**Title: Comparison of different simulation programs in modeling the energy savings of cool roofs**

**Topic(s): Measurement Techniques and Standards**

**Keywords: cool roofs, building energy simulations, energy savings**

## Abstract

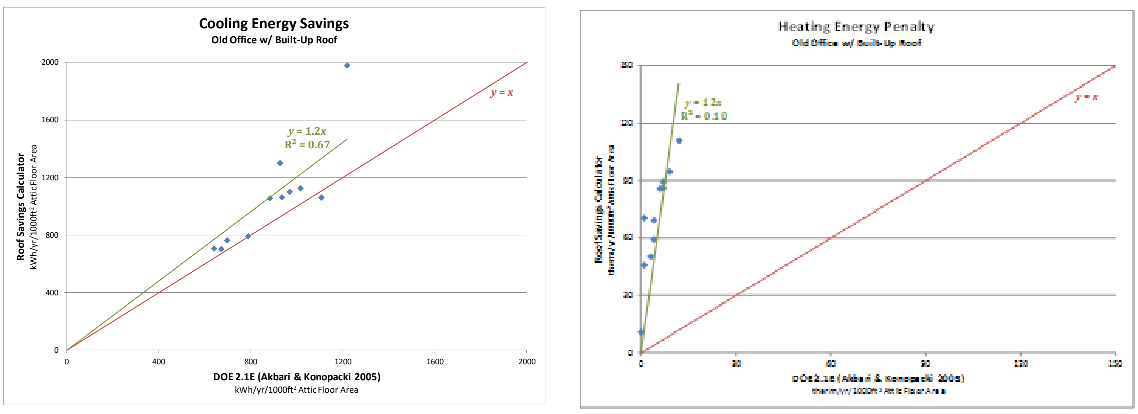
The *Roof Savings Calculator* is a web-based application first developed in 2010 that uses detailed building energy simulations to calculate the energy savings of cool roofs for different building types in over 200 U.S. locations. Although modeling the heat flows of a roof may be straightforward at first glance, modeling the energy savings due to changes in the roof albedo is complicated because it involves modeling the interzone heat transfer between the attic and the conditioned space below. Since direct measurement of energy savings is also problematic, the authors have decided to compare what several independent detailed simulation programs show for the energy savings from cool roof strategies.

## Introduction

The *Roof Savings Calculator (RCS)* is a web-based application developed in 2010 that allows users to calculate the energy performance for changes in the characteristics of the roof/attic system as the roof albedo and construction, attic insulation, etc. The RCS was introduced at the Third IC2UHI conference (New et al. 2014), for which this paper represents an update. The calculations in RCS are done using *doe2attic*, a modified version of the *DOE-2.1E* program (Winkelmann et al. 1993) where the modeling of the attic space has been replaced with *AtticSIM*, a simulation program developed at ORNL specifically for the thermal simulation of attic spaces (Miller et al. 2003).

In the course of developing *doe2attic*, comparisons were done against the original *DOE-2.1E* program previously used to estimate roof energy savings, as well as against *EnergyPlus*, a whole-building simulation program developed later and still maintained by USDOE as their primary simulation tool (Crawley et al. 2003). These comparisons revealed substantial differences, some of which are to be expected for three independently developed programs (*doe2attic*, *DOE-2.1E, and EnergyPlus*) but the magnitude of the differences was unexpected, particularly in the heating penalty during the winter for "Cool Roofs". The previous 2014 IC2UHI paper (New et al. 2014) reported that while the cooling energy savings calculated by the RCS were within 15% with those from a previous 2002 LBNL report, the heating energy penalties were 6-12 times greater (see Figure 1). Because of this difference, the *RSC* showed that "Cool Roofs" would be detrimental in the northern third of the US, whereas the previous LBNL study showed them to be beneficial is all 14 US climates studied.

***Figure 1. Comparison of Cooling Energy Savings and Heating Energy Penalties for Cool Roofs in Old Office Prototype in 14 US Climates (from New et al. 2014)***



This divergence in results led to further investigation to determine which results were closer to actual roof/attic energy performance. In 2015, the authors discovered a mistake in the coupling between *AtticSim* and *DOE-2.1E* whereby *DOE-2.1E* was passing Response Factors that *AtticSim* was interpreting as Conduction Transfer Functions.[1] We also found it difficult to couple the detailed duct model in *AtticSim* back into *doe2attic*, and finally decided to abandon it and use the simpler steady-state duct model in *DOE-2.1E*. The main difficulty with the *AtticSim* duct model was when the feedback of the duct losses were added back into the attic space, the solution was found to be unstable with wild fluctuations in the attic air temperature.

There was also an attempt to compare RSC simulations to monitored data for two test houses in Fresno (Rosada et al. 2014), but the comparisons were inconclusive due to multiple differences between the two houses. Although the objective of Rosada et al. 2014 was to derive the actual energy savings between one house with a roof of typical albedo and another with a roof of high albedo, there were numerous differences between the two houses that made it hard to reach any definitive conclusions. For example, the roof construction of the two houses were different (the standard home had low-albedo asphalt shingles and the cool home high-albedo concrete tiles of higher heat capacity), as were the window construction, size, and orientation, while the measured non-HVAC electricity of the two houses differed by 35%. Although the *doe2attic* simulations were able to match the measured attic temperatures quite closely (see Figure 2), they were off substantially in matching the electricity and gas consumption of the two houses (see Figures 3 and 4).

***Figure 2. Comparison of modeled and measured attic temperatures in two test houses***

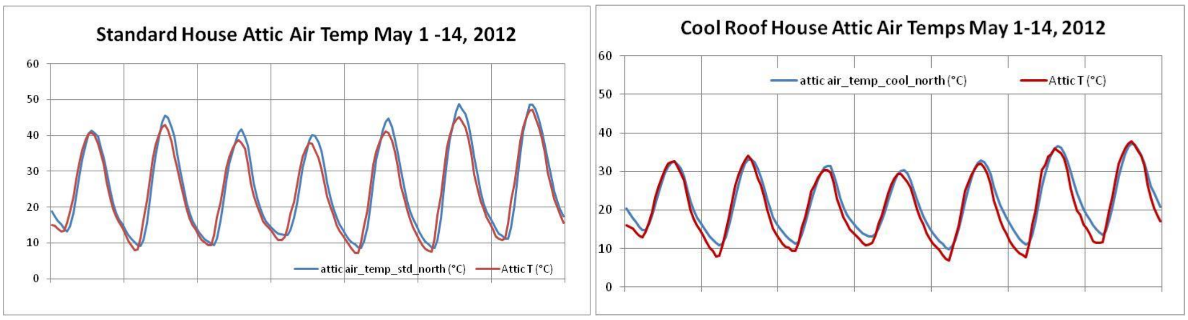
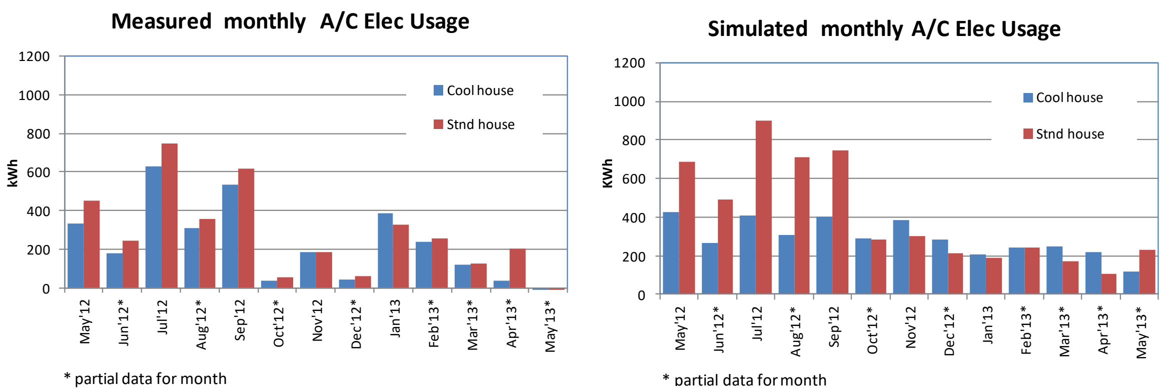
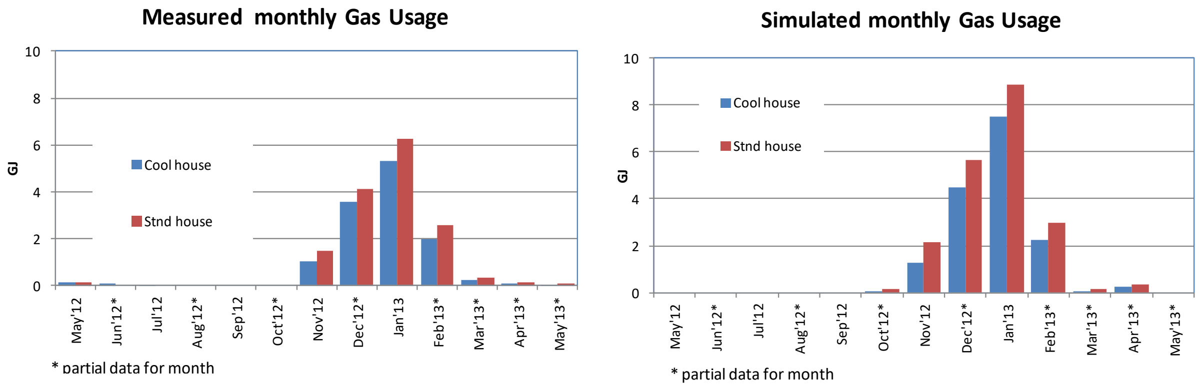



***Figure 3. Comparison of modeled and measured A/C Electricity usage***



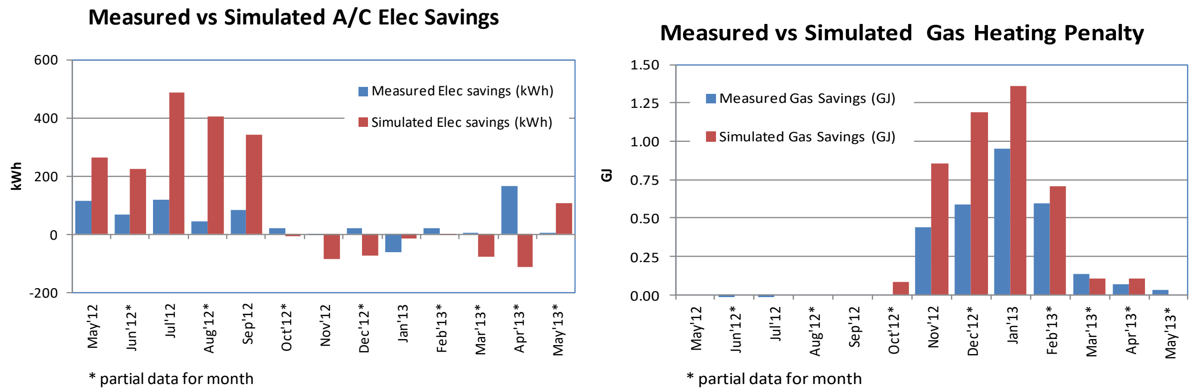

[1] Response Factors and Conduction Transfer Functions are both time-series derivations for modeling dynamic heat flow through a surface, but the time series are written in different forms.

*Figure 4. Comparison of measured and simulated gas usage*




If the differences in energy usage between the two houses are all attributed to the roof albedo, it would be possible to estimate the gas heating penalties or A/C electricity savings for Cool Roofs (see Figure 5). However, there are then such large differences between the measured and simulated energy use data, especially in the A/C electricity savings, that makes it difficult to reach any meaningful conclusions about the accuracy of either the measured or simulated data.

*Figure 5. Comparison of measured and simulated cooling energy savings and heating penalties*




Because of the difficulty in reconciling measured to simulated data, it was felt more fruitful to compare simulation programs to each other, and track the simulations step-by-step to find the cause for the differences in simulated energy savings. This paper will investigate how the following three simulation programs model attic spaces: *DOE-2.1E*, *doe2attic*, and *EnergyPlus*, with other programs such as *CSE TRNSYS*, and *ESPRr* to be added in the future

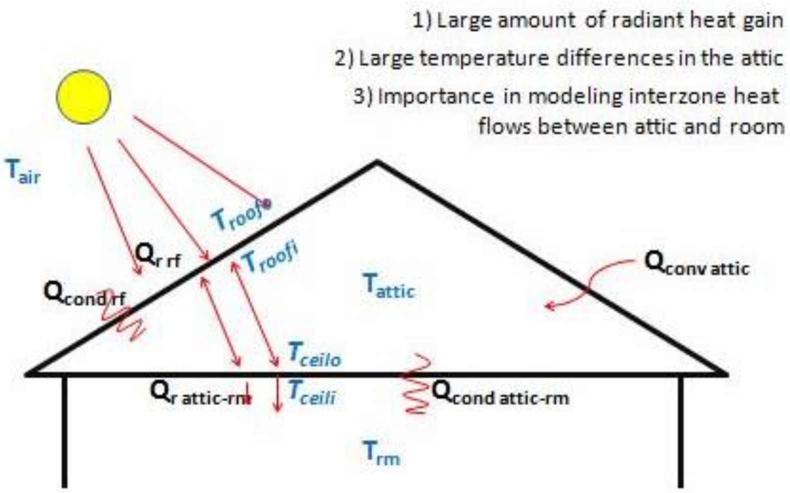
This paper will first describe the differences between how these three programs model heat transfer in the attic and through the attic floor to the space below, and then compare what the programs derive for the attic air temperature, the radiant exchange between the roof assembly and the attic floor, the heat flow through the attic floor, and the energy consumption of the HVAC system. Although modeling the heat flows of a roof may seem straightforward at first glance, deriving the impact on building energy use involves several additional steps, some of which are among the most difficult in building energy simulations. These include: (1) the radiant exchange between the interior surfaces of the attic, (2) the large amount of outdoor air through attic vents necessary to prevent condensation in the winter and overheating in the summer, (3) the heat flow across the attic floor to the space below, and (4) turning the mechanical system on or off to maintain indoor conditions in the space below. The simulations become even more complicated if the ducts are located in the attic, as they typically are in US residences.

It is important to remember that of all the above factors, only the third factor (heat flows across the attic floor to the sapce below) has a direct impact on the energy consumption of the house. Therefore, although most  simulation work have focused rightly on improving the modeling of the attic space and ducts, the calculated  energy performance of attic measures can be equally affected by something as apparently unrelated as the  thermostat control or window venting strategy of the space below. For example, if a house in a mild winter  climate like San Francisco has a night setback schedule, the heating hours would be reduced by a third or more  and the heating energy penalty of a high-albedo roof will be much lowered. Similarly, if the house uses window ventilation or window drapes during the summer, the cooling hours could be reduced to zero, and likewise  the cooling energy savings.

**How are attics modeled in different simulation programs?**

The attic can be described as an unconditioned space attached to the top of the building. Since the roof is exposed to the outdoor environment, including not only the ambient air conditions but also solar radiation  during the day, while the attic floor is sheltered and also buffered by heat exchange with the conditioned  space below, the temperature differences between the interior surfaces of the attic (roof, floor, and gables)  can be as much as 40C on hot summer days and 20C on cold winter nights.   Figure 6 is a schematic drawing of all the heat flow paths through an attic.

***Figure 6. Heat flows paths in an attic.***




***DOE-2.1E.*** In DOE-2, conduction and radiation are not modeled separately, but combined into a single term with a Sol-Air Temperature that produces the same amount of heat flow through exterior surfaces such as the roofs.  DOE-2 also solves only for the zone air temperature and does not track radiative heat exchange between the inside surfaces of the space, such as between the underside of the roof and the topside of the attic floor. The attic air temperature is solved using the Weighting Factor Method that uses computes a time-series for the space (attic) giving the fraction of heat (Q) that appears in the space at each subsequent hour./   Heat flow through the attic floor to the space below is calculated simply as the U-factor times the temperature difference between the attic and the space below.  Like with other simulation programs, the air temperature of the space below the previous time step is used.

***doe2attic***.  In *doe2attic*, the attic simulation is done with *AtticSim*,which is a computer program developed by ORNL for predicting the thermal performance of residential attics and is publicly available as ASTM Standard C1340 (ASTM 2004). AtticSim uses the Heat Balance Method to derive the thermal conditions of the attic, and tracks explicitly conductive, convective, and radiative heat flows.  This is a significant benefit for the accurate modeling of attic heat flows through the attic floor to the space below, due to the significant amount of radiative heat exchange between the underside of the roof and the topside of the attic floor. Since *doe2attic*  models all other spaces using *DOE-2.1E*, the heat flow through the attic floor  is simulated using the air temperature of the space below calculated by *DOE-2.1E* for the previous time step, and fed back to *DOE-2.1E* as an additional load at the same time step.

***EnergyPlus.*** *EnergyPlus* also uses the Heat Balance Method to derive the thermal condition within a zone, making the *EnergyPlus* modeling of an attic equivalent to that done by *AtticSim*. *EnergyPlus* has the additional benefit of allowing shorter time steps from one hour down to five minutes. Such shorter time steps should improve the accuracy of *EnergyPlus* to model the heat flow through the attic when the air temperature of the space below fluctuates, as when there's a night setback in a residential house or when the HVAC in a commercial building is turned off during the off hours.

From the point of view of building science, *EnergyPlus* when used at a subhourly time step, e.g., 15 minutes, would have the highest fidelity in capturing the heat flows of an attic, followed by *doe2attic*, which is limited to an hourly time step, and finally by *DOE-2.1E*, which in addition to using an hourly time step, also does not track the radiant heat exchange within the attic and also models the heat flow through the attic floor as a "Quick wall" with no thermal mass.

**Comparison of Heat Flows and HVAC Energy Consumption simulated by different computer programs**

In order to compare the simulated heat flows and energy consumption of *DOE-2.1E, doe2attic,* and *EnergyPlus*, it was necessary to recreate the building and attic models developed for *doe2attic* in *DOE-2.1E* and *EnergyPlus.* Creating the *DOE-2.1E* models is quite easy, since it shares the same input language as *doe2attic*, with the only difference the extra inputs needed by *AtticSim* to model the attic space and duct system. In fact, *doe2attic* has a built-in debug option that disables *AtticSim* and models the attic and duct sdystem using standard DOE-2. However, creating the *EnergyPlus* equivalent of the *doe2attic* models is much more difficult and time-consuming due to various reasons including: (1) unit conversion, since DOE-2 and AtticSim uses I-P (English) units whereas EnergyPlus uses S-I (metric) unit; (2) differences in how building components like window shades are described, and (3) differences in how controls and operations such as window ventilation, etc., are modeled.

Due to these differences, it has been much more difficult than anticipated to find convergence in the simulated heating and cooling energy use, which will skew the resultant energy savings or penalties from Cool Roof measures. It was not possible to resolve these differences for the draft paper, which if accepted, would be carried out in the following months.

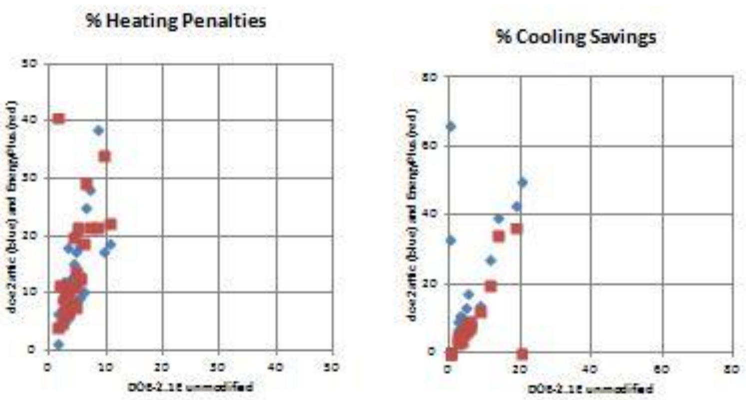
For this draft, the results from *doe2attic, DOE-2.1E* and *EnergyPlus* will be presented as they are, along with observations of the possible causes for the relatively large discrepancies between the first two programs and *EnergyPlus*.

The simulations were done for a suite of 26 test cases, 15 of which are residential buildings in California cliates, and the remaining 11 being medium office buildings in various US climates. For each test case, simulations were repeated for a standard roof of lower albedo, and a Cool Roof of higher albedo, making the total number of 112 simulations. For each simulation, the total heating and cooling energies are recorded, as well as hourly data on the air temperature of the attic and space below, the heat flow through the roof surfaces and the attic fllor or celing to the space below. To make the hourly output data easier to digest, they have been aggregated to average daily profiles for each month.

## Comparison of doe2attic, EnergyPlus, and DOE-2.1E unmodified) for LBNL's test runs

| | | | DOE-2.1E unmodified | | | | | | DOE-2.1E+AtticSim (doe2attic) | | | | | | EnergyPlus V7.0 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Bldg Type | Roof Type | HG MBTU | HG penalty | % HG penalty | CG kWh | CG savings | % CG savings | HG MBTU | HG penalty | % HG penalty | CG kWh | CG savings | % CG savings | HG MBTU | HG penalty | % HG penalty | CG kWh | CG savings | % CG savings |
| GA_Atlanta | modified | bur | 77.30 | 3.60 | 4.7 | 15206 | 83.1 | 5.4 | 73.90 | 6.20 | 8.4 | 15066 | 1418 | 8.6 | 35.62 | 3.52 | 11.0 | 15696 | 1225 | 8.4 |
| CA_Fresno | sold | Asphalt | 20.06 | 0.27 | 1.3 | 1246 | 37 | 3.0 | 21.27 | 1.44 | 6.9 | 1613 | 167 | 10.4 | 6.77 | 0.26 | 4.0 | 1301 | 51 | 3.9 |
| CA_Fresno | sold | Tile | 19.52 | 0.55 | 2.8 | 1106 | 46 | 4.1 | 15.77 | 1.36 | 8.6 | 1343 | 161 | 12.5 | 6.59 | 0.60 | 7.0 | 1330 | 89 | 6.7 |
| CA_Fresno | sold | Metal | 19.41 | 0.65 | 3.3 | 1205 | 56 | 4.6 | 20.79 | 2.57 | 11.4 | 1649 | 290 | 17.6 | 6.84 | 0.56 | 8.6 | 1347 | 100 | 7.4 |
| CA_Arcata | sold | Asphalt | 20.56 | 0.62 | 3.1 | 0 | 0 | 0.0 | 20.31 | 1.61 | 9.3 | 0 | 0 | 0.0 | 22.28 | 1.05 | 4.7 | 0 | 0 | 0.0 |
| CA_Arcata | sold | Tile | 29.62 | 1.18 | 4.0 | 0 | 0 | 0.0 | 21.07 | 2.73 | 12.9 | 0 | 0 | 0.0 | 21.80 | 1.62 | 8.3 | 0 | 0 | 0.0 |
| CA_Arcata | sold | Metal | 29.26 | 1.41 | 4.8 | 0 | 0 | 0.0 | 28.50 | 5.04 | 17.7 | 0 | 0 | 0.0 | 22.53 | 1.71 | 7.6 | 0 | 0 | 0.0 |
| CA_Los-Angeles | sold | Asphalt | 6.75 | 0.21 | 3.1 | 55 | 6 | 10.9 | 5.03 | 0.82 | 16.3 | 58 | 16 | 27.6 | 2.04 | 0.23 | 11.3 | 80 | 16 | 20.0 |
| CA_Los-Angeles | sold | Tile | 6.18 | 0.44 | 7.1 | 46 | 6 | 13.0 | 3.81 | 0.80 | 26.5 | 53 | 21 | 39.6 | 1.95 | 0.42 | 21.5 | 88 | 22 | 34.4 |
| CA_Los-Angeles | sold | Metal | 6.04 | 0.51 | 8.4 | 54 | 10 | 18.5 | 4.34 | 1.58 | 36.7 | 76 | 33 | 43.4 | 2.03 | 0.44 | 21.7 | 104 | 38 | 36.5 |
| IL_Chicago | modified | bur | 141.90 | 3.90 | 2.7 | 10566 | 573 | 5.6 | 138.80 | 6.90 | 5.0 | 10740 | 1006 | 9.4 | 66.82 | 6.03 | 9.0 | 10880 | 1017 | 9.4 |
| CA_Los-Angeles | modified | bur | 15.40 | 1.50 | 9.7 | 10623 | 684 | 6.4 | 14.30 | 2.50 | 17.5 | 11573 | 1639 | 14.2 | 6.73 | 2.31 | 34.3 | 12440 | 1509 | 12.1 |
| TX_Fort-Worth | modified | bur | 51.50 | 2.50 | 4.8 | 19873 | 756 | 3.8 | 49.80 | 4.50 | 9.0 | 20703 | 1331 | 6.4 | 21.30 | 2.94 | 13.8 | 20147 | 1446 | 7.2 |
| TX_Houston | modified | bur | 32.50 | 1.80 | 5.5 | 22354 | 801 | 3.5 | 30.30 | 2.90 | 9.6 | 23670 | 1326 | 5.6 | 13.63 | 1.69 | 12.3 | 22739 | 1425 | 6.3 |
| FL_Miami | modified | bur | 7.40 | 0.10 | 1.4 | 28573 | 801 | 3.5 | 7.30 | 0.10 | 1.4 | 32276 | 1422 | 4.4 | 0.32 | 0.13 | 40.6 | 29736 | 1533 | 5.2 |
| LA_New-Orleans | modified | bur | 28.30 | 1.70 | 6.0 | 22116 | 846 | 3.8 | 26.40 | 2.80 | 10.6 | 22961 | 1361 | 6.1 | 9.59 | 1.61 | 16.9 | 21881 | 1456 | 6.8 |
| NY_New-York | modified | bur | 104.80 | 3.00 | 2.9 | 11196 | 516 | 4.6 | 100.80 | 5.70 | 5.6 | 11765 | 699 | 6.1 | 40.22 | 4.10 | 10.2 | 12316 | 1106 | 9.0 |
| PA_Philadelphia | modified | bur | 105.50 | 3.60 | 3.4 | 11736 | 592 | 5.0 | 102.70 | 6.30 | 6.1 | 12310 | 1033 | 8.4 | 51.68 | 4.92 | 9.5 | 12125 | 1049 | 8.6 |
| AZ_Phoenix | modified | bur | 31.50 | 3.30 | 10.7 | 29103 | 1536 | 5.3 | 20.50 | 3.90 | 19.0 | 29966 | 2596 | 8.7 | 9.63 | 2.15 | 22.4 | 27218 | 2119 | 7.8 |
| MD_Baltimore | modified | bur | 94.40 | 3.50 | 3.7 | 12875 | 634 | 5.0 | 90.70 | 6.20 | 6.8 | 13185 | 1111 | 8.4 | 44.15 | 4.94 | 11.0 | 13093 | 1140 | 8.7 |
| CA_Santa-Maria | sold | Tile | 21.89 | 1.18 | 5.3 | 5 | 1 | 20.0 | 12.76 | 2.39 | 18.7 | 4 | 2 | 50.0 | 11.58 | 1.49 | 12.9 | 1 | 0 | 0.0 |
| CA_Santa-Maria | sold | Metal | 21.26 | 1.38 | 6.5 | 5 | 0 | 0.0 | 16.71 | 4.22 | 25.3 | 6 | 4 | 66.7 | 11.70 | 2.40 | 20.1 | 0 | 0 | 0.0 |
| CA_Daggett | sold | Asphalt | 10.62 | 0.21 | 1.9 | 1961 | 35 | 1.8 | 11.45 | 1.30 | 11.4 | 2499 | 171 | 6.9 | 0.96 | 0.11 | 11.5 | 2426 | 67 | 2.8 |
| CA_Daggett | sold | Tile | 10.27 | 0.44 | 4.2 | 1924 | 43 | 2.2 | 7.96 | 1.23 | 15.4 | 2163 | 200 | 9.2 | 0.96 | 0.19 | 19.8 | 2439 | 115 | 4.8 |
| CA_Daggett | sold | Metal | 10.34 | 0.51 | 4.9 | 1966 | 54 | 2.8 | 11.40 | 2.39 | 21.0 | 2480 | 283 | 11.4 | 0.97 | 0.21 | 21.6 | 2451 | 128 | 5.2 |
| CA_Santa-Maria | sold | Asphalt | 23.58 | 0.56 | 2.4 | 6 | 0 | 0.0 | 16.43 | 2.41 | 12.4 | 3 | 1 | 33.3 | 12.10 | 0.85 | 7.0 | 0 | 0 | 0.0 |

## Comparison of doe2attic, EnergyPlus, and DOE-2.1E unmodified) for LBNL's test runs




Red = EnergyPlus V70
Blue = doe2attic (i.e., RSC)

**CONCLUSIONS**

- The radiative component of ceiling heat flows is very significant and can often be greater than the conduction component.
- The main reason why the results from DOE-2 (and other programs that treat ceiling heat flows as purely conduction) differ from AtticSim and EnergyPlus is that it is missing this radiative component.
- No methodological problem has been uncovered to date on the doe2attic engine, i.e., DOE-2.1E coupled with AtticSim, used in the RSC, outside of input issues with the duct model.
- There is more reason to suspect that the previous DOE-2.1E simulations are incorrect, rather than the current results from RSC.

- More comparisons with measured data should still be done, as are in ORNL's plans, but that should not be a reason for keeping the RSC offline.

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