=.19  .. $ 7.55" FGovr2x4 R1-17.4$
R28INS=MAT   TYPE=PROPERTIES TH=1.000  COND=.0362
   DENS=.5  S-H=.19  .. $ 12" blown FG R-27.62 $
R28INSJ=MAT   TYPE=PROPERTIES TH=.7083  COND=.0362
   DENS=.5  S-H=.19  .. $ 8.5" FG above 2x4 R19.57 $
R38INS=MAT   TYPE=PROPERTIES TH=1.3756 COND=.0362
   DENS=.5  S-H=.19  .. $ 16.5" Blown FG $
R38INSJ=MAT   TYPE=PROPERTIES TH=1.0839 COND=.0362
   DENS=.5  S-H=.19  .. $ 13" FG above 2x4 $
FRAM=MAT    TYPE=PROPERTIES TH=.2917  COND=.0833
   DENS=28  S-H=.39  .. $ 3.5 in.2x4 wall,clg$
RJST=MAT     TYPE=PROPERTIES TH=.7917  COND=.0833
   DENS=28  S-H=.39  .. $ 9.5 in.2x10 flr jst$
JSTS=MAT     TYPE=PROPERTIES TH=1.    COND=.0833
   DENS=28  S-H=.39  .. $ 12 IN.  $
BANDJST=MAT   TYPE=PROPERTIES TH=.125   COND=.0833
   DENS=28  S-H=.39  .. $ 1.5 IN. $
GYPBD=MAT    TYPE=PROPERTIES TH=.04167 COND=.0926
   DENS=50  S-H=.26  .. $ 0.5" wall,clg gyp $
STUCCO=MAT   TYPE=PROPERTIES TH=.0833 COND=0.8083
         DENS=120. S-H=.20 .. $ 1.0 in. concrete stucco $
AIRGAP=MAT   TYPE=RESISTANCE RES=1.0 ..
   $ 3/4 in. unvented air space under stucco$
CONFILL=MAT  TYPE=PROPERTIES TH=.25   COND=1.06
   DENS=140 S-H=.22   .. $ Heavyweight concrete$
SHEATH=MAT   TYPE=PROPERTIES TH=.04167 COND=.0783
   DENS=50  S-H=.31  .. $1/2 in. OSB under stucco$
FOAM=MAT     TYPE=PROPERTIES TH=.08333 COND=.016667
   DENS=2.0 S-H=.29  .. $ R-5 foam for interior of CMU$
SOIL=MAT     TYPE=PROPERTIES TH=.95    COND=.75
   DENS=115 S-H=.20  .. $ Rec 1 ft. too thick$
EARTH=MAT    TYPE=PROPERTIES TH=2.5    COND=.5
   DENS=120 S-H=.20  ..
FIC-DIRT-FLR=MAT  TYPE=RESISTANCE RES=1000.  ..
   $ No steady ht through crawlspc flr; OK 1 ft soil$
$ LAYERS $
CMUSTUC=LA   MAT=(STUCCO,"CMU HW 8in Hollow (CB11)",FOAM,GYPBD) ..
INTWALLC=LA   MAT=(GYPBD,"Air Lay <4in Vert (AL21)",GYPBD) ..
   $Through center cavity interior walls$
INTWALLS=LA  MAT=(GYPBD,FRAM,GYPBD) .. $Through stud interior walls$
ROOFJST=LA   MAT=("Asph Siding (AR02)","Bldg Paper Felt (BP01)",
   "Plywd 1/2in (PW03)","Air Lay >4in Slope (AL32)",R25INSJ,FRAM,GYPBD) ..
ROOFINS=LA   MAT=("Asph Siding (AR02)","Bldg Paper Felt (BP01)",
   "Plywd 1/2in (PW03)","Air Lay >4in Slope (AL32)",R25INS,GYPBD) ..
ROOFEQUIV=LA  MAT=("Asph Siding (AR02)","Bldg Paper Felt (BP01)",
   "Plywd 1/2in (PW03)","Air Lay >4in Slope (AL32)",REQUIV,GYPBD) ..
FLRINS=LA    MAT=(R17BATINS,"Plywd 1/2in (PW03)","PartBd Underlay 5/8in (PB04)",
   "Carpet & Rubber Pad (CP02)") I-F-R=.92 ..
FLRJST=LA    MAT=(RJST,"Plywd 1/2in (PW03)","PartBd Underlay 5/8in (PB04)",
```

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   "Carpet & Rubber Pad (CP02)") I-F-R=.92 ..
BANDJ=LA    MAT=(STUCCO,SHEATH,BANDJST) ..
CMUWALL=LA   MAT=("CMU HW 8in ConcFill (CB12)") .. $Concrete filled cement block$
UNDGWALLC=LA  MAT=(SOIL,"CMU HW 8in ConcFill (CB12)") ..
    $Conventional crawlspace wall below grade$
DIRTFLR=LA    MAT=(FIC-DIRT-FLR,SOIL)  I-F-R=0.92  .. $Updated procedure$
$ CONSTRUCTION $
$ 11.2% of framed floors is 2 x 10 floor joists; with R-'15.2'batts, Rflr=16.45
$ Handle by using 'AREA TIMES Fraction' for center cavity+framing in parallel
$ Ceiling insulation depth adjusted for eaves, Rceil=28.35 with equivalent FG
CMU-STUCCO    CONS   TYPE=LAYERS LAYERS=CMUSTUC ABS=.762  .. $Above grade wall$
ROOF-JST     CONS   TYPE=LAYERS LAYERS=ROOFJST  ABS=.85  .. $Roof equiv through trusses$
ROOF-INS     CONS   TYPE=LAYERS LAYERS=ROOFINS  ABS=.85  ..
       $Roof equiv through insulation$
ROOF-EQUIV    CONS   TYPE=LAYERS LAYERS=ROOFEQUIV ABS=.85 ..
       $Overall equivalent roof$
IWALLCAV     CONS   TYPE=LAYERS LAYERS=INTWALLC  .. $Interior walls through cavity$
IWALLSTD     CONS   TYPE=LAYERS LAYERS=INTWALLS  .. $Interior walls through studs$
DOORFRONT    CONS   TYPE=U-VALUE U-VALUE=.37  .. $Solid foam core steel door$
DOORBACK     CONS   TYPE=U-VALUE U-VALUE=.48  .. $2 pane glass in foam core steel door$
FLRICONS     CONS   TYPE=LAYERS LAYERS=FLRINS  ..  $Floor over crawlspc through insulation$
FLRJCONS     CONS   TYPE=LAYERS LAYERS=FLRJST  ..  $Floor over crawlspace through joist$
CRWLSPWALLC  CONS   TYPE=LAYERS LAYERS=UNDGWALLC  ..
       $Conventional below grade wall$
CRWLSPEXWALLC CONS   TYPE=LAYERS LAYERS=CMUWALL  ..
       $Conv above grade crawlspc walls$
CRWLSPBAND    CONS   TYPE=LAYERS LAYERS=BANDJ  ..
       $Band jst atop conv crawlspace walls$
CRWLSPFLR     CONS   TYPE=LAYERS LAYERS=DIRTFLR  ..  $Dirt crawlspace floor$
$ Porch Shade $
B-S  X=35.54   Y=0   Z=8  AZ=180  W=10.67  H=8  TILT=0  ..
$ Gable and Eave Shading: Gables at 4 in 12 pitch (tan TILT=4/12) $
B-S  X=-2      Y=-2    Z=8  AZ=180  W=50.21  H=2   TILT=0  .. $Front overhang$
B-S  X=48.21   Y=30.21 Z=8  AZ=0    W=50.21  H=2   TILT=0  .. $Back overhang$
B-S  X=0       Y=-2    Z=8  AZ=90   W=16.98  H=2   TILT=18.43  .. $Down gable$
B-S  X=-2      Y=30.21 Z=8  AZ=270  W=16.98  H=2   TILT=18.43  .. $Down gable$
B-S  X=46.21   Y=30.21 Z=8  AZ=270  W=16.98  H=2   TILT=18.43  .. $Upside gable$
B-S  X=48.21   Y=-2    Z=8  AZ=90   W=16.98  H=2   TILT=18.43  .. $Upside gable$
$ Space Conditions $
ALLFLR=FLOOR  SHAPE=NO-SHAPE AREA=1304 ..
HOUSE=SPACE   SHAPE=NO-SHAPE
        AREA=AREALESSPORCH  VOLUME=AREALESSPORCH TIMES 8
        TEMPERATURE=(72) NUMBER-OF-PEOPLE=3 $BA Profiles$
        PEOPLE-SCHEDULE=Occupancy-SCH $N-O-P=#bedrooms$
        PEOPLE-HG-LAT=166.1 PEOPLE-HG-SENS=219.7
        LIGHTING-W/AREA=3.331 $BA formulas for lights;plug$
        LIGHTING-SCHEDULE=Lighting-SCH LIGHTING-TYPE=INCAND
        EQUIPMENT-W/AREA=10.64 EQUIP-SCHEDULE=ApplPlug-SCH
        EQUIP-SENSIBLE=.697 EQUIP-LATENT=.103 $No latent refrig.;washer$
        INF-METHOD=S-G  FRAC-LEAK-AREA=INFILT  FLOOR-WEIGHT=0
        FURNITURE-TYPE=LIGHT FURN-FRACTION=0.4 FURN-WEIGHT=8.0 ..
   IWALL-CAV=INTERIOR-WALL
        INT-WALL-TYPE=INTERNAL AREA=IWALLAREA TIMES 0.9
        CONSTRUCTION=IWALLCAV ..
   IWALL-STUD=INTERIOR-WALL
        INT-WALL-TYPE=INTERNAL AREA=IWALLAREA TIMES 0.1
```

```
      CONSTRUCTION=IWALLSTD ..
  NWALL-CMU=EXTERIOR-WALL  $N is back of house$
      WIDTH=46.21 CONSTRUCTION=CMU-STUCCO GND-REFLECTANCE=0.24
      X=46.21  Y=28.21  HEIGHT=8  AZIMUTH=0 ..
    BACKDOOR=DOOR
      WIDTH=3 CONSTRUCTION=DOORBACK
      X=15.2  Y=0  HEIGHT=6.75 ..
    NWIND=WINDOW  GLASS-TYPE=WINDOWGT
      X=28.0  Y=4  W=1.92  H=2.92 .. $Bathroom window$
  SWALL-CMU=EXTERIOR-WALL  $S is front of house$
      WIDTH=35.54  CONSTRUCTION=CMU-STUCCO GND-REFLECTANCE=0.24
      X=0 Y=0 AZIMUTH=180 HEIGHT=8 ..
    SWIND1=WINDOW  GLASS-TYPE=WINDOWGT
     X=19.0  Y=2.5  W=2.92  H=4.92  .. $One of living room windows$
  SWIND2=WINDOW  GLASS-TYPE=WINDOWGT
     X=22.5  Y=2.5  W=2.92  H=4.92  .. $Other living room window$
  SWIND3=WINDOW  GLASS-TYPE=WINDOWGT
      X=5.8  Y=2.5  W=2.92  H=4.92  .. $Bedroom 2 window$
  EWALL-CMU=EXTERIOR-WALL  $E is right of house facing front$
      WIDTH=20.21 CONSTRUCTION=CMU-STUCCO GND-REFLECTANCE=0.24
      X=46.21  Y=8  AZIMUTH=90 HEIGHT=8 ..
  WWALL-CMU=EXTERIOR-WALL  $W is left of house facing front$
      WIDTH=28.21 CONSTRUCTION=CMU-STUCCO GND-REFLECTANCE=0.24
      X=0  Y=28.21  AZIMUTH=270 HEIGHT=8 ..
    WWIND=WINDOW  GLASS-TYPE=WINDOWGT
      X=5  Y=2.5  W=2.92  H=4.92  .. $Bedroom 3 window$
  SWALL-POR-CMU=EXTERIOR-WALL
      WIDTH=10.67 CONSTRUCTION=CMU-STUCCO GND-REFLECTANCE=0.24
      X=35.54 Y=8 AZIMUTH=180  HEIGHT=8 ..
    SWIND1P=WINDOW  GLASS-TYPE=WINDOWGT
      X=3 Y=2.5  W=2.92  H=4.92  .. $Bedroom 1 window$
  EWALL-POR-CMU=EXTERIOR-WALL
      WIDTH=8  CONSTRUCTION=CMU-STUCCO GND-REFLECTANCE=0.24
      X=35.54 Y=0 AZIMUTH=90  HEIGHT=8  ..
    FRONTDOOR=DOOR
      WIDTH=3  CONSTRUCTION=DOORFRONT
      X=2  Y=0 HEIGHT=6.667 ..
  BACKROOF=ROOF $Tilted for solar; OK back,front not meeting at ridge$
      X=45.35  Y=27.35  Z=8  AZ=0  W=44.50
      H=13.25  CONS=ROOF-EQUIV  TILT=18.43  ..
  FRONTROOF=ROOF $W adjusted on front portion to not include porch$
      X=.85  Y=.85  Z=8  AZ=180  W=38.06
      H=13.25  CONS=ROOF-EQUIV  TILT=18.43  ..
  INSFLR=INTERIOR-WALL  $ Floor above crawlspace $
      TILT=180  CONSTRUCTION=FLRICONS
      AREA=AREALESSPORCH TIMES .888  NEXT-TO=CRAWL ..
  JSTFLR=INTERIOR-WALL
      TILT=180  CONSTRUCTION=FLRJCONS
      AREA=AREALESSPORCH TIMES .112  NEXT-TO=CRAWL ..
$ Crawlspace walls above ground are treated as exterior walls except at
$ the porch.  Walls for support of porch are ignored.
CRAWL=SPACE  SHAPE=NO-SHAPE
      AREA=AREALESSPORCH  VOLUME=AREALESSPORCH TIMES 4.
      TEMPERATURE=(63)  FLOOR-WEIGHT=0 I-M=AIR-CHANGE  F-WGT=0.
      I-CFM=CFMPER Z-TYPE=UNCONDITIONED F-F=0.  F-TYPE=LIGHT ..
  NCRWLEXP=E-W  H=2.5 W=46.21  $North exposed wall$
```

```
        X=46.21 Y=28.21 Z=-2.5 AZ=0   CONS=CRWLSPEXWALLC ..
   ECRWLEXP=E-W  H=2.5 W=20.21  $East exposed wall without porch wall$
        X=46.21 Y=8     Z=-2.5 AZ=90  CONS=CRWLSPEXWALLC ..
   SCRWLEXP=E-W  H=2.5 W=35.54  $South exposed wall without porch wall$
        X=0     Y=0     Z=-2.5 AZ=180 CONS=CRWLSPEXWALLC ..
   WCRWLEXP=E-W  H=2.5 W=28.21  $West exposed wall$
        X=0     Y=28.21 Z=-2.5 AZ=270 CONS=CRWLSPEXWALLC ..
   NCRWLUG=U-W  H=1.5 W=46.21  $North underground wall$
        X=46.21 Y=28.21 Z=-4.0 AZ=0   CONS=CRWLSPWALLC ..
   ECRWLUG=U-W  H=1.5 W=20.21  $East underground wall without porch wall$
        X=46.21 Y=8     Z=-4.0 AZ=90  CONS=CRWLSPWALLC ..
   SCRWLUG=U-W  H=1.5 W=35.54  $South underground wall without porch wall$
        X=0     Y=0     Z=-4.0 AZ=180 CONS=CRWLSPWALLC ..
   WCRWLUG=U-W  H=1.5 W=28.21  $West underground wall$
        X=0     Y=28.21 Z=-4.0 AZ=270 CONS=CRWLSPWALLC ..
   CRWLFLR=U-F  A=AREALESSPORCH  CONS=CRWLSPFLR  U-EFF=0.5  TILT=180 ..
        $After trial-and-error for U-EFF to get crawlspace temperature
$ Electric and Fuel Meters
"EM1" = ELEC-METER TYPE = UTILITY ..
"FM1" = FUEL-METER TYPE = NATURAL-GAS ..
MASTER-METERS
  MSTR-ELEC-METER  = "EM1"  MSTR-FUEL-METER  = "FM1" ..
$  SYSTEM SCHEDULES WITH CONSTANT THERMOSTAT 68 HEAT 76 COOL$
HTSCH=SCHEDULE    TYPE=TEMPERATURE THRU DEC 31 (ALL)(1,24) (68) ..
CLSCH=SCHEDULE    TYPE=TEMPERATURE THRU DEC 31 (ALL)(1,24) (76)..
FNSCH=SCHEDULE    TYPE=ON/OFF THRU DEC 31 (ALL)(1,24)(1)  ..
$ Schedule for Hourly Reports for detailed profiles of electricity use
HR-SCH-S=SCHEDULE TYPE=ON/OFF THRU DEC 31 (ALL) (1,24) (1) ..
$  SYSTEMS AND ZONES SERVED $
MAIN=SYSTEM      TYPE=RESYS2 CONTROL-ZONE=HOUSEZONE DUCT-ZONE=CRAWLZONE
            DUCT-AIR-LOSS=DUCTLOSS DUCT-AIR-LOSS-OA=0.0 DUCT-UA=DUCTUA
            SUPPLY-FLOW=980. SUPPLY-KW/FLOW=0.000254 SUPPLY-DELTA-T=0.8
            INDOOR-FAN-MODE=INTERMITTENT  FAN-CONTROL=CONSTANT-VOLUME
            FAN-PLACEMENT=BLOW-THROUGH
            MAX-SUPPLY-T=105.  MIN-SUPPLY-T=55. $Same as defaults$
            FAN-SCHEDULE=FNSCH  COOLING-CAPACITY=36000. $30046 autosize$
            COOLING-EIR=ACEFF $COOL-SH-CAP=18000.  autosize$
            $SEER=12(assume 14 during peak); Use default part load curve$
            HEAT-SOURCE=HEAT-PUMP  HP-SUPP-HT-CAP=-34120. $default HP size$
            $Use 10 kW max strip heat only thru MIN-HP-T,MAX-HP-SUPP-T$
            HEATING-EIR=.487 $Rated SHPF=7; use default part load curve$
            MIN-HP-T=10.  MAX-HP-SUPP-T=17. $Default 10, 17; Max 70 both$
            CRANKCASE-HEAT=0.  $Disabled$ ..
HOUSEZONE=ZONE   TYPE=CONDITIONED SPACE=HOUSE D-H-T=72  D-C-T=72
            HEAT-TEMP-SCH=HTSCH  COOL-TEMP-SCH=CLSCH ASSIGNED-FLOW=980.
            THERMOSTAT-TYPE=TWO-POSITION  ..
            $Note: No throttling range allowed$
CRAWLZONE=ZONE    TYPE=UNCONDITIONED SPACE=CRAWL D-H-T=52  D-C-T=75 ..
$ DHW Use Schedule, average for all days of the year
$ Daily sum = 1.0,  Peak schedule value = 0.0921
DHW-DS =DAY-SCHEDULE   TYPE = FRACTION
(1,24)  (0.0126,0.0042,0.0042,0.0000,0.0000,0.0042,0.0167,0.0711,
       0.0753,0.0921,0.0711,0.0586,0.0544,0.0502,0.0377,0.0335,
       0.0377,0.0418,0.0544,0.0753,0.0628,0.0544,0.0460,0.0418)  ..
DHW-SCH =SCHEDULE TYPE = FRACTION
       THRU DEC 31 (ALL)  DHW-DS  ..
```

```
$ DHW Monthly Inlet temperatures for Knoxville, TN
MAINS-T-SCH = SCHEDULE  TYPE=TEMPERATURE
        THRU JAN 31 (ALL) (1,24) (53.5)    THRU FEB 28 (ALL) (1,24) (52.8)
        THRU MAR 31 (ALL) (1,24) (55.0)  THRU APR 30 (ALL) (1,24) (59.4)
        THRU MAY 31 (ALL) (1,24) (64.9)  THRU JUN 30 (ALL) (1,24) (70.0)
        THRU JUL 31 (ALL) (1,24) (73.5)     THRU AUG 31 (ALL) (1,24) (74.4)
        THRU SEP 30 (ALL) (1,24) (72.5)     THRU OCT 31 (ALL) (1,24) (68.3)
        THRU NOV 30 (ALL) (1,24) (62.8)   THRU DEC 31 (ALL) (1,24) (57.6)  ..
DHWLOOP = CIRCULATION-LOOP
        TYPE = DHW
        PROCESS-FLOW = 0.915
        PROCESS-SCH = DHW-SCH
        HEAT-SETPT-T = 120.
        DHW-INLET-T-SCH = MAINS-T-SCH ..
DHWHTR = DW-HEATER
        TYPE = ELEC
        DHW-LOOP = DHWLOOP ..
LOADS-REPORT            REPORT-FREQUENCY=HOURLY $For hourly reports$
          VERIFICATION=(LV-K) SUMMARY=(LS-A,LS-B,LS-C,LS-D,LS-F)
          HOURLY-DATA-SAVE=FORMATTED  ..
SYSTEMS-REPORT   VERIFICATION (SV-A,SV-C)  SUMMARY=(SS-A,SS-H)
          REPORT-FREQUENCY=HOURLY  HOURLY-DATA-SAVE=FORMATTED  ..
PLANT-REPORT     SUMMARY(BEPS,BEPU,PS-B) ..
$HOURLY REPORTS
LHR-0=REPORT-BLOCK  V-T=GLOBAL  V-L=(4,15) ..
$Variables: 4=DBT;15=SOLRAD
LHR-1=REPORT-BLOCK V-T=BUILDING-LOADS V-L=(3,21) ..
$Variables: 3=Heating from wall conduction;21=Cooling from wall conduction
LHR-N=REPORT-BLOCK  V-T=NWALL-CMU V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
LHR-S=REPORT-BLOCK  V-T=SWALL-CMU V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
LHR-E=REPORT-BLOCK  V-T=EWALL-CMU V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
LHR-W=REPORT-BLOCK  V-T=WWALL-CMU V-L=(1,2,5,6,17,18) ..
$Variables: 1=Total solar after shading;2=Fraction shaded;5=Unwgt wall to zone Q (Btu/h)
$ 6=Outside surface T (R);17=Direct solar B/h/ft² before shading;18=Sky+gr diff after
SHR-1=REPORT-BLOCK  V-T=HOUSEZONE  V-L=(6) ..
$Variables: 6=TzoneF
SHR-2=REPORT-BLOCK V-T="EM1" V-L= (1,3,4,5,8,10,20) ..
$1=lights;3=equip;4=heat;5=cool;8=fans;10=suppl;20=total
SYS-REP=HOURLY-REPORT  REPORT-SCHEDULE=HR-SCH-S
REPORT-BLOCK=(LHR-0,LHR-S)  ..
END ..
COMPUTE ..
STOP ..
```