TECHNICAL NOTES

Thermal Performance Analysis of Highly Reflective Coating on Residences in Hot and Arid Climates

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Abstract: A 1-D transient model (RESHEAT), developed by the writers, was used to study the thermal performance of a highly reflective paint applied sequentially to the outer walls and roof of a simulated residence in a hot and arid region of the southwestern United States. The model uses climatological inputs from a file that includes hourly data on ambient temperatures, insolation, cloud cover, and so on, at the particular location. The model focuses particularly on the potential cooling load reduction due to the reduced heat pickup from the inside attic surfaces to the outer surfaces of the supply duct. This simulation showed that a reduction of 33.6% (cooling load) on the average is achieved over the base case where no reflective paint is used when the outer surface of the roof and walls are painted. Alternatively, only a 11% reduction would be achieved if the reflective paint is applied only to the roof. Savings of $42 per month are conservatively estimated from calculations made when applying this technology to a typical residence (roof and walls) equipped with a 4 ton refrigeration unit in the Southwest.

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Introduction

The use of different energy-conserving residential technologies is slowly seeing a revival as electric energy costs keep inching upward, especially in the Southwest-

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ern United States. The electric utility costs in California in particular have seen a sharp rise, a fact that is also affecting other states nearby, such as Nevada and Arizona. In Nevada the local authorities have allowed the local power utility to increase its fuel charges to its customers on a graduated basis, so that in a matter of about 4 years this increase will go up by 75% from its present level. Radiant barriers have already been used in several developments in California and are slowly penetrating other Southwest residential construction markets. This usually entails gluing a highly reflective foil to the underside of a typical particle board of 1.2 by 2.4 m, normally placed face down over the roof rafters. However, a similar technology that is slow to take hold is a ceramically based paint applied on the exterior of roofs as well as walls to reflect a good portion of the solar rays, and in so doing to lower the cooling load on the total structure.

Parker and Sherwin (1998) compared the summer attic thermal performance of six roof construction types and found that a white tile roof was best for controlling attic heat gain. Their data showed that the white roof reduced the heat gain throughout the attic by about 75% from that of a black shingle tile roof. Their paper also alluded to the fact that one of the consequences of placing the white tile is the reduction in heat picked up by the supply air passing through ducting in the attic. Akbari et al. (1997) also showed that reflective roofs for residential and commercial buildings can reduce the cooling load. Their calculations of savings used 11 U.S. metropolitan cities and extrapolated their calculations to project the total savings if such roofs were applied across the whole United States to about $750 million in annual energy payments, while their estimate for the reduction in peak electricity power reduction is around 7 GW.

Other studies have looked at the potential use of ceramic coatings for roofs, such as Parker et al. (1991, 1993, 1997), Allen et al. (1993), Sevegnani et al. (1997), and Petrie et al. (1998), which have also contributed to the experimental knowledge of some of these radiant paint applications in hot and humid climates. With today's shaky electric energy generation potential and sharp increases in energy prices, this technology merits another look to determine its impact when applied to a typical southwestern residence.

Description of Physical and Simulation Model

A simulated home in the Las Vegas area has been chosen as the model with the typical characteristics of a tract home in that area. The single-story home of 182 m^2 (1,950 ft^2) has a plan layout of 20.0 by 9.1 m, a ceiling height of 2.4 m, a roof truss pitch of 4:12, and an attic ventilation rate of about 1:300. The floor is a concrete slab, and the glazing is set at a standard percentage of wall area of about 15%.

The simulation model is assumed to have a typical air conditioning unit that delivers about 0.81 m^3/s (1,800 cfm), where all the supply ducting is placed in the attic space above the insulation. The wall construction is assumed to be wood frame with studs of 5.0 cm by 10.0 cm by 2.4 m nominal dimensions. The insulation placed in the wall cavity was assumed to be R-11 fiberglass batt insulation, and ceiling insulation of R-30 and R-19 was assumed for comparison purposes. The particular ceramic coating radiation characteristics have a solar reflectivity $\rho = 0.8$ and an infrared emissivity $\varepsilon = 0.8$.

The study will focus on three cases: (1) a roof-only coating, (2) an exterior wall coating, and (3) a wall and roof coating. These cases are used to evaluate the resulting differences in cooling load savings when the product is used to cover different structures of the building. The simulation model also uses detailed hourly weather data for the Las Vegas area from a weather tape previously available to the writer that incorporates and blends the yearly data for over 30 years so as to obtain a typical representation of local weather conditions.

The code (residential heat transfer, or RESHEAT) has been developed by the writers over the course of a few years and in response to some of the perceived needs for better analysis in this area of energy conservation. It uses several pieces of information obtained from three CDs provided by the National Oceanographic and Atmospheric Administration (NOAA), such as ambient temperatures, cloud cover, and instantaneous solar insolation, all on an hourly basis, and treats the data as input to the model. Internally the code then recalculates the different direct solar intensities for the different orientations and adds any diffuse solar radiation to the solar flux.

The code is a 1-D transient heat transfer model developed by the writers that uses temperature nodes and the appropriate heat balance equations to describe the heat transfer at over 90 locations around the structure.

The basic heat transfer equation used in this code is as follows:

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{\alpha}\frac{\partial T}{\partial \tau} \tag{1}$$

This equation is the basis of the nodal equations developed using energy balances around the 90 or so nodes that were solved. The energy balance consists of the following basic thermodynamic law in Eq. (2):

$$E^{\bullet}_{\text{in}}+E^{\bullet}_{g}=E^{\bullet}_{\text{out}}+E^{\bullet}_{st} \tag{2}$$

Eq. (1) is subjected to proper boundary and initial conditions to be solved completely. These conditions can be in a variety of forms, such as conduction, convection, or radiation, and can also be a combination of these heat transfer conditions, for example, at the outer surface of the roof [roof tile surface, Eq. (4)]. The surface sees a variety of combined boundary conditions, including radiation [first and second terms on left-hand side (LHS)] and convection (third term, LHS). It is to be noted here that since this is a 1-D model the convection boundary conditions are typically treated by the use of Eq. (3):

$$q_{\text{conv}}=hA(T_s-T_f) \tag{3}$$

Two nodal equations will be presented here to show the variety of boundary conditions that may be involved.

Exterior Roof Node

$$\dot{q}_{\text{solar}}-\sigma\varepsilon_1(T_{\text{sky}}^4-T_1^4)+h_1(T_{\text{amb}}-T_1)+k_{\text{tile}}\frac{(T_2-T_1)}{\Delta x}-(\rho c_p)_{\text{tile}}\frac{\Delta x}{2}\cdot\frac{(T_{1_{\text{current}}}-T_{1_{\text{previous}}})}{\Delta\tau}=0 \tag{4}$$

The last two terms on the LHS are, respectively, conduction through the roof tile and the storage term in that tile.

HVAC Duct (Exterior Surface)

$$\frac{k_{\text{air}}}{D}\mathrm{Nu}_{(\text{free/forced})}(T_{\text{atticair}}-T_s)+k_{\text{insul}}\frac{(T_{\text{duct}}-T_s)}{\Delta x}-(\rho c_p)_{\text{insul}}\frac{\Delta x}{2}\,\frac{(T_{s_{\text{current}}}-T_{s_{\text{previous}}})}{\Delta\tau}+\sum_{j=1}^{N}\Lambda_{s,j}\sigma T_j^4=0 \tag{5}$$

The first term on the LHS is the combined convection term on the outside surface of the duct surface; the second LHS term is conduction through the duct insulation; the third LHS term is thermal storage through the insulation; and the last term is the net radiation term from the attic interior surfaces to the outer surface of the duct.

These nodal locations usually include all the interfaces between the different construction materials and describe overall heat transfer modes that take place inside the attic and the conditioned space by the use of the appropriate conduction, convection, and radiation heat transfer terms simultaneously. The model also considers the thermal storage effects that usually exist in a structure because the heat process through it is of a transient nature when exposed to the solar heat loads.

Hence all the thermophysical properties of the different construction and insulation and roof tiles have been incorporated as part of the input data. The model also considers the heat exchange by radiation from the external surfaces of the structure to the effective sky temperature. Convective heat transfer coefficients are used as correlations from several sources in the heat transfer literature. These correlations incorporate a temperature-dependent expression that is updated as the simulation progresses in real time. The radiation terms are usually not linearized [as seen in Eq. (5), the unknowns are left as high-order polynomials], and hence result in a set of overall nonlinear algebraic equations (implicit scheme) to solve. The solution is completed by using a special subroutine for solving these equations and progressing with the solution in time. The time step is usually chosen for integration purposes, which will achieve a temperature variation of less than 1% in the integrated temperature value after a 24 h period when a smaller time step is chosen.

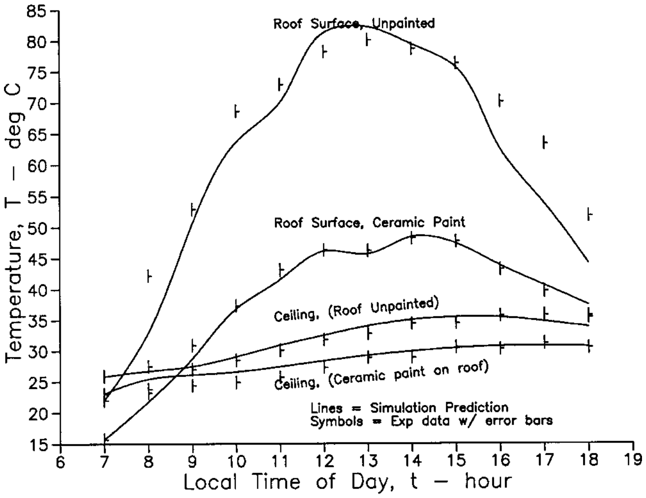

Fig. 1. RESHEAT versus experimental data

Simulation Results

Fig. 1 compares RESHEAT simulation results with some experimental data obtained in the Las Vegas area on two very similar days in a summer season from an earlier set of data. The data are relevant to an extension of a house in Las Vegas that was monitored experimentally and has a gabled roof similar to that of the house simulated in this study. The writers wanted to provide these data to show the quantitative nature of the agreement between the predicted and experimental data as no experimental data were obtained for the present study. This set of data also shows in general the beneficial effect that the paint has in reducing the surface temperatures of the outer roof and ceiling temperatures for a typical residence. This implicitly also gives some confidence that the different thermal mechanisms built into the code are reasonably accurate under transient conditions. Fig. 2 concentrates on two orientations for the walls, east and west, along with the history of the outdoor ambient air temperature for comparison. As expected the temperatures on the east will peak out during the morning hours, while those on the west do so during the afternoon hours. This is of course in line with the generic increase observed for the insolation in these two orientations. The comparison here is for the base case (no paint) versus the case with the reflective paint, and where the insulation in the wall is R-11 and that in the attic is R-30.

Due to the higher absorbed solar energy in the wall (base case), the temperature difference between that case and the coated wall case is significant. In fact, one can notice a difference of around 45°F for the east side versus about a 33°F difference for the west wall. This has to do in part with the fact that on the east side in the morning the ambient air usually has not peaked yet, while the solar absorption would peak early for that orientation. The west side wall has behavior

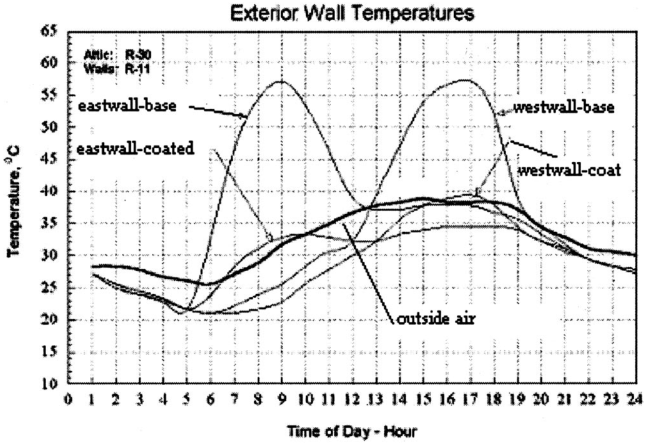

Fig. 2. East and west wall temperatures

very similar to that of the east wall, but now the ambient temperature has picked up several degrees during the morning hours. That difference is about 10°F between 9:00 a.m. and about 5:00 p.m. Notice here that both wall orientations shed their heat and hence lower their temperatures to a value lower than the ambient temperature later at night around midnight. The reason is that all walls are exchanging radiation heat transfer with the effective sky temperature as well. The sky temperature model usually provides an estimate for that temperature, which is a few degrees lower than the ambient instantaneous temperature for a clear night sky.

Fig. 3 presents another interesting result of the application of the coatings to the roof structure. As seen, there is a significant and consistent decrease in the outer surface temperatures of the roof structure as well as the average attic air due to the reduction of heat flow through the whole roof structure. The reduction of these temperatures will play an important role in reducing the overall heat gain to the supply air ducts placed in the attic.

To demonstrate some of the cooling load history, Fig. 4 compares the grand sensible heat (GSH) plot for the four cases considered: (1) coated roof, (2) walls coated, (3) walls and roof coated, and (4) the base case. The GSH is usually defined as the total magnitude of the instantaneous cooling load debited to the space. This includes wall, glass, roof, occupant cooling loads, and in this model, the amount of heat pickup that the supply air ducts usually receive by being placed in a relatively hot environment in the attic. This additional cooling load is due to the fact that the ducts receive heat by radiation and convection from the warm inner surfaces of the attic and the attic ambient air, respectively. This portion is usually not well considered in typical cooling load calculations.

The model assumes that a typical surface area of supply air ducts (obtained from actual duct layouts) exists inside the attic space, and a calculation is made to estimate the heat added to the duct. Some interesting observations are noted here.

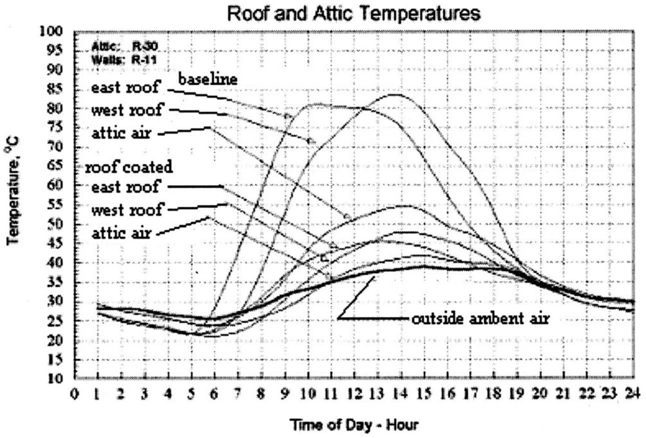

Fig. 3. Roof and attic temperature histories

There are significant differences in this total cooling load among the different cases, especially at the peak value. The largest GSH is for the baseline case (no paint applied), which peaks at around 12,000 W, while the second highest is the coated roof, at about 10,290 W, the third being only the walls coated, at about 8,529 W, and finally the lowest cooling load, when walls and roof are painted, at a value of 7,058 W.

Fig. 5 is a bar plot of the comparative values of the air conditioning run time among the various cases for an extended period of over 2 weeks. In these runs the total cumulative run time for the A/C units is kept track of and reported. The values of insulation are noted on each respective run by designating the insulation

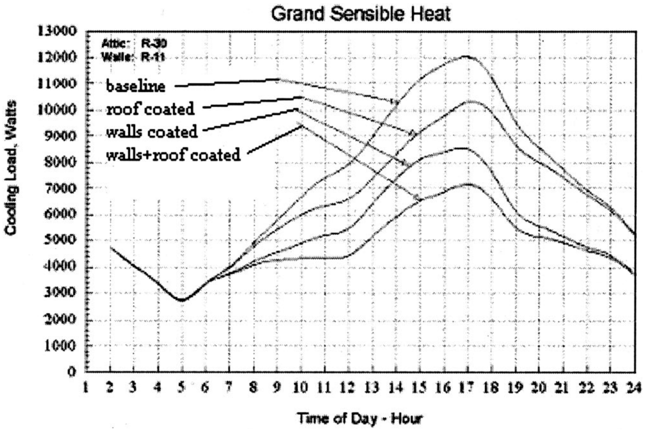

Fig. 4. Grand sensible heat comparisons

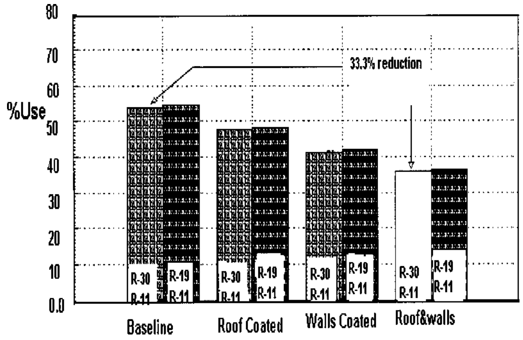

Fig. 5. Air conditioner percentage time usage

placed in the attic as the top number and that in the walls as the bottom one. The designation of what case was run in regard to the application of the coating is displayed on the horizontal axis for clear identification. This run time should also correspond reasonably closely to the electric energy consumed during the run period and would be an indication of potential savings.

A general observation for this figure is that the baseline case with no reflective paint applied shows the highest electric power consumption. This is to a certain degree an expected result. What follows indicates that if the walls are painted as opposed to the roof, that seems to indicate a reduction in A/C use for the first case with respect to the second. This can be partially explained by the fact that the walls usually have a much lower value of insulation than the roof and the attic is somewhat ventilated, which makes the relative benefit of the reflective paint on the walls more than that on the roof. The roof here is also assumed to have a concrete roof tile layer, and these tiles, with a thickness of about 1.75 to 2.0 cm and a density of 2,500 kg/m^3, make for a heavy layer placed over the roof rafters and hence act as a thermal storage system in the direction of the heat flow. The final case studied in this graph is that when both the walls and the roof have a reflective coating, in which case this situation shows the lowest A/C use of the previous three cases. In fact the decrease of the A/C use between this latter case and the baseline case is about a 33.3% reduction. This in some cases could not only be a significant reduction of the energy consumption, but could also justify the use of a smaller piece of refrigeration equipment, which would somewhat reduce the capital cost of the HVAC unit.

One of the heat transfer processes considered in detail in RESHEAT is the heat pickup by the supply air duct when these ducts, as is usually the case, are placed in the attic. The major source of heat is the radiation heat transfer from inside the attic surfaces (which form an enclosure) and the convective heat transfer from the ambient attic air. Fig. 6 shows a detailed plot of this heat pickup for the two cases of baseline versus roof-coated application. For the size of the home considered it suggests a significant decrease of the heat gain in the duct with a reduction of about 5,000 Btu/h at the peak time (1,462 W). Other studies by Moujaes and

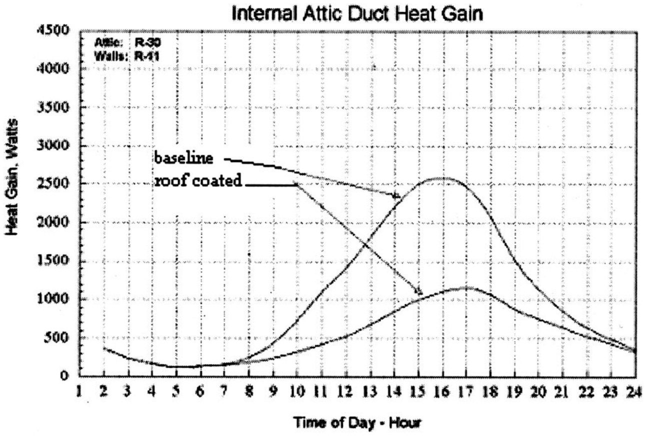

Fig. 6. Duct heat gain difference between baseline and coated roof

Brickman (1998) have shown that the major portion of this heat pickup is due to radiation and not convection from the air surrounding the duct.

Finally, Table 1 summarizes hour by hour the instantaneous cooling loads for a typical July day at the chosen location for the two cases: (1) roof-only coating, and (2) roof and walls coating. These runs show the different percent savings for the majority of the day where the sun is still in the sky. The second case would show the larger percentage savings, with levels reaching as high as 40% at the peak cooling time.

Another item calculated in this simulation is the ''*UA* credit,'' a term derived from the uniform energy code, whose calculations would indicate to a potential builder or owner of a residence what type of *UA* credit would be accrued by using different energy conserving technologies. The *UA* is simply the product of a heat transfer coefficient U by an area A. This quantity usually has been obtained by taking the value of the total heat gain savings listed in Table 1 and dividing it by the instantaneous difference between the outside ambient temperature and the indoor design temperature used in the simulation. This value can theoretically be used by the builder or developer to obtain thermal credits that can be used or spent to allow other architectural esthetic features to be used in the house (that is, larger windows) and still qualify as an energy efficient home.

Unfortunately, when it comes to application of reflective coatings as a general class of energy conservation technologies, this *UA* value is highly sensitive to the location and conditions under which the calculation is made and is not recommended for use in other locations. The basic reason for this is that the basic net reduction of heat transfer is due to the reduction in radiation heat transfer through the structure and is usually a function of the temperature of each of the systems involved in the heat transfer raised to the fourth power, which is to say, highly nonlinear. This is in stark contrast to the credit that may be accrued from the application of more insulation in the walls or roof because the improvement in

Table 1. Summary of UA Credits Calculated from RESHEAT Program

			Grand sensible heat—roof coat only				Grand sensible heat—roof and walls coated			
Time of day (h)	Outside temperature (°C)	Inside temperature (°C)	Baseline grand sensible heat (W)	Heat gain savings (W)	Savings (%)	UA credit (W/C)	Baseline grand sensible heat (W)	Heat gain savings (W)	Savings (%)	UA credit (W/C)
8	29.0	25.3	4,940	137	3	39	4,940	837	17	251
9	32.0	25.3	5,821	356	6	58	5,821	1,547	27	253
10	33.5	25.3	6,716	692	10	89	6,721	2,363	35	304
11	35.0	25.3	7,443	1,055	14	112	7,443	3,048	41	323
12	36.5	25.3	7,967	1,327	17	118	7,967	3,500	44	315
13	37.5	25.3	9,047	1,612	18	146	9,048	3,858	43	316
14	38.0	25.3	10,241	1,869	18	146	10,241	4,289	42	336
15	38.5	25.3	11,233	2,018	18	152	11,233	4,671	42	351
16	38.0	25.3	11,789	1,965	17	[a]154	11,789	4,879	41	382
17	38.0	25.3	12,075	1,734	14	136	12,076	4,882	40	[a]383
18	38.0	25.3	11,250	1,330	12	104	11,250	4,615	41	361
19	37.0	25.3	9,560	877	9	75	9,560	4,030	42	346
20	34.5	25.3	8,570	547	6	61	8,571	3,391	40	382

Note: Location: Las Vegas (36°N, 115°W); Season: Summer (July-typical); Insulation: R-30 ceiling/R-11 walls; Install mode: (1) roof only, (2) roof and wall. Important: The predicted sensible heat reductions and UA credits shown in this table are only valid for the locale and meteorological conditions (temperatures, sun angles, etc.) listed in and at the end of the table.

[a] Highest credit.

the heat resistance of the structure is a direct function of the total value of the resistance of the wall or the roof, which is a physical property of the insulation material and is usually considered a constant under normal heat transfer calculations. Hence a lot of caution is stressed by the writers on the limitations of using this value when doing these thermal credit calculations. The only reason this approach is presented here is to show how sometimes a complicated thermal process is distilled down and evaluated in a simplistic way to assess its energy-conserving potential. The writers do not recommend this approach for evaluating this technology, however.

Conclusions

This simulation study has shown that the application of a highly reflective paint to the outside would definitely decrease the cooling load the air conditioning unit has to remove from the residence to maintain thermal comfort. On a typical day in the summertime, a 41% reduction is shown to exist between the case where the roof and walls are painted compared with the base case. In contrast, only a 17% reduction was seen when only the roof is painted. Usually the cooling capacity of a unit is sized according to its maximum cooling load for the design day conditions. So the results mentioned above there is a potential for decreasing the size of the cooling unit as well. This can decrease the initial cost of the unit as well as running costs. However over the period of several days, including the nighttime simulation, the roof plus wall combination reduces the energy consumption by about 33.3%.

This reduction in the percent savings between 41 and 33% is due to the effectiveness of the technology, which is not expected to extend to the nighttime hours. To give a real picture of the amount of savings in dollars for this technology for the house used in the simulation, it is assumed that the seasonal energy efficiency ratio (SEER) of the A/C unit is around 10 and that the unit runs at about 75% of its peak power demand, with a typical cost of 10 cents/KW·h, using a 4 to (refrigeration) unit. The total savings per month are approximately $42/month. Using an estimated value of 30 cents/sq ft for this material (installed), and assuming that the house including the roof area is about 334 m^2 (3,600 sq ft), then the total cost of the installation is $1,080. Using the assumed energy prices and assuming the A/C unit is used for about 5 months in the Southwest, then the savings are around $210/year. This means that the simple payback period for this application is around 5 years. This calculation did not, however, take into account any potential reduction in the capital cost of the unit or in the size of the ducting, or finally a likely increase in electric energy costs, all or part of which can help to reduce the payback period to less than 5 years.

Another point that has not been discussed and is not part of the simulation at this point is that if the temperatures inside the walls and ceiling are lowered by the reflective coating, then a net improvement in the ‘‘Effective Radiant Temperature’’ (ERT) inside the space can also be achieved. This calculated temperature is the equivalent radiation temperature a typical occupant of the residential space experiences in his or her surroundings when inside the space and at a certain indoor ambient temperature set by the thermostat. Hence a reduction of ERT by this application gives an improved feeling of thermal comfort in the space and hence a possibility of slightly raising the indoor air temperature setting on the thermostat to achieve the same level of thermal comfort. In brief, a reduction of the cooling can be gained by also slightly raising the thermostat setting. It is estimated from the local power company in Las Vegas that for every 1°F increase in the thermostat setting there is a corresponding decrease of about 3% in the electric energy demand of the cooling system. The paints are now commercially available, but still in need of more aggressive marketing. One drawback in some cases to using these paints is more aesthetic for the end user, who may feel too much of the color white on a residence is not desirable. As their use increases, their price for larger jobs is anticipated to decrease, which should help to make them more popular. The energy crunch that the Southwest and probably other parts of the country are seeing would also accelerate the application of these passive energy-conserving technologies.

The comparison shown in Fig. 1 indicates that the code has accurately predicted the major heat transfer phenomena for the intended application and at this point does not warrant a more careful in-depth, parametric sensitivity study of the different inputs that may affect the results of the model in a pronounced way.

Notation

The following symbols are used in this paper:

A = surface area;
C_p = specific heat;
D = duct inside diameter
$\dot{E}$ = rate of energy flow per unit time;
h = convective heat transfer coefficient;
k = thermal conductivity;
Nu = Nusselt number;
q = heat transfer rate;
$\dot{q}_{\mathrm{solar}}$ = rate of absorbed solar energy at outer tile surface;
T = temperature;
x = spatial location;
α = thermal diffusivity;
σ = Steffan-Boltzman constant;
ε = surface emissivity;
ρ = density;
Λ = matrix for view factors; and
τ = time.

Subscripts

Amb = ambient air temperature away from relevant surface;
Atticair = relevant to average air temperature in attic;
conv = convection;
duct = supply duct in attic;
f = fluid;
g = generated;
in = entering;

insul = insulation;
out = leaving;
s = surface;
sky = effective sky temperature for radiation purposes;
st = stored; and
tile = roof tile property.

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