A WEB-BASED SIMULATION TOOL ON THE PERFORMANCE OF DIFFERENT ROOFING SYSTEMS

Yu Joe Huang¹, Joshua R New², William A Miller², Kenneth W Childs², Ronnen Levinson³
¹White Box Technologies, Moraga CA, United States of America; ²Oak Ridge National Laboratory, Oak Ridge TN, United States of America; ³Lawrence Berkeley National Laboratory, Berkeley CA, United States of America

ABSTRACT

The Roof Savings Calculator (www.roofcalc.com) provides the general public with a web-based program for calculating the energy savings of different roofing and attic systems on four different building types (residential, office, retail, and warehouse) in 239 US TMY2 locations. The core simulation engine of the RSC is doe2attic, which couples the AtticSim program developed by Oak Ridge National Laboratory with the DOE-2.1E program originally developed by Lawrence Berkeley National Laboratory in the early 1980’s and maintained through the late 1990’s. Although simulating heat flows through the roof may seem at first to be easy, modeling the net impact of roofing strategies on building heating and cooling energy use can be challenging. Few simulation programs can model reliably thermal conditions in an attic that has large day-night temperature swings, high ventilation rates, significant radiant exchange between the roof and the attic floor, as well as the complex thermal interactions between the ducts and the attic air and inside surfaces.

The doe2attic program has been tested against detailed measurements gathered in two residential buildings in Fresno, California from cooling energy use to air and surface temperatures, and heat fluxes of the roof and attic floor. The focus of this paper is on the doe2attic simulation program, and not the RSC user interface that has been described in other papers.

INTRODUCTION

The Roof Savings Calculator (RSC) is a web-accessible tool that leverages the AtticSim program for advanced modeling of modern attic and cool roofing technologies, in combination with hour-by-hour whole building energy performance provided by DOE-2.1E, to provide simulations that quantify annual energy and cost savings between a customizable baseline building and a cool-roof building. RSC was developed beginning in 2009 through collaborations among Oak Ridge National Laboratory (ORNL), White Box Technologies (WBT), Lawrence Berkeley National Laboratory (LBNL), and the Environmental Protection Agency (EPA) in the context of a California Energy Commission (CEC) Public Interest Energy Research (PIER) project to make cool-color roofing materials a market reality. The RSC was developed to replace DOE’s Cool Roof Calculator (DOE 2015) and EPA’s Energy Star Roofing Calculator (EPA 2012).

The primary objective in developing RSC was to provide a web-based tool with which users can easily estimate realistic cooling energy savings that can be achieved by installing Cool Roofing products on the most common residential and commercial building types in the US stock. Other goals included educating the public with regard to cool roofing options, helping manufacturers of cool-color materials deploy their products, and assisting utilities and public interest organizations to refine incentive programs for Cool Roofs. The first version of the RSC was completed in 2012, but the validation described in this paper was not done until 2014.

THE DOE2ATTIC PROGRAM

The RSC uses doe2attic as its simulation engine, which is a coupling of two simulation programs, each well-established in its domain – AtticSim for modeling attics, and DOE-2.1E for modeling whole buildings. By combining the two programs, the RSC is able to model in detail the thermal processes in the attic, including the effects of the duct system, and then calculate the impact these processes would have on the thermal comfort and energy usage of the entire building. In doe2attic, AtticSim has been modified into a large subroutine within DOE-2.1E that is called during the SYSTEMS module and returns to the main program the heat flows through the ceiling to the space below, as well as the heat losses or gains for any ducts that pass through the attic space. All the input data needed by AtticSim, such as the ambient outside conditions, the physical descriptions of the attic and the duct system, the air temperature of the room below, the supply air temperature, flowrate, and fraction ontime of the duct system, etc., are all extracted from or calculated by DOE-2.1E. The following three subsections briefly describe AtticSim and DOE-2.1E, and how the two programs have been coupled.

a. Description of AtticSim

AtticSim is a computer tool for predicting the thermal performance of residential attics. The code is publicly available as ASTM Standard C1340 (ASTM 2004). It mathematically describes the conduction through the gables, eaves, roof deck, and ceiling; the convection at the exterior and interior surfaces; the radiant heat exchange between surfaces within the...
attic enclosure; the heat transfer to the ventilation air stream; and the latent heat effects due to sorption and desorption of moisture at the wood surfaces. Each of these heat flow paths is solved separately using methods either based on the literature or developed at ORNL. Conduction is calculated using conduction transfer functions, convection using correlations in the literature, radiative exchange with the enclosure method using first principles equations, as is ventilation using a method by Peavy.

To simplify the simulation of radiant heat exchange, AtticSim assumes fixed view factors between seven attic surfaces (2 roofs, 2 gables, 2 eaves, and 1 floor/ceiling) and the ducts (if they are located in the attic). Thus, AtticSim is limited to modeling only flat (e.g. commercial), open gable, saltbox, or shed roofs. Heat balance equations are used to combine the heat flows at the inside and outside surfaces and on the attic air mass. For a thorough description of the equations and their implementation in AtticSim, please refer to ASTM 2004.

Because of the strong interaction between the attic and any ducts located there, AtticSim also has an algorithm for predicting the effect of air-conditioning ducts in the attic (Petrie et al. 2004). Typical construction places ductwork within the attic, which can triple the loads for the attic assembly for moderately leaky ducts (Petrie et al. 2004, Parker et al. 1993). AtticSim models the impact of conduction, leakage, surface convection, and radiative exchange between the ducts and the attic surfaces, even when the HVAC system is turned off, but does not calculate pressure or air loop connections. Petrie et al. 1998 validated the duct algorithm in AtticSim against experimental data for an attic assembly tested first without and then with a radiant barrier attached to the underside of the roof deck. Validations showed the duct algorithm predicted the duct air temperature change (inlet-to-outlet of the supply duct) within ±0.2°C (±0.3°F) of the test results.

AtticSim was the subject of an extensive field validation conducted by Ober and Wilkes (1997) for ASHRAE, which provides mathematical documentation of the code and validation results for low-slope and steep-slope field data collected from seven different field sites. The code was later validated for steep-slope asphalt shingle and stone-coated metal roofs (Miller 2006). AtticSim was also benchmarked against clay and concrete tile and painted metal roof and attic assemblies that exhibit above-sheathing ventilation (i.e., roof on a roof) where heat in an inclined air space is carried by buoyant air away from the roof deck and out the roof ridge (Miller et al. 2007).

b. Description of DOE-2.1E

DOE-2.1E is a whole-building energy simulation program that was originally developed by Lawrence Berkeley National Laboratory in the early 1980s (Version 2.1A) (LASL 1980, LBL 1982), with continued development through 1993 (Versions 2.1B through 2.1E) (Winkelmann et al. 1993). DOE-2.1E is the most recent version in the public domain, although there have been later efforts and user-interfaces developed by private companies.

DOE-2 operates on an hourly time-step, and uses Response Factors to model the dynamic heat flows through the building envelope. At the zone level, DOE-2 uses Weighting Factors (also called Zone Response Factors) to model the dynamic response of the space, taking into account its thermal mass or capacitance, heat loss through radiation and convection. DOE-2 is made up of two programs, an input processing program called doebdl and a simulation program called doesim, which in turn contains four separate modules that are invoked sequentially. The LOADS module simulates the heat flows in and out of the building and calculates the net balance at a fixed reference temperature, where negative is interpreted as a heating load and positive as a cooling load. The SYSTEMS module takes the results from LOADS, simulates the operation of the HVAC system, and derives the actual zone temperatures, amount of heating and cooling provided by the system, and the energy consumed. If the building has a central plant, the heating and cooling demands from SYSTEMS are passed to the PLANT module that simulates the energy consumed by the plant to meet the SYSTEMS demands. The version used for doeattic is DOE-2.1E Version 124, released by LBNL in April 2004.

c. Combining AtticSim with DOE-2.1E

DOE-2.1E and AtticSim are both written in FORTRAN and the method of integration primarily relies upon the idea of using the attic floor/ceiling as a boundary condition for interaction between the two programs, except that heat losses and gains in the duct systems are added directly to the zone air below. For all simulations, the attic floor/ceiling is assumed sealed with no air leakage crossing from the conditioned space into the attic. The heat flows at the attic’s roof, gables, eaves, and floor are calculated in AtticSim using the thermal response factor technique by Mitalas and Stephenson (1981), whereby the dynamic response of a layer is modeled using Conduction Transfer Functions (CTF), while the heat gain to the space is modeled using the heat balance technique. DOE-2.1E uses a similar technique of Response Factors (RF) to calculate heat flows through the building envelope, but uses Weighting Factors (WF), which is a parameterization of a heat balance solution, to model the heat gain to the space.

In doe2attic, new subroutines have been added to doebdl and doesim (now called doe2attichdl and doe2atticsim) to extract the descriptions of the attic space and surfaces and reformat them as AtticSim inputs. For example, the attic surface RFs calculated by doe2attichdl are transformed to CTFs before they are passed to AtticSim. Since there are many
2) Correction to HVAC “on Time” Fraction

When AtticSim calls the transient duct subroutine (DUCTTR) to calculate performance for an hour it supplies a variable (ONTIME) giving the fraction of time during the hour that the HVAC system is on. AtticSim calculates the number of cycles per hour using Eq. 3. A plot of the number of cycles per hour versus the specified on time is shown in Fig 1.

\[ N_{cycles} = 3 \times 4 \times ONTIME \times (1 - ONTIME) \tag{3} \]

Unfortunately, this procedure did not guarantee that the specific on time is achieved for the hour, because a cycle might not be complete during the hour. To correct this discrepancy, AtticSim was modified to always have an integer number of cycles per hour as illustrated in Figure 2.

Figure 1. Cycles per hour as a function of ONTIME

The time that the HVAC is on during a cycle is given by Eq. 4, and the time that it is off is given by Eq. 5

\[ t_{on} = ONTIME / N_{cycles} \tag{4} \]
\[ t_{off} = (1 - ONTIME) / N_{cycles} \tag{5} \]

During the course of the project, new insights were gained and improvements made in modeling of duct losses. These are described in detail in Miller et al. 2014, and summarized below:

1) Correction to HVAC Loads due to ducts

Any net mass gain or loss in the conditioned space due to leakage in the ducts has to be compensated. If leaks from the supply ducts exceed leaks into the return ducts then air is drawn into the conditioned space from the outdoors to make up the net difference.

\[ \dot{Q}_{ducts} = \sum_{i=1}^{n_{ducts}} (\dot{m}_{in,c_p}T_{in} - \dot{m}_{out,c_p}T_{out})_i + \dot{m}_{net,c_p}T_{outdoor} \tag{1} \]

If leaks into the return ducts exceed leaks from the supply ducts then indoor air has to be exhausted from the conditioned space to make up the net difference.

\[ \dot{Q}_{ducts} = \sum_{i=1}^{n_{ducts}} (\dot{m}_{in,c_p}T_{in} - \dot{m}_{out,c_p}T_{out})_i - \dot{m}_{net,c_p}T_{indoor} \tag{2} \]

2) Change in Duct Length for Large Buildings

When performing its energy balance calculation on a duct AtticSim divides the duct length into a number of equal-length segments. Each segment has a maximum length of 1 foot, and there are a

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1 The reason for this fixed attic geometry has to do with the heat balance solution in AtticSim. There has been some exploratory work with having flexible attic geometry, which is beyond the scope of this project.
maximum of 100 segments. Thus the maximum length for any duct was 100 feet. However commercial buildings commonly have duct runs much greater than 100 feet in length, so there was a need to remove this restriction from AtticSim in order to simulate large buildings. Two alternatives were considered: (1) keep the 1 foot segment length but increase the number of segments or (2) keep a maximum of 100 but increase the segment length. Both approaches have shortcomings. Increasing the number of segments will drastically increase the time required to run a simulation. Increasing the segment length can introduce inaccuracies in the calculations – particularly near the duct entrance where temperatures may be changing rapidly along the duct length. Thus, a third hybrid approach was implemented where the segment length is 1 foot at the duct entrance but each segment along the duct is progressively longer than the previous segment. This allows the code to handle the rapidly changing condition near the entrance, while limiting the number of segments by having longer segments further down the duct where change is much more gradual. Figure 3 shows the required growth factor to obtain the desired duct length using 100 segments. Also shown in the figure is the equation used by AtticSim to calculate the growth factor. This modification was tested by comparing results from a version of AtticSim where the number of 1-foot segments was increase to give the desired length to a version with 100 segments with increasing length down the duct. For the cases tested the two versions gave essentially the same results for duct lengths up to 1000 feet, but the case with 100 increasing-length segments runs much faster.

![Equation used for model growth factor](image)

**Fig 3. Equation used for model growth factor**

**VALIDATION OF DOE2ATTIC**

Although there have been multiple studies comparing AtticSim and DOE-2.1E separately to measured data (Parker 2005, Sullivan and Winkelmann 1998), there is still a need to validate the combined doe2attic program, particularly for the impact of roof measures on HVAC energy use. This is particularly true for building energy modeling, since input parameters and in this case, the “handshaking” between two complex programs, can cause large discrepancies between the simulated results and measured data even if the fundamental algorithms are sound.

Empirical validation of doe2attic addressing not only the simulation program, but also the modeling methodology, was done using measured data obtained by one of the co-authors for two similar houses in Fresno CA with different roof conditions that were monitored for a year from May 2012 through April 2013 (Rosado et al. 2014). Since the objective of that monitoring effort was to measure the thermal performance and energy usage for two roofing systems, the data set was particularly detailed for the attics, making it particularly useful for validating the doe2attic program.

Detailed descriptions of the two houses, their operations and indoor conditions, monitoring instrumentation, and a summary of the monitored results are provided in Rosado et al. 2014. To use the measured data to validate doe2attic, the lead author created detailed computer models of both houses based on the information in Rosado et al. 2014, supplemented by additional information provided by a co-author. These models were then simulated in doe2attic using the onsite weather data, and the results compared to the monitored data that included the surface temperatures of the roof, attic and room air temperatures, ceiling heat flux, return air temperature and relative humidity, and electricity use (Rosado et al. 2014).

a. **Description of the two houses**

The two monitored houses are typical new construction located in a residential development on the outskirts of Fresno California. They were actually “show homes” during the monitoring period that were unoccupied but kept on a fixed operating schedule for space conditioning and lighting, with no other internal loads except for intermittent customer foot traffic. In the computer models of the houses, the metered non-HVAC electricity was converted into internal loads schedules. As indicated in Table 1, the main difference between the two houses is in their roofing systems, where the Standard Home has asphalt shingles with an albedo of 0.07, while the Cool Home has light-colored concrete tiles with an albedo of 0.51.

b. **Onsite weather data**

Fresno has a subtropical climate characterized by relatively mild winters, but hot moderately humid summers with large diurnal swings. An onsite weather station had been installed that recorded temperature, humidity, and global horizontal solar radiation. For many technical reasons, there were

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2 The equation was obtained by curve fit using the commercial software package TableCurve 2D.
Table 1. Summary of house characteristics

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard Home</th>
<th>Cool Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living floor area (m²)</td>
<td>187</td>
<td>189</td>
</tr>
<tr>
<td>Number of stories</td>
<td>1</td>
<td>Same</td>
</tr>
<tr>
<td>Ceiling height (m)</td>
<td>2.74</td>
<td>3.05</td>
</tr>
<tr>
<td>Frame construction</td>
<td>Wood</td>
<td>Same</td>
</tr>
<tr>
<td>Roof Type</td>
<td>Asphalt shingle</td>
<td>Concrete tile</td>
</tr>
<tr>
<td>Initial albedo</td>
<td>0.07</td>
<td>0.51</td>
</tr>
<tr>
<td>Mass (kg/m²)</td>
<td>17.3</td>
<td>47.4</td>
</tr>
<tr>
<td>Thermal capacity (kJ/m²-K)</td>
<td>21.8</td>
<td>39.8</td>
</tr>
<tr>
<td>Waterproofing layer and deck</td>
<td>black felt over plywood sheathing</td>
<td>Same</td>
</tr>
<tr>
<td>Slope</td>
<td>18.4°</td>
<td>22.6°</td>
</tr>
<tr>
<td>Air gap height (cm)</td>
<td>No gap</td>
<td>1.9 - 4.4</td>
</tr>
<tr>
<td>Attic Total ventilation area (m²)</td>
<td>1.66</td>
<td>1.62</td>
</tr>
<tr>
<td>Gable end vent - qty. x area (m²)</td>
<td>2 x 0.25</td>
<td>4 x 0.17</td>
</tr>
<tr>
<td>Eave vent - qty. x area (m²)</td>
<td>20 x 0.04</td>
<td>19 x 0.04</td>
</tr>
<tr>
<td>Dormer vent - qty. x area (m²)</td>
<td>6 x 0.06</td>
<td>3 x 0.06</td>
</tr>
<tr>
<td>Radiant barrier</td>
<td>None</td>
<td>Same</td>
</tr>
<tr>
<td>Insulation (m²·K/W)</td>
<td>Roof</td>
<td>3.3</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>3.3</td>
<td>Same</td>
</tr>
<tr>
<td>Ducts</td>
<td>1.1</td>
<td>Same</td>
</tr>
<tr>
<td>Windows</td>
<td>Construction</td>
<td>2-pane, low-E</td>
</tr>
<tr>
<td>U-factor (W/m²-K)</td>
<td>1.9 - 2.0</td>
<td>1.6 - 1.7</td>
</tr>
<tr>
<td>Area (m²)</td>
<td>South</td>
<td>3.25</td>
</tr>
<tr>
<td>South</td>
<td>4.74</td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>3.40</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>11.90</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>11.00</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26.30</td>
<td></td>
</tr>
<tr>
<td>HVAC system</td>
<td>Estimated COP (Wh/Wh)</td>
<td>3.5</td>
</tr>
<tr>
<td>Air conditioner</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Cooling capacity (kW)</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>Gas furnace</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>AFUE (%)</td>
<td>92.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Same</td>
<td></td>
</tr>
</tbody>
</table>

Ref: Rosado et al. 2014

significant amounts of missing data. Since this weather station did not contain an anemometer, wind speed data were obtained from the nearest California Irrigation Management Information System (CIMIS) station located 2 km to the west. Data from the nearest major weather station (Fresno Yosemite International Airport, WMO 723890) were also obtained to be used for filling missing data and evaluating the quality of the onsite weather data.

The differences in temperature and wind speed seemed explainable due to the local terrain factors (see Figure 4 for dry-bulb and dewpoint temperatures, Figure 5 left for wind speeds). However, the locally measured global solar radiation under clear skies was found to be consistently 9% higher than that calculated using the 2009 ASHRAE Clear Sky Model (ACSM09, Gueymard and Thevenard 2013).

According to the co-author, the radiation sensor (LiCor) had not been calibrated, so it was felt that the ACSM09 was more likely to be correct, and the measured solar lowered by 9% when used to produce the final weather file. This modification was further corroborated when satellite-derived solar data was obtained for the same time (May – Dec 2012) and location from CPR 2015, and found to correlate very well with no visible bias (see Figure 5 right). From this analysis, the weather data is judged to be quite reliable for the site.

c. Comparison of simulated and measured attic air temperatures

Figures 6 and 7 show the simulated and measured attic air temperatures in the Standard Home during the summer and the winter, while Figures 8 and 9 show the same in the Cool Home. The simulated temperatures were found to be extremely close to the measured temperatures, although the simulated nighttime minima were a few degrees lower.
d. Comparison of simulated and measured ceiling heat fluxes

Figures 10 and 11 show the simulated and measured ceiling heat fluxes in the Standard Home during the summer and the winter, while Figures 12 and 13 show the same in the Cool Home. Although the simulated agreed well with the measured heat fluxes in the Cool Home attic, they were noticeably dampened in the Standard Home attic. The contribution of radiant exchange is being evaluated.

e. Comparison of simulated and measured room air temperatures

Figures 14 and 15 show the simulated and measured room air temperatures in the Standard Home during the summer and the spring. Since the room temperatures are simulated not by AtticSim but by DOE-2.1E, these plots are in fact a validation of the DOE-2 room model. Figure 15 shows that during the swing season the DOE-2 room model is floating a degrees or more higher than shown in the measured data.
f. Comparison of simulated and measured A/C electricity consumption

Figures 16 and 17 show the simulated and measured A/C electricity usage in the Standard Home during the summer and the spring. Despite the higher floating temperatures shown in Fig. 15, the modeled A/C electricity usage during the spring is actually lower than that of the measured usage.

Figures 18 and 19 compare the simulated and measured A/C electricity usage for the entire monitoring period. The simulated usages are 8% and 13% lower than the measured usages for the Standard Home and Cool Home, respectively.
CONCLUSIONS

The first version of the RSC went online in late 2012, although the testing and validation described in this paper was not started until 2014 and is still ongoing. The wealth of monitored data permitted a level of detail in the validation that helped justify algorithmic behavior but also raised additional complexities and challenges. Although the calculator shows close correlation with attic air temperatures, indicating that AtticSim is modeling correctly attic heat transfer, the discrepancy in the Standard Home ceiling heat fluxes remains unexplained. Since many of the boundary conditions (roof surface temperatures and heat flows, etc.) have been defined, efforts are focused on ensuring proper physics rather than empirical correction factors.

For RSC users interested in cool roofs, the comparison of simulated to measured cooling electricity consumption indicates relatively small underpredictions of 8-13%. Although it is easy to further reduce this difference by slight adjustments to uncertain parameters such as thermostat setpoint, internal-loads intensity, or window shading schedule, current efforts are focused on modeling and expected trends between sets of measured data.

Thus, the main objective of this validation is to verify that doe2attic is working as designed, and that the results are in accordance with the authors' understanding of building physics.

REFERENCES


