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In-Depth Analysis of Simulation Engine Codes for Comparison with DOE's Roof Savings Calculator and Measured Data

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Energy and Transportation Sciences Division

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ABSTRACT

The Roof Savings Calculator (RSC) was developed through collaborations among Oak Ridge National Laboratory (ORNL), White Box Technologies, Lawrence Berkeley National Laboratory (LBNL), and the Environmental Protection Agency in the context of a California Energy Commission Public Interest Energy Research project to make cool-color roofing materials a market reality. The RSC website and a simulation engine validated against demonstration homes were developed to replace the liberal DOE Cool Roof Calculator and the conservative EPA Energy Star Roofing Calculator, which reported different roof savings estimates.

A preliminary analysis arrived at a tentative explanation for why RSC results differed from previous LBNL studies and provided guidance for future analysis in the comparison of four simulation programs (doe2attic, DOE-2.1E, EnergyPlus, and MicroPas), including heat exchange between the attic surfaces (principally the roof and ceiling) and the resulting heat flows through the ceiling to the building below. The results were consolidated in an ORNL technical report, ORNL/TM-2013/501.

This report is an in-depth inter-comparison of four programs with detailed measured data from an experimental facility operated by ORNL in South Carolina in which different segments of the attic had different roof and attic systems.

1 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 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 website [1] and a simulation engine validated against demonstration homes were developed to replace the liberal DOE Cool Roof Calculator [2] and the conservative EPA Energy Star Roofing Calculator [3], which reported different roof savings estimates.

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. Goals included developing a fast simulation engine benchmarked against cool-color roofing materials, educating the public with regard to cool roofing options and savings, helping manufacturers of cool-color materials deploy their products, and assisting utilities and public interest organizations to refine incentive programs for cool roofs. The recent emphasis on domestic building energy use, market penetration for cool roofing products, and job creation has made the work a top priority of the Department of Energy's (DOE) Building Technologies Office (BTO).

2 ATTIC MODELS

Various models have been developed that simulate attic thermal performance [39]. A steady state attic heat balance model was created by Joy (1958) which solved a series of simultaneous differential equations for inside and outside boundary conditions while not accommodating capacitance, temperature-dependent heat transfer coefficients, or heat transfer through non-roof/non-floor surfaces.

A transient attic simulation model for the Electric Power Research Institute was created by Blancett et al. (1970). TRNSYS (1978) and NBSLD (1981) were three-hourly simulation models designed to calculate dynamic attic thermal performance. Peavy (1979) developed a more comprehensive transient attic model providing a more realistic simulation than previous models.

Wilkes modified Peavy's model to include gabled roof ends and various other improvements. Between 1989 and 1991, ORNL developed the ASTM C-1340 procedure response-factor computer calculation method to estimate heat gain or loss through residential ceilings.

In 1988, Fairey and Swami developed a simplified steady-state model, and Parker et al. in 1991 created a transient, stratified air model for attic thermal performance simulation. This formed the conceptual framework of the FSEC 3.0 attic model.

In 1997, TenWolde developed a detailed thermal and moisture model for the Forest Products Laboratory. A residential attic was created by the Florida Solar Energy Center in 1999 within DOE-2 for the software EnergyGauge USA.

3 PRELIMINARY ANALYSIS OF DOE'S ROOF SAVINGS CALCULATOR

From 2009 to 2011, WBT worked with ORNL to create the RSC, an easy-to-use Web-based calculator for estimating the energy impacts from various roof and attic strategies on the heating and cooling energy use of four building types—residential, office, retail, and warehouse—in 239 US locations. WBT's main responsibility in that project was to develop a custom program, doe2attic, for simulating roofs and attics by linking the DOE-2.1E (doesim) whole-building simulation program with ORNL's AtticSim program. RSC was planned as an industry-consensus energy-savings calculator that companies and national laboratories could use to promote the energy benefits of cool roofing products. After the initial RSC roll-out in mid-2011, questions were raised because the results produced by RSC for "cool roofs" had some differences from previous studies, especially those reported by LBNL. Although RSC calculated cooling savings were similar to those from previous LBNL studies, it also calculated significant penalties during the heating season, which the LBNL studies showed to be very small.

After RSC went online on April 22, 2010, LBNL's Heat Island Group used it to estimate the energy savings from cool roofs in residential buildings in various California climates and in commercial buildings (medium-sized office) in various US climates. They found that, compared with earlier studies done at LBNL [23],[24],[25], the cooling savings were within 15% of each other; but the heating penalties were 6–12 times larger in RSC. Note that this discrepancy is in part due to the fact that the heating penalties in the previous LBNL studies were small in absolute terms but a large percentage in relative terms. RSC showed average heating penalties to be up to 60% of the cooling savings; the LBNL study showed them to be 5%.

A project was implemented to validate RSC in two ways:

(1) The computer simulations behind RSC (doe2attic) were compared against three other simulation programs—EnergyPlus, DOE-2.1E, and MicroPas. EnergyPlus is a whole-building simulation program currently supported by DOE, and DOE-2.1E and MicroPas were used in the previous LBNL studies for roofs in commercial and residential buildings, respectively. This effort was documented in the ORNL report ORNL/TM-00002013/00501.

(2) The same four programs were compared with detailed measured data from an experimental facility operated by ORNL in South Carolina in which different segments of the attic have different roof and attic systems. Most of the present report consolidates part two of the comparison study.

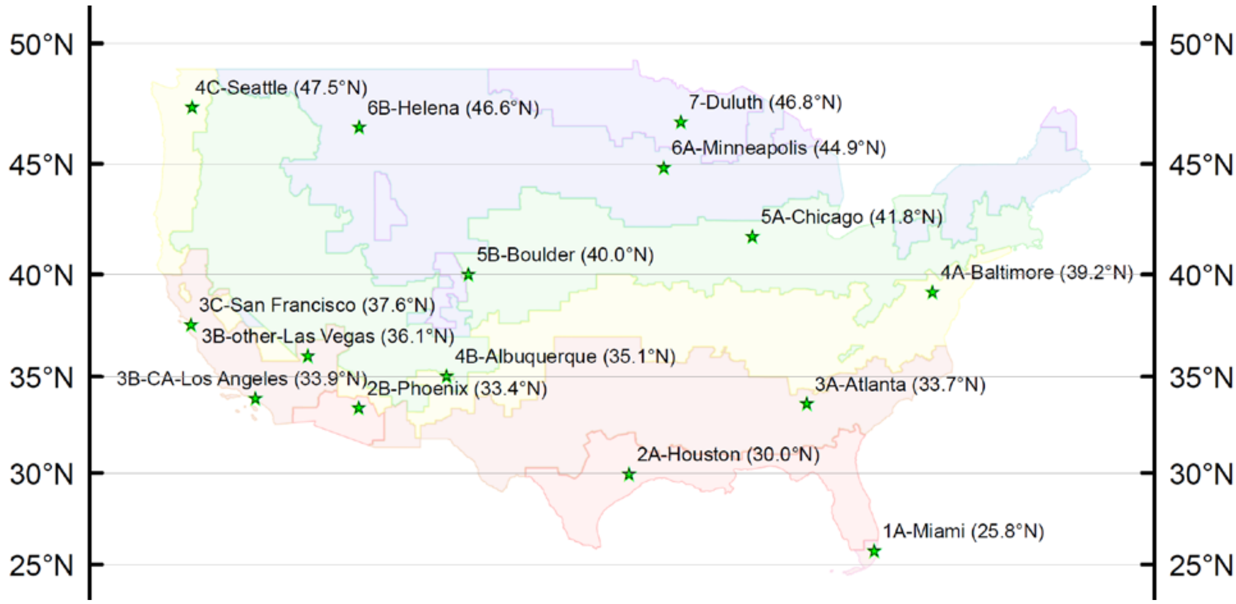


Figure 1. Sixteen cities that represent ASHRAE climate/subclimate zones.

4 PRELIMINARY COMPARISON OF RSC TO OTHER SIMULATION ENGINES

4.1 SIMULATION PROGRAMS

4.1.1 DOE-2.1E

DOE-2.1E [4] is a whole-building energy simulation program originally developed by LBNL in the early 1980s (Version 2.1A) [5]. Its development continued through 1993 (Versions 2.1B through 2.1E) [6]. DOE-2.1E is the most current version of DOE-2 in the public domain, although there are later efforts and user interfaces developed by private companies. Counting its many versions and user interfaces, DOE-2 is the most widely used building energy simulation program in the world today.

Although DOE stopped all support for DOE-2 in 1999, WBT and others have continued to maintain it and even add features to it. For example, Huang [7] added an improved foundation model to the code at the request of the CEC. Once LBNL approves making DOE-2.1E open source, WBT intends to create an Open Source Center for Building Simulations to maintain the DOE-2.1E software for the community of building scientists and practitioners.

4.1.2 AtticSim

AtticSim is a computer tool for predicting the thermal performance of residential attics. The code is publicly available as an ASTM protocol [8]. It mathematically describes conduction through the gables, eaves, roof deck, and ceiling; convection at the exterior and interior surfaces; radiant heat exchange between surfaces within the attic enclosure; heat transfer to the ventilation air stream; and latent heat effects due to sorption and desorption of moisture at the wood surfaces. Solar reflectance, thermal emittance, and water vapor permeance of the sundry surfaces are input. The model can account for different insulation R-values and/or radiant barriers attached to the various attic surfaces. It also has an algorithm for predicting the effect of air-conditioning ducts placed in the attic [9].

AtticSim was the subject of an extensive field validation conducted by Ober and Wilkes for ASHRAE [12] that 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 [13]. AtticSim was also benchmarked against clay, concrete tile, painted metal roofing, and attic assemblies incorporating above-sheathing ventilation (ASV; it allows heat in an inclined air space to be carried by buoyant air away from the roof deck and out the roof ridge) [14].

4.1.3 Integration of *DOE-2/AtticSim*

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 as a boundary condition for interaction between the two codes. For all simulations, the attic floor is assumed to be sealed with no air leakage crossing from the conditioned space into the attic. The heat flows at the attic roof, gables, eaves, and floor are calculated using the thermal response factor technique by Mitalas and Stephenson [15]. This method requires the thermal conductivity, specific heat, density, and thickness of each attic section for calculating conduction transfer functions. DOE-2.1E uses a similar technique of response factors (RF) [34] to calculate heat flows through the building envelope, but it uses weighting factors (WF) to model the heat gain. A comparison between response factors and weighting factors were conducted to determine their negligible similarity as shown in Table 1.

Table 1. Sample output from *DOE-2.1E* and *AtticSim* for the RFs computed through the stud path in the gable end of an attic

Attic Surface	*DOE-2.1E* Response Factors		
West_facing_gable_stud_path			
0	0.0725388229	0.0098278262	0.9016193748
1	-0.0203016642	0.0267347004	-0.6602395177
2	-0.0007713751	0.0100655956	-0.1315478235
3	-0.0002378091	0.0031069645	-0.0405923724
4			
COMMON_RATIO	0.3085973561		
Attic Surface	**AtticSim Response Factors**		
West_facing_gable_stud_path			
0	0.0725388265	0.0098278265	0.9016194031
1	-0.0203016643	0.0267347006	-0.6602395663
2	-0.0007713751	0.0100655958	-0.1315478232
3	-0.0002378091	0.0031069647	-0.0405923734
4	-0.0000733872	0.0009588012	-0.0125266982
COMMON_RATIO	0.3085973437		
	Differences between DOE-2.1E and AtticSim		
0	0.000000004	0.000000000	0.000000028
1	0.000000000	0.000000000	-0.000000049
2	0.000000000	0.000000000	0.000000000
3	0.000000000	0.000000000	-0.000000001
4	-0.000073387	0.000958801	-0.012526698
COMMON_RATIO	-0.000000012		

AtticSim is an ASTM protocol [8] and is publicly available. It has been extensively peer reviewed and benchmarked against field data and therefore was an excellent candidate for use with the whole-building model. DOE-2 can be described as an “air heat balance” program, i.e., it solves only for the zone air temperature. Although incident solar radiation is considered using the “sol-air temperature” method, internal radiation exchange within a zone is ignored. Therefore, when DOE-2 models an attic, any radiation exchange due to the temperature differences between the underside of the roof and the top of the ceiling layers is not considered. The net effect of this modeling method is that DOE-2 cannot be expected to model accurately the impact of cool roof strategies in which the amount of solar radiation entering the attic is changed. In such cases, DOE-2 does not adequately describe the radiation exchanges occurring in attics. AtticSim does not predict whole-building performance. Combined, however, the two tools offer a powerful feature that can translate reduced heat flux from cool roof and attic technologies to annual energy and cost savings in a way that can be benchmarked against demonstration homes.

4.2 ROOF SAVINGS CALCULATOR VALIDATION

4.2.1 Reported Discrepancies in RSC

Roof researcher Scott Kriner of Green Metal Consulting, while performing comparative calculations[1] with the "roofcalc" program, discovered it showed a significant penalty for using a cool metal roof (0.50 and 0.60 SR) vs. asphalt shingle roof (SR 0.20) in Atlanta: the heating penalty far outweighed the cooling benefit. A net penalty for such a significant change in the type and solar reflectance (SR) of the roof was unexpected. All comparisons were against asphalt single with SR 0.20, TE 0.90, no ASV, and no radiant barrier; all other parameters were identical to those of the metal roofing. In general, the penalties that roofcalc indicated in some southern US cities for increasing SR by using painted metal compared with 0.20 SR asphalt shingle could not be explained. For 0.30 SR painted metal, the effects of adding ASV and then adding ASV and a radiant barrier were examined. The impact of the radiant barrier seemed to far outweigh that of ASV or SR increases.

In some cities, ASV creates a penalty compared with direct-to-deck roofing attachment. Overall, Kriner found many of the results calculated by roofcalc not to be credible. Although it is understandable that a high-SR surface can create a heating penalty in northern climates, the calculations appeared to show that threshold to be too far south. It was difficult to justify how introducing ASV in any climate could penalize the cooling/heating savings and how a radiant barrier could have such a significant benefit upon the roof thermal performance.

The following table summarizes the results of the calculations shown by v0.91 of DOE's Roof Savings Calculator (www.roofcalc.com).

Table 2. Annual cooling/heating energy savings vs. asphalt shingle* ($/year)

		Cool Metal Roofing SR (0.85 TE)						
City	CZ	0.30 SR	0.30 SR ASV	0.30 SR ASV+RB	0.50 SR	0.60 SR	Electricity Price (1) (cents/kWh)	Natural Gas Price (2) ($/Kft^3)
Miami, FL	1	1	38	272	67	99	11.90	18.18
Austin, TX	2	10	-6	322	27	35	11.17	11.73
Atlanta, GA	3	-4	-67	381	-34	-51	10.11	13.81
Baltimore, MD	4	14	-55	426	-10	-23	12.41	10.06
Chicago, IL	5	4	-173	388	-16	-27	11.34	7.79
Minneapolis, MN	6	1	-87	437	-27	-43	11.04	7.82
Fargo, ND	7	-2	-87	364	-27	-41	8.62	6.55

* Asphalt shingle at 0.20 SR and 0.90 TE
(1) Source: Nov 2012 average retail price of electricity to residential customers by state (US Energy Information Administration, Form EIA-826)
(2) Source: Nov 2012 average natural gas price to residential customers by state (US Energy Information Administration)

[1] Please request T06/ Cool Roof Calcs 021913.xlsx for more details of the simulation.

Description	Reflectance	Emissivity	SRI	New York	Los Angeles	Chicago	Houston	Miami	Phoenix	Kansas City	Minneapolis	San Francisco
BUR Aggregate	10	0.90	19	0	0	0	0	0	0	0	0	0
Mineral Modified Bitumen	25	0.88	25	-398	60	-219	-33	36	-50	-224	-255	-208
Aluminum Coating Aged	55	0.45	48	67	505	78	255	265	300	128	74	162
Aluminum Coating	65	0.45	65	-132	915	21	408	524	438	33	-63	-87
White Metal	70	0.85	85	-2090	1216	-855	305	983	46	-963	-1339	-1914
White Coating Aged	75	0.90	93	-999	1518	-330	637	1235	406	-489	-737	-1426
White Single Ply Aged	76	0.87	94	-1097	1504	-389	615	1235	350	-546	-811	-1504
White Coating	85	0.90	107	-1195	1073	-410	778	1540	471	-599	-935	-1906
White Single Ply	85	0.87	107	-1277	1674	-463	744	1515	410	-648	-994	-1950
Mineral Modified Bitumen	33	0.92	35	-602	328	-299	-2	226	-2	-328	-396	-446
Mineral Modified Bitumen	45	0.79	55	-639	554	-301	96	359	96	-323	-418	-479
Mineral Modified Bitumen	63	0.88	75	-1117	1165	-460	180	876	180	-559	-770	-1204
Mineral Modified Bitumen	81	0.80	100	-1374	1574	-528	323	1333	323	-689	-1013	-1841
Metal	35	0.82	35	-1287	-32	-636	-45	-29	-45	-554	-698	-107
Metal	49	0.83	55	-1623	-453	-729	18	340	18	-704	-938	-741
Metal	63	0.84	75	-1934	985	-808	51	755	51	-864	-1192	-1488
Single Ply	32	0.90	35	-313	293	-146	34	204	34	-172	-218	-282
Single Ply	64	0.80	75	-767	1170	-276	287	837	287	-363	-530	-890
Single Ply	82	0.79	100	-1113	1632	-380	433	1355	433	-544	-839	-1631
Coating	43	0.58	35	81	262	61	175	133	175	101	72	154
Coating	49	0.83	55	-413	759	-142	228	508	228	-189	-277	-426
Coating	63	0.86	75	-716	1203	-236	331	873	331	-335	-496	-899
Coating	79	0.90	100	-1076	1604	-358	432	1353	432	-532	-812	-1608

4.2.2 Empirical Validation of AtticSim

A 2003 study conducted by F.W. Dodge [22] shows that tile roofs comprise ~30% of the new and retrofit roof markets in California. Therefore, ORNL conducted field experiments in Southern California to benchmark both AtticSim as a stand-alone tool, and the new RSC tool. AtticSim has a history of validation against several different profiles of tile, stone-coated metal, asphalt shingle, and standing seam metal roofs, all of which were field-tested at ORNL. However, AtticSim was also benchmarked against two houses at the Ft. Irwin military base in California to assist WBT with its benchmarking of RSC.

The two demonstration homes were configured to provided four cases for comparison: (1) concrete tile applied directly to the deck—one with a cool-color coating, the other not coated; and (2) concrete tile elevated 1.5 in. (0.038 m) above the roof deck using double battens and ventilated via eave and ridge vents—one with a cool-color coating, the other not coated.

For House N5, AtticSim predictions lead the measured flux for about 2 hours. Results show a thermal capacitance effect between the measured flux reduced from thermometry and AtticSim predictions. The shift is most evident during periods of peak irradiance.

For House N8, AtticSim simulated the daily trends in ceiling heat flux the daytime trends in ceiling heat flux within about 0.3 Btu/(h · ft^2), while the nighttime heat flux predictions were more accurate. This occurred because the temperature difference across the R-38 (RSI 6.7) batt insulation was at best only 3.6°F (2°C) during the day, while at night the temperature drop across the ceiling insulation was about 14.4°F (8°C). Since heat flux was computed from temperature measurements, there was enhanced uncertainty when differences between temperatures were comparatively small.

For the DOE-2.1E/AtticSim benchmark houses, both codes predicted the field measurements within ± 2°F (1.1°C) except for the early morning hours of ~ 2–8 a.m. The benchmarking results showed that the DOE-2/AtticSim program was predicting the attic air temperature with about the same accuracy as the stand-alone AtticSim code. Hence the integration of AtticSim into DOE-2 appeared to be working adequately.

4.2.3 Preliminary Results

As previously discussed, earlier studies done at LBNL [23][24][25] showed cooling savings within 15% deviation from RSC calculations, but the calculated heating penalties were 6–12 times larger in the RSC (due in part to the small amount of heating in absolute terms). The RSC showed average heating penalties to be up to 60% of the cooling savings, the LBNL study showed them to be 5%.

After the preliminary analysis, the following conclusions were reached by the LBNL study:

1. The radiative component of ceiling heat flows is very significant and is often greater than the conductive component, especially on warm winter days.

2. The main reason for the different heat flows between DOE-2.1E and RSC is that the DOE-2.1E by default ignores the radiative components or models it more simplistically via incorporation of additional models like that of Gartland [44].

In summary, the following observations were made:

- The ceiling heat flows deriving from the radiative heat transfer component between the underside of the roof and the attic floor; walls; and heating, ventilation, and air-conditioning (HVAC) ducts is quite significant and is often greater than the conduction component.
- The tentative 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 the latter do not contain the radiative component or model it more simplistically.
- No methodological problem has been uncovered to date in 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 as of the time of this writing, but further validation is ongoing and may uncover modeling issues as the divergence between modeled and empirical data are compared.

5 ORNL'S NATURAL EXPOSURE TEST (NET) FACILITY IN CHARLESTON, SC

ORNL has a Natural Exposure Test facility in Charleston, SC. Figure 2 represents the various attic assemblies available at the NET, and Figure 3 details the locations of instrumentation.

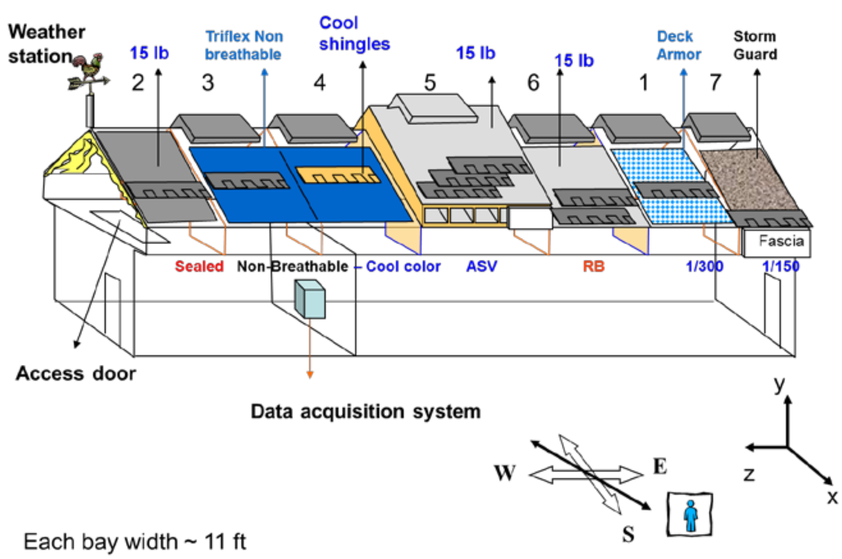


Figure 2. Different types of attic systems in the Natural Exposure Test Facility in Charleston, SC.

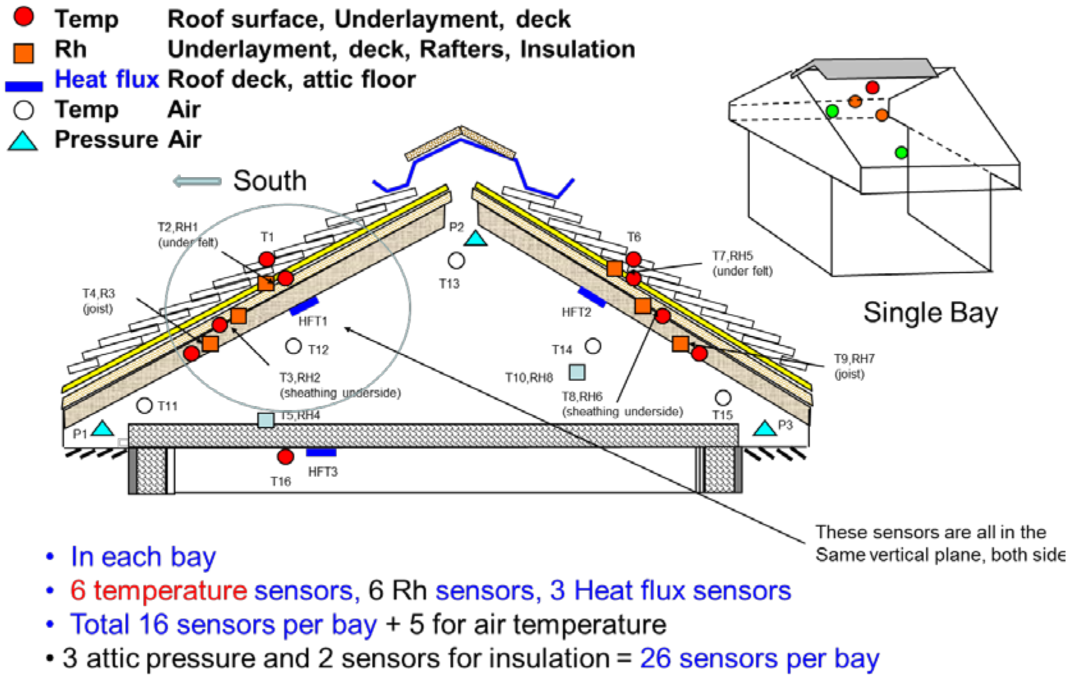


Figure 3. Locations of the sensors in the NET facility in Charleston, SC.

6 NEXT-GENERATION ATTICS AND ROOF SYSTEMS —WIND-DRIVEN ATTIC VENTILATION

Attic ventilation is an important factor in determining heat flow through the ceiling separating the conditioned interior space and the unconditioned attic space. Attic ventilation is also necessary for moisture control in the attic space. The AtticSim computer code is a widely recognized tool for modeling the thermal and hydric performance of attic spaces. In fact, AtticSim is the basis for ASTM Standard C1340, "Standard Practice for Estimation of Heat Gain or Loss through Ceilings under Attics Containing Radiant Barriers by Use of a Computer Program" [8].

Nonpowered attic ventilation is a result of a combination of buoyancy-driven and wind-driven flow. Even at relatively low wind speeds, wind-driven ventilation can dominate. Therefore, it is important to have an accurate model for wind-driven ventilation in AtticSim. The model for wind-driven ventilation in AtticSim is based on field measurements from a single experiment conducted by Burch and Treado [37] and further analyzed by Peavy [38]. Since that work is based on a single house design, it does not account for possible variability due to factors such as the slope of the roof or size of the building. Also, since the house had an L-shaped footprint, the results may not be applicable for the more common rectangular footprint assumed by AtticSim.

Since it would be prohibitively expensive to perform physical experiments on the large number of building variations needed to determine the influence of various factors, numerical experiments were carried out with a computational fluid dynamics (CFD) computer program on the two roof types modeled by AtticSim: (1) conventional roofs, for which the roof slope is the same on both sides of the ridge; and (2) shed roofs, for which one side is sloped and the other side is vertical. The code used is COMSOL, which is a commercial physics modeling tool that can handle CFD, heat transfer, and other physics relevant to attic performance. Results were examined from a large number of cases in which the driving force is the component of the wind perpendicular to the ridge line (i.e., flow paths involving soffit vents and ridge vents). It was found that the wind-driven volumetric flow rate through the attic could be reasonably estimated with an equation of the form

$$Q_w = C_F \cdot F_{width} \cdot F_{area} \cdot A_{soffit} \cdot V \cdot |\sin \alpha| \quad (1)$$

where

Q_w	=	wind-driven volumetric flow rate
C_F	=	flow coefficient (vent opening effectiveness) which is a function of roof slope
F_{Width}	=	correction factor for building width
F_{area}	=	correction factor for unequal soffit and ridge vent areas
A_{soffit}	=	area of one soffit vent (the other soffit, if present, has same area)
V	=	wind speed
α	=	wind direction measured from a line parallel to ridge line

Values for the coefficients in Eq. (1) for different roof types are given in Figure 4–Figure 11. For conventional roofs with soffit vents only (i.e., no ridge vents) the F_{area} coefficient is equal to one.

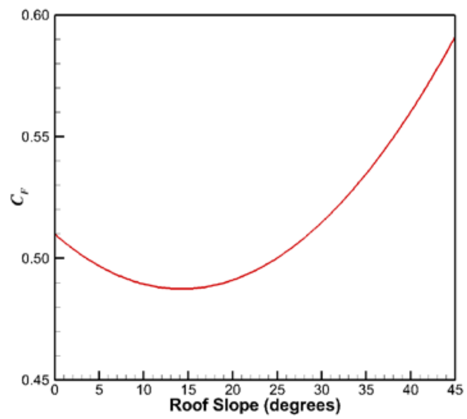


Figure 4. Flow coefficient for conventional roof with soffit vents but no ridge vent.

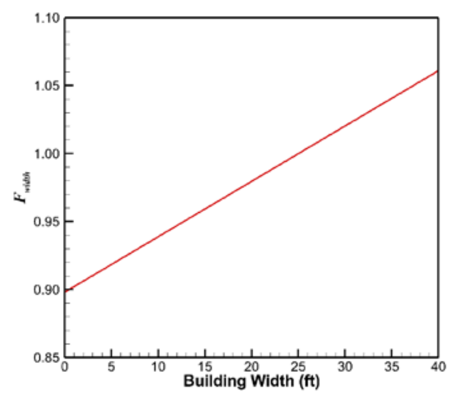


Figure 5. Building-width correction factor for conventional roof with soffit vents but no ridge vent.

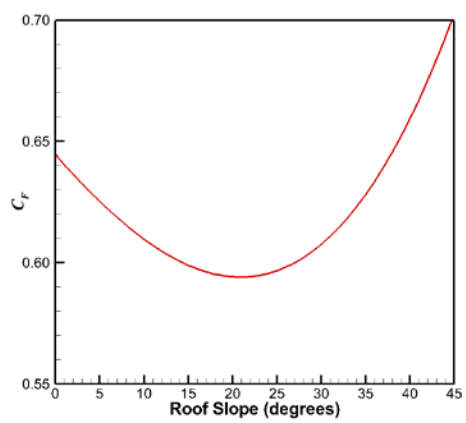


Figure 6. Flow coefficient for conventional roof with soffit vents and ridge vent.

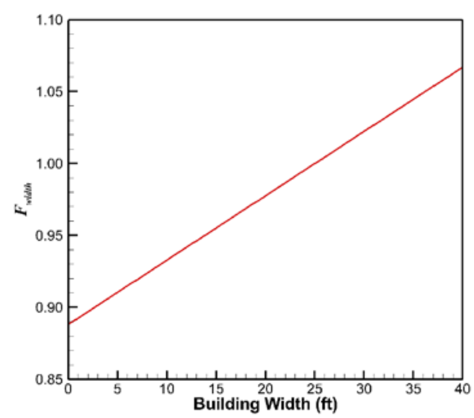


Figure 7. Building-width correction factor for conventional roof with soffit vents and ridge vent.

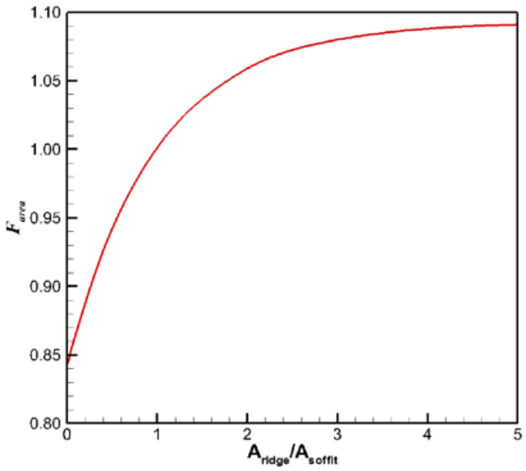


Figure 8. Unequal-soffit-ridge-area correction factor for conventional roof with soffit vents and ridge vent.

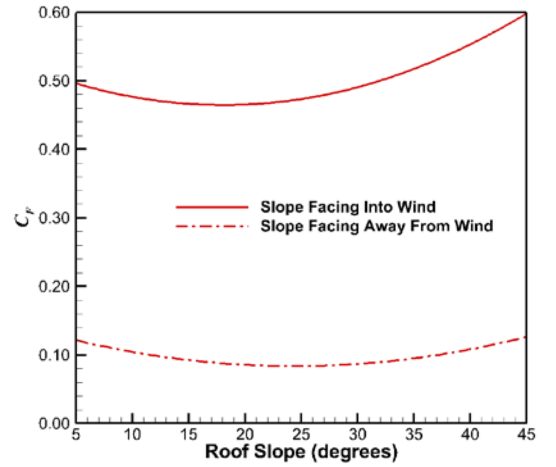


Figure 9. Flow coefficient for shed roof with soffit vent and ridge vent.

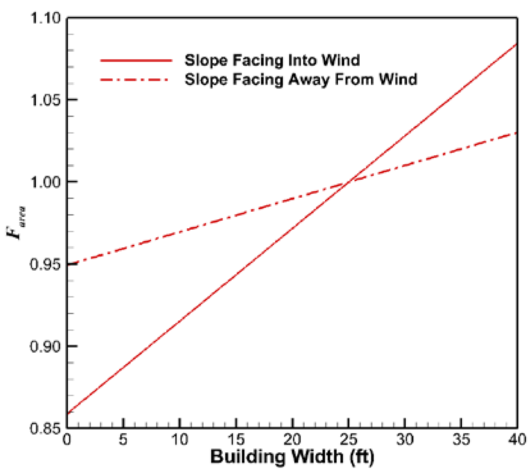


Figure 10. Building-width correction factor for shed roof with soffit vent and ridge vent.

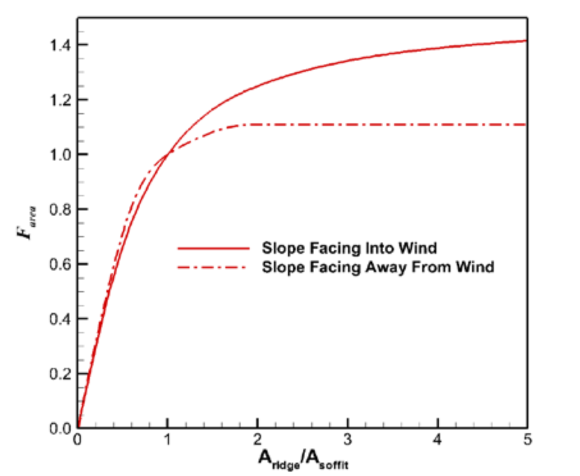


Figure 11. Unequal-soffit-ridge-area correction factor for shed roof with soffit vent and ridge vent.

For attics with gable vents, there is a gable-to-gable flow path driven by the component of wind parallel to the ridge line. The volumetric flow rate for this path is given by

$$Q_w = C_F \cdot A_{gable} \cdot V \cdot |\cos\alpha| \quad . \tag{2}$$

A value for C_F of approximately one seems indicated. The combined effect of multiple flow paths is given by

$$Q_w = \sqrt{{Q_{perp}}^2 + {Q_{parallel}}^2} \tag{3}$$

where

W_{perp} = flow driven by wind component perpendicular to ridge
$W_{parallel}$ = flow driven by wind component parallel to ridge.

Data on attic ventilation are available from the Charleston NET facility. They were obtained using the tracer gas technique. Both the old and new versions of the attic ventilation model were compared with data for a period in November 2012. The AtticSim calculation was driven by weather data measured at the NET facility. The comparison is presented in Figure 12. The predicted air exchange rate for the new wind-driven attic ventilation algorithm in AtticSim is a much better match to the measured data than was the rate obtained using old algorithm. The new AtticSim algorithm produces a good match to the measured air exchange rate (air changes per hours, ACH) except when the rate is fairly high (more than the 15 ACH predicted by AtticSim). The tracer gas technique being used is proportional to the logarithm of the concentration at any time and therefore short time intervals can result in unacceptable uncertainty in the determination of the air exchange rate [45]. The tracer gas technique represents the average rate over a much shorter time than the one hour time used by AtticSim, which explains in part the discrepancy between measurement and simulation.

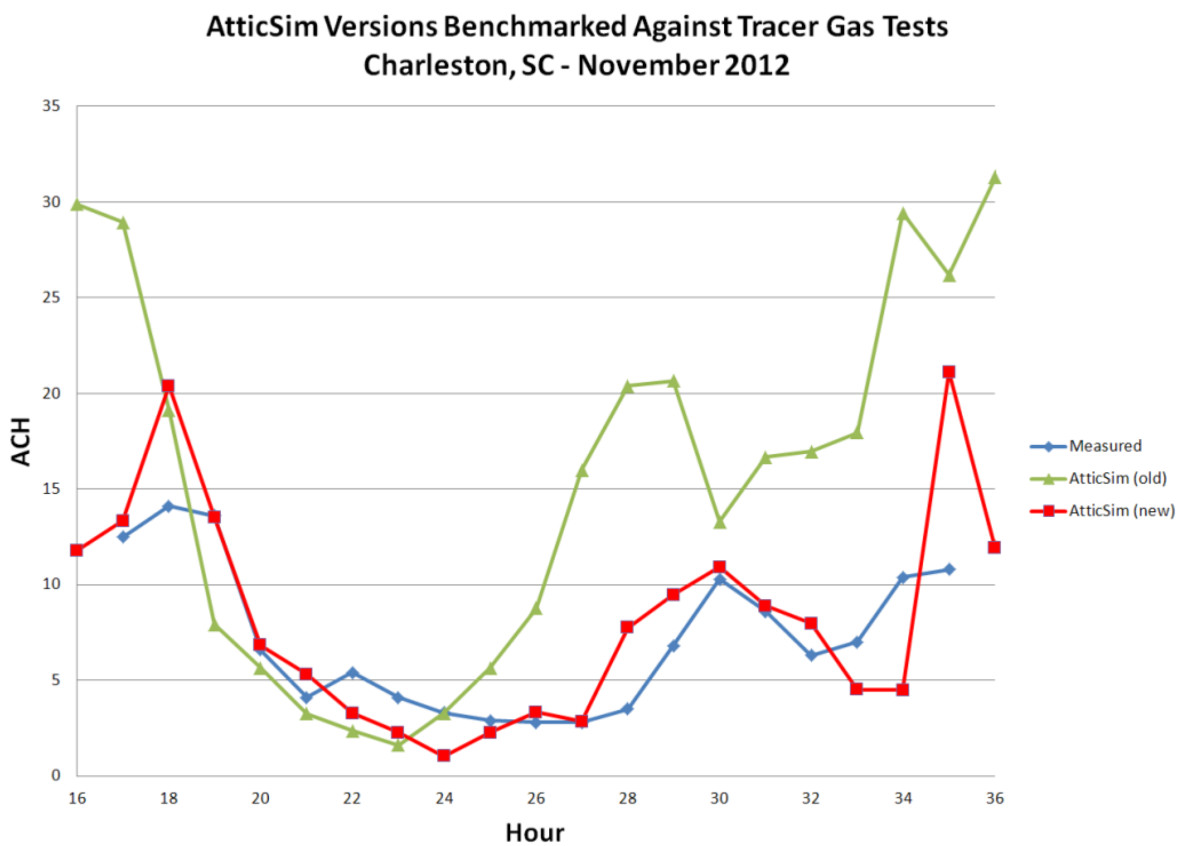


Figure 12. Measured and calculated air change rates in Charleston NET Facility Attic 1

6.1 BENCHMARKING

Benchmarks were made for NET experimental attic systems Attic 01 and Attic 07 for the week of field data ending 06/24/2011[2]. The actual R-value of the ceiling insulation in the two assemblies was R-43.

[2] Please request the following files for more details:
Analysis and output files T02/Attic01_062411_Results.xlsm, T02/Attic01_38.dat, T02/Attic07_38.dat,

6.1.1 Attic 01

The following are the charts for the Attic 01 roof assembly measured data and AtticSim comparisons. The NET facility did not have a pygerometer for measuring infrared radiation. Without the pygerometer, no good estimates of the sky temperature could be calculated; this is critical for attic energy balance calculations. Therefore, roof temperature at the shingle was used as an input boundary condition due to the absence of infrared pygerometer instrumentation. Additional equipment has since been added and irradiance at the NET is well documented for ongoing work.

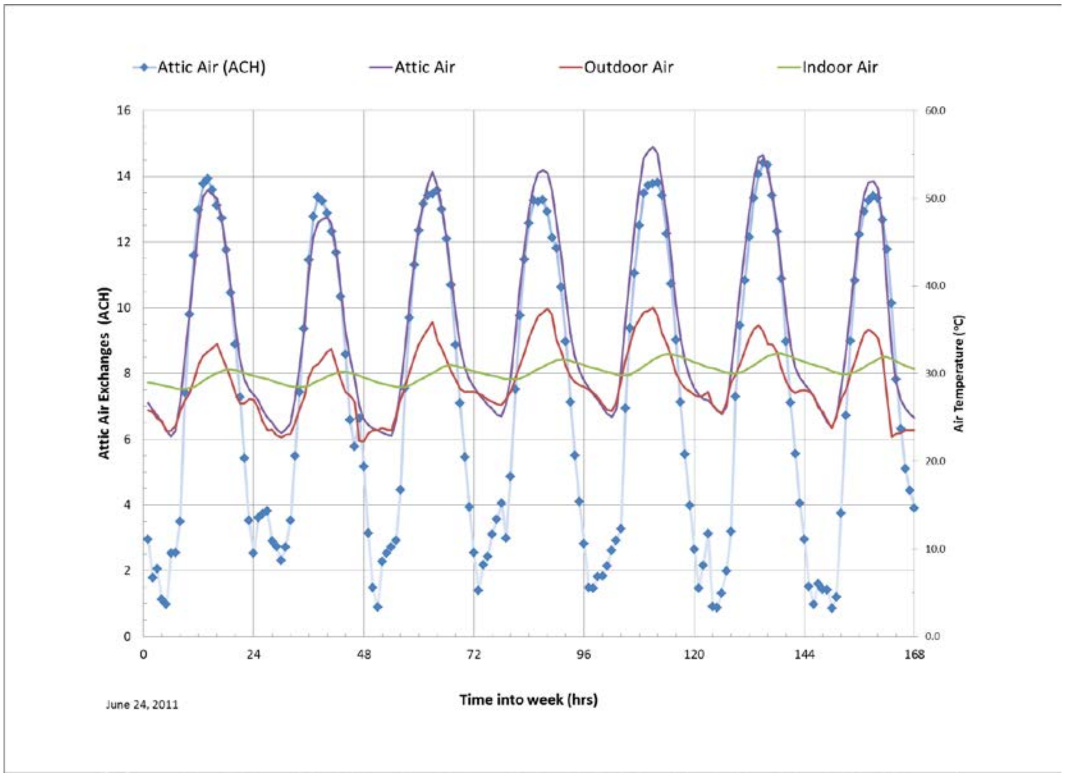


Figure 13. Attic 01's Air Changer per Hour (ACH) calculated by AtticSim and measured temperatures.

T02/Attic07_062411_Results.xlsm, and T02/Ceiling_WAM_38_ctf.txt.
Boundary condition files: T02/BC_data_Attic01_062411.csv and T02/BC_data_Attic07_062411.csv

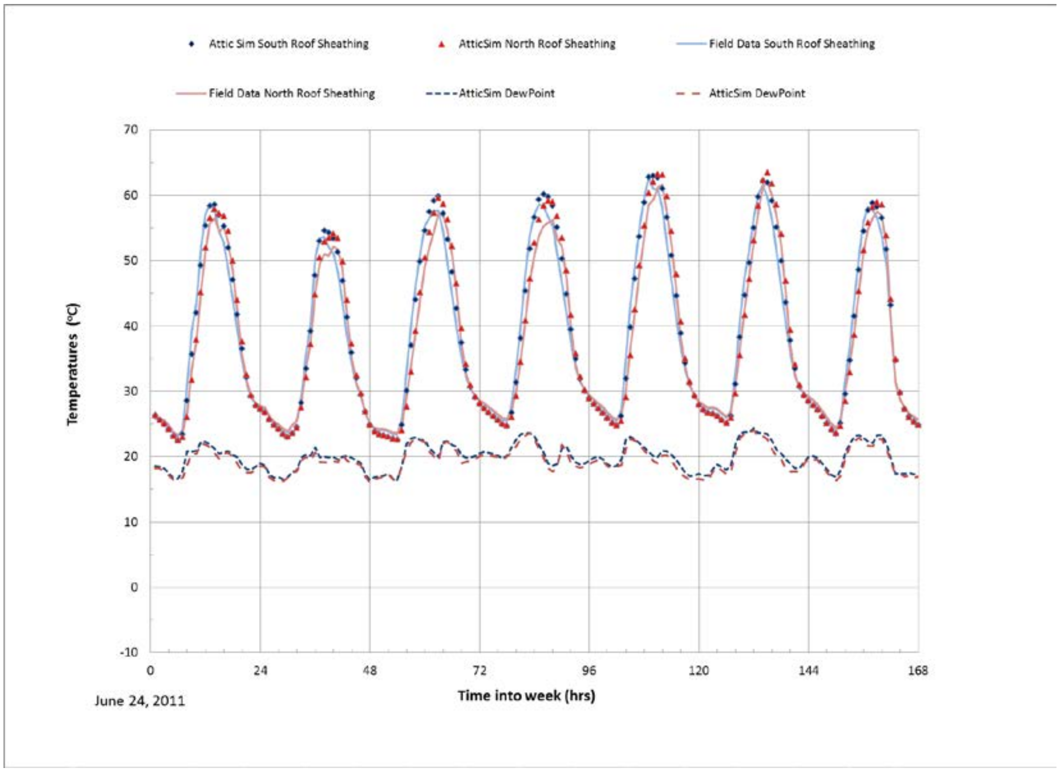


Figure 14. Attic 01's comparison of measured and simulated temperatures of sheathing.

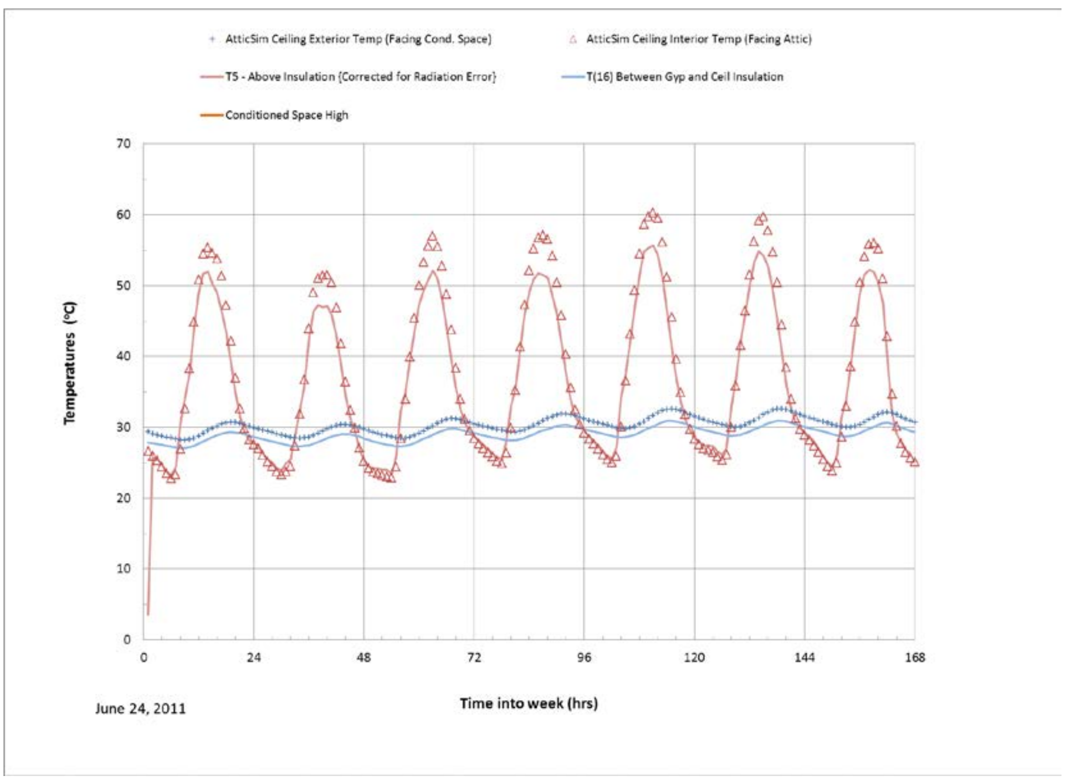


Figure 15. Attic 01's comparison of measured and simulated ceiling temperatures.

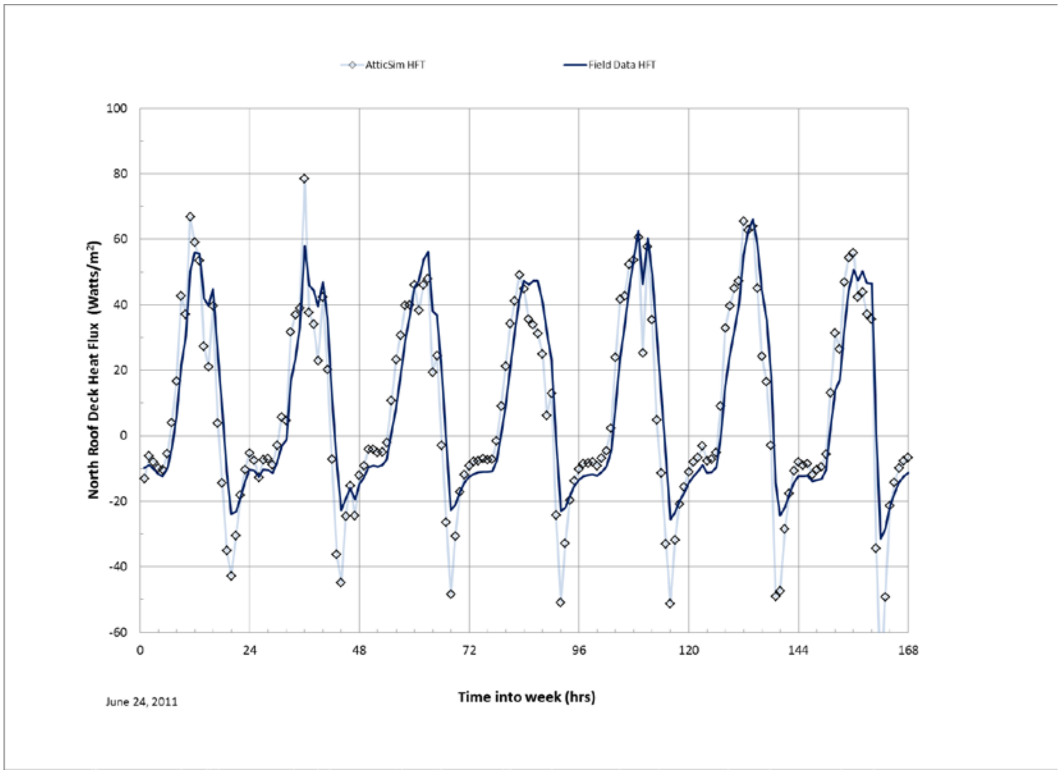


Figure 16. Attic 01's comparison of measured and simulated heat flux through the north deck.

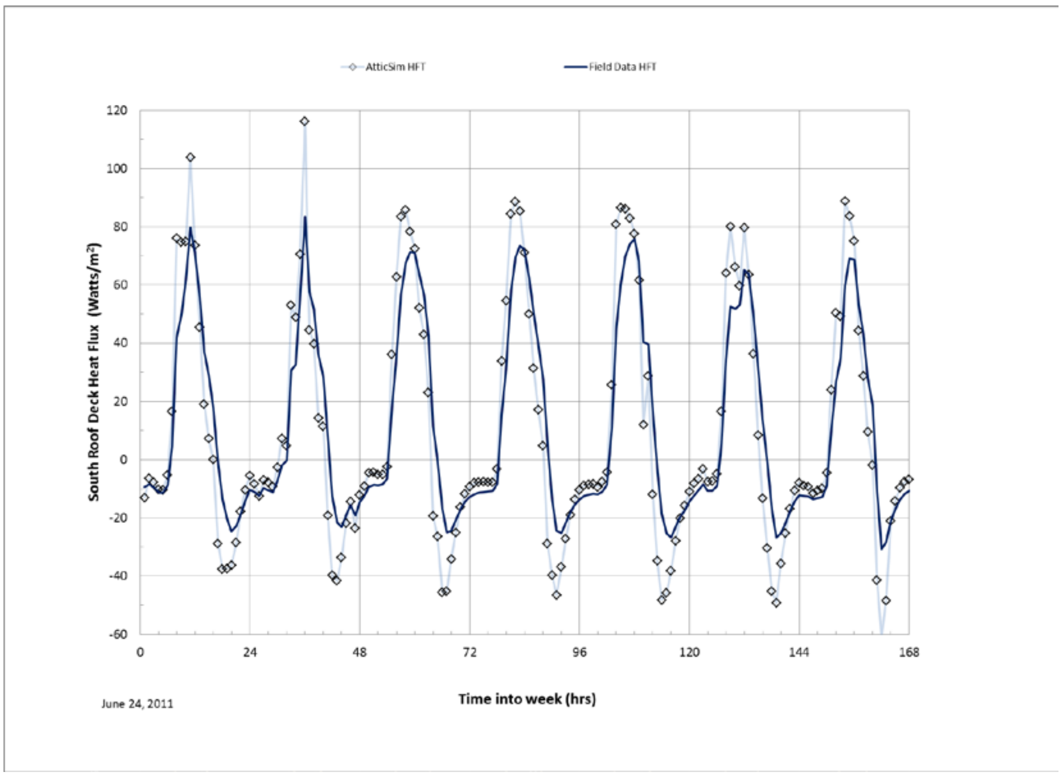


Figure 17. Attic 01's comparison of measured and simulated heat flux through the south deck.

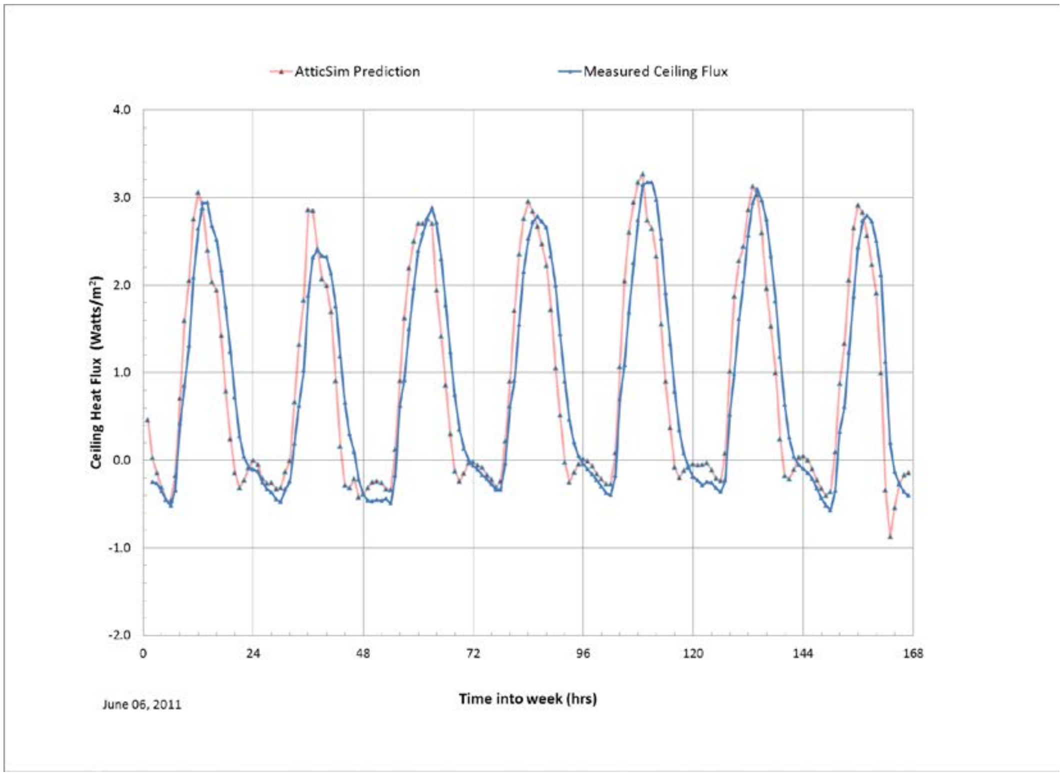


Figure 18. Attic 01's comparison of measured and simulated heat flux through the ceiling.

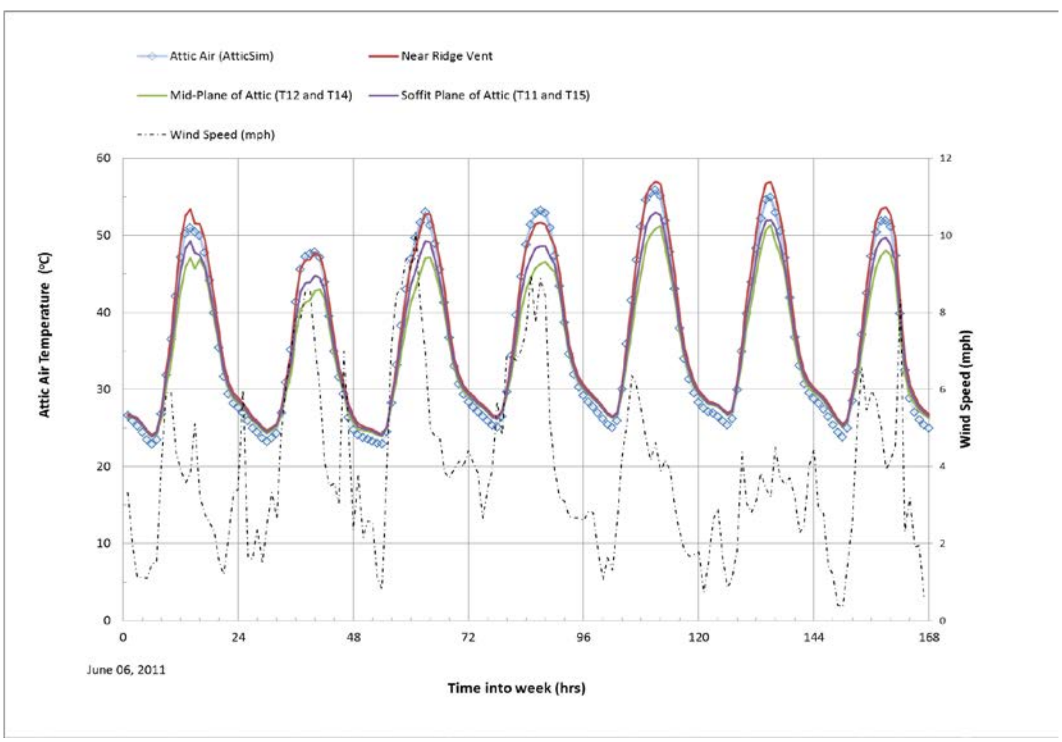


Figure 19. Attic 01's comparison of measured and simulated attic air temperatures.

6.1.2 Attic 07

The following are the charts for the Attic 07 roof assembly.

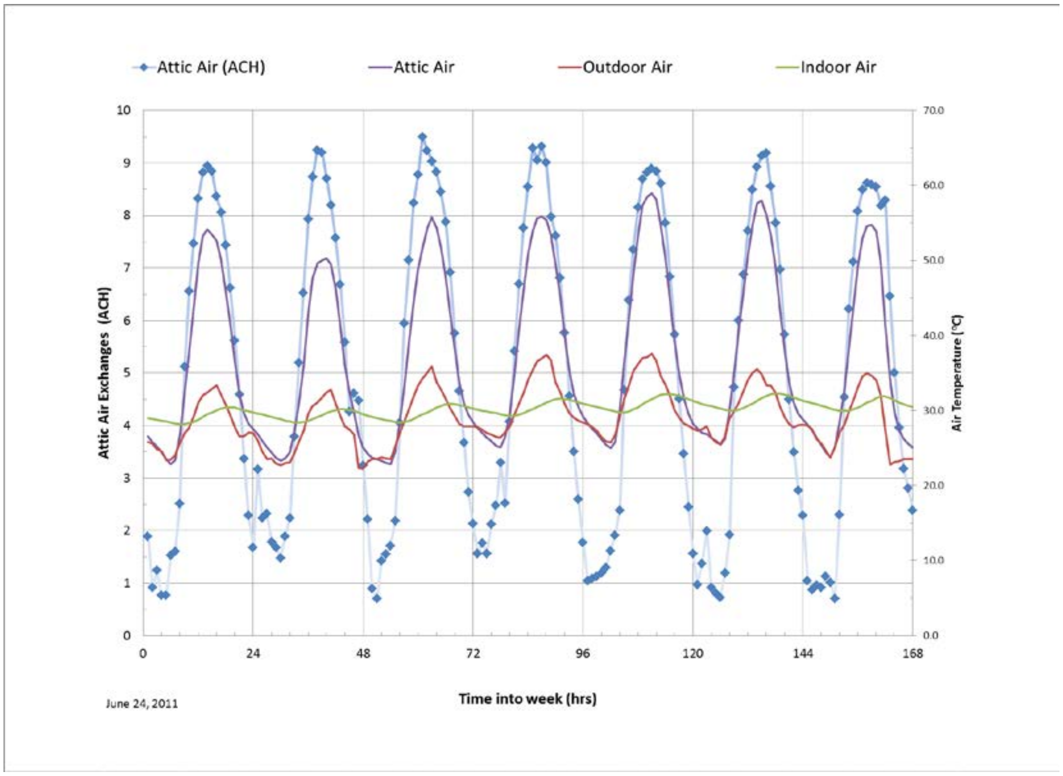


Figure 20. Attic 07's Air Changer per Hour (ACH) calculated by AtticSim and measured temperatures.

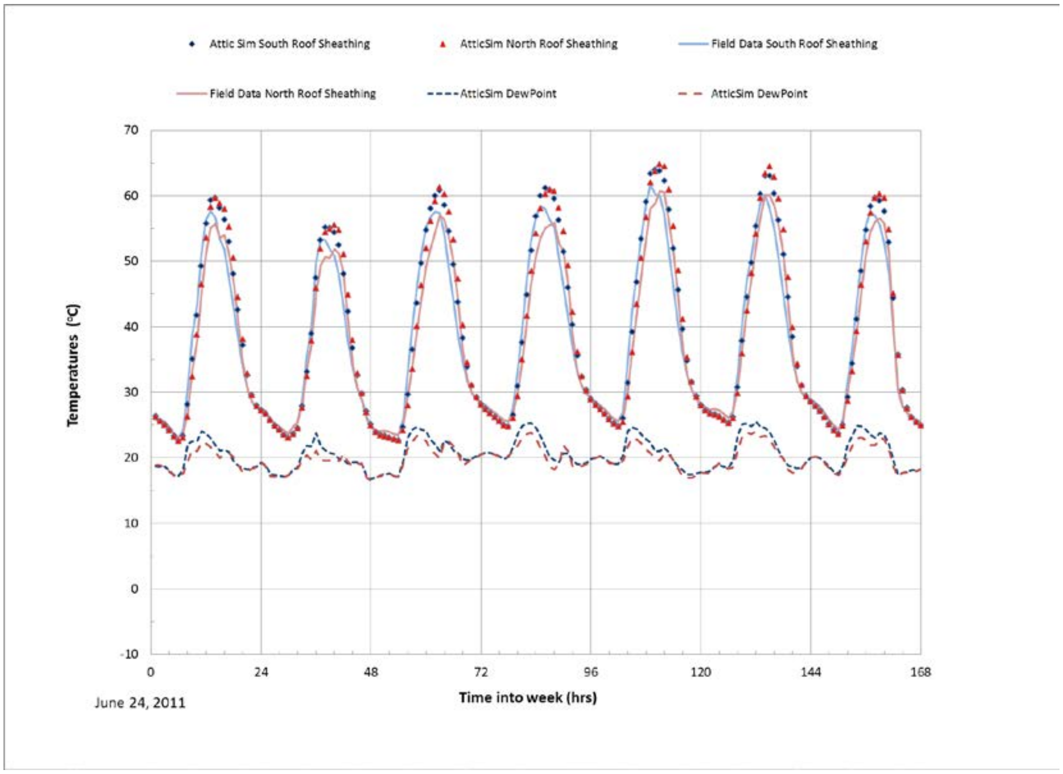


Figure 21. Attic 07's comparison of measured and simulated temperatures of sheathing.

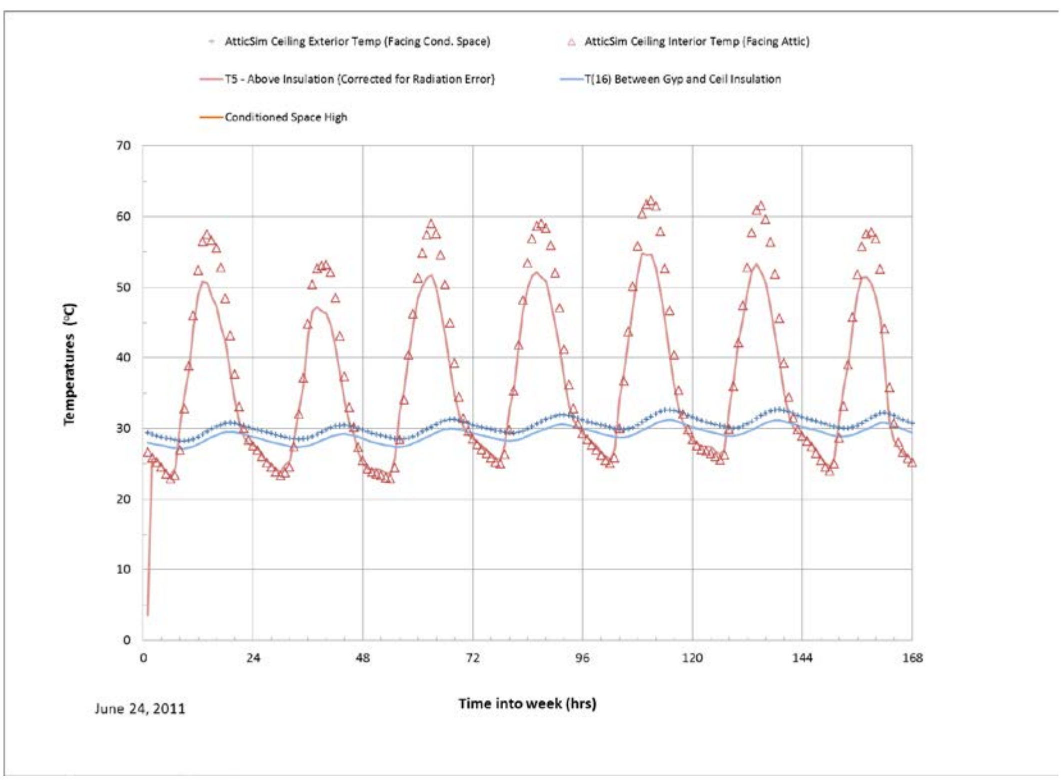


Figure 22. Attic 07's comparison of measured and simulated ceiling temperatures.

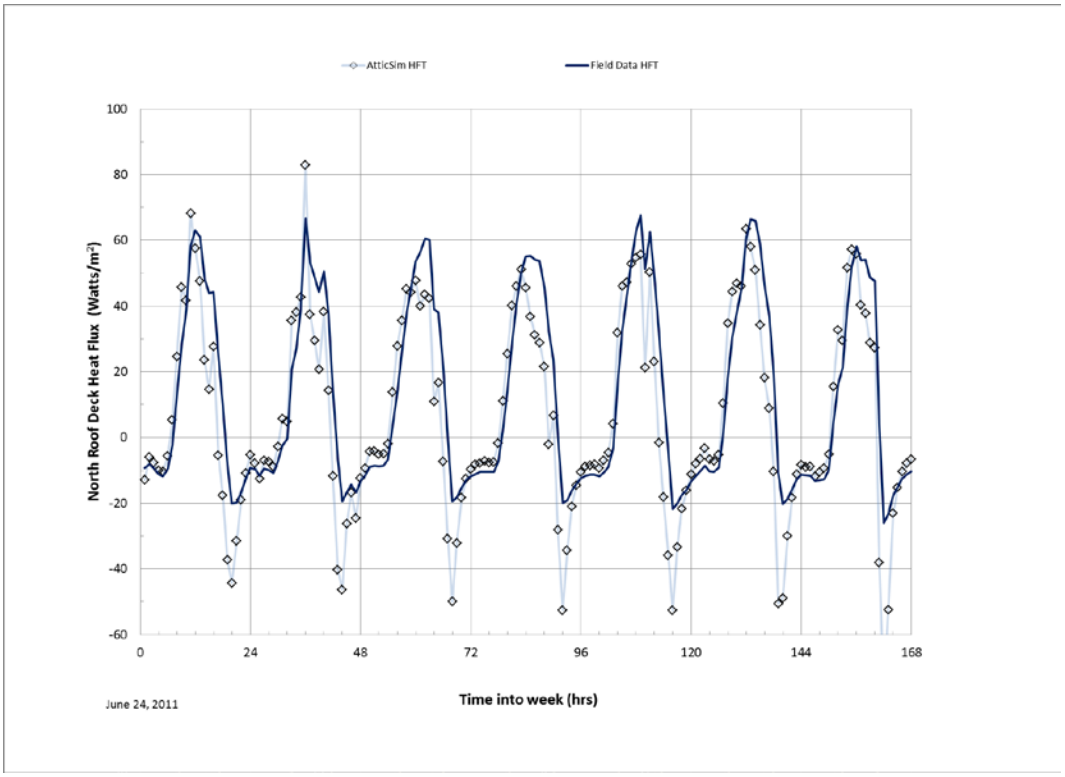


Figure 23. Attic 07's comparison of measured and simulated heat flux through the north deck.

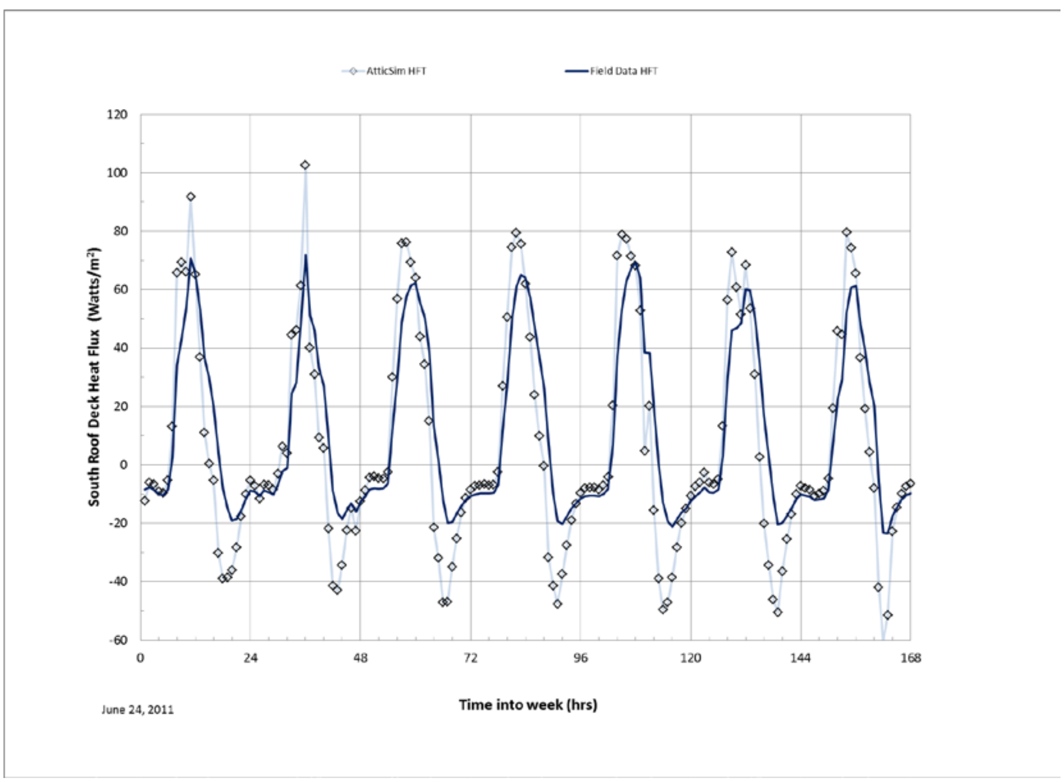


Figure 24. Attic 07's comparison of measured and simulated heat flux through the south deck.

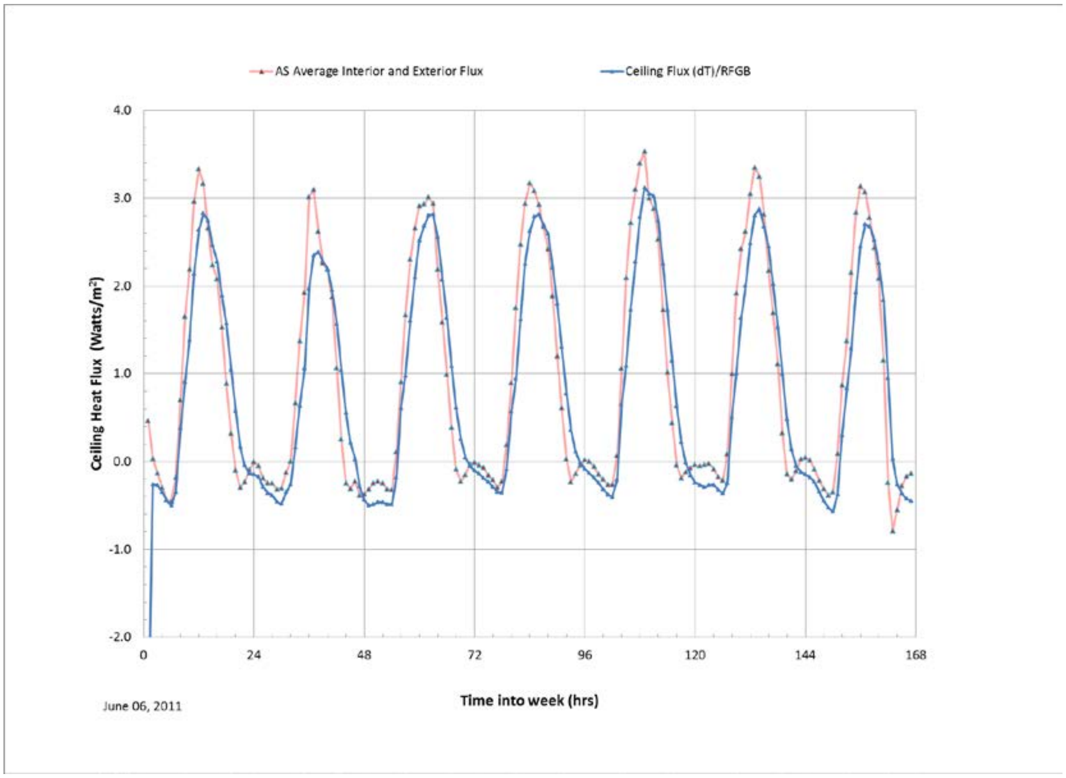


Figure 25. Attic 07's comparison of measured and simulated heat flux through the ceiling.

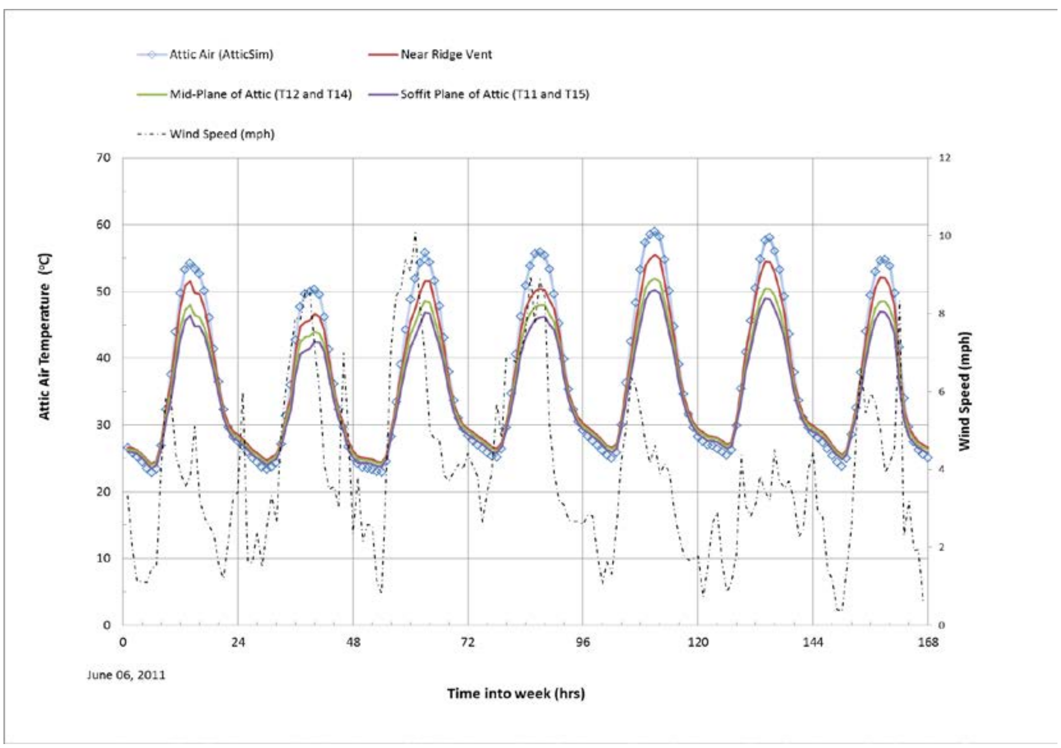


Figure 26. Attic 07's comparison of measured and simulated attic air temperatures.

7 POTENTIAL PROBLEMS OBSERVED WITH PREDICTION OF ATTIC AIR TEMPERATURE IN ATTICSIM

Two experiments were conducted to help describe potential problems observed with prediction of attic air temperature computed by RSC/AtticSim.[3] The first uses Huang's Input file with F77 AtticSim (Design Guide version), R-0 and R60 ceilings yielded almost identical attic air temperatures. The second uses Miller's conduction transfer function (CTF) Input for attic floor with F77 AtticSim (Design Guide version), the R60 ceiling (black curve) yielded reasonable attic air temperature.

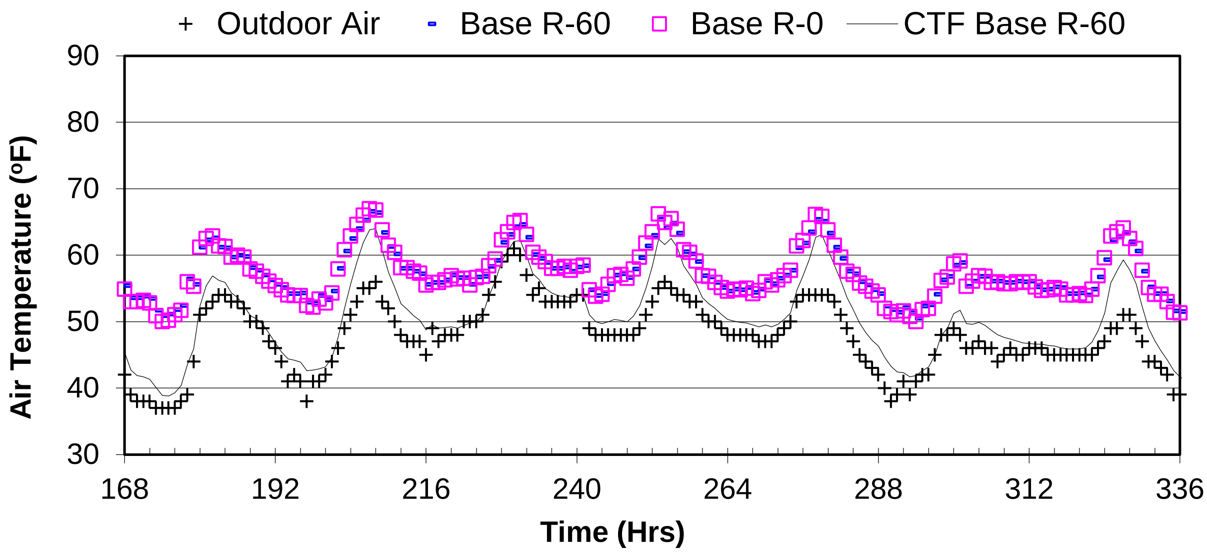


Figure 27. Base attic.

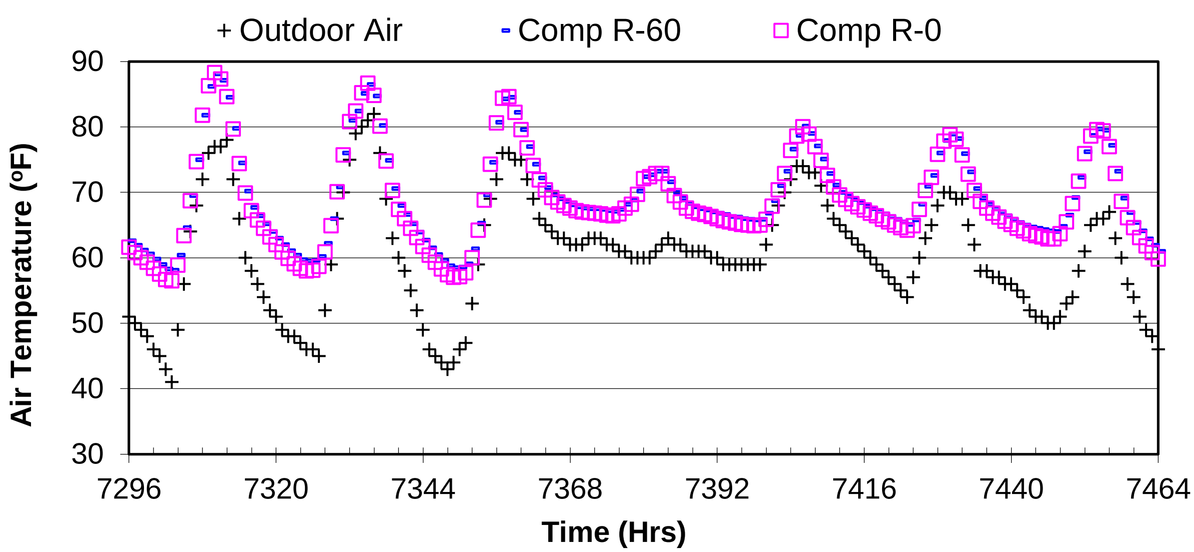


Figure 28. CTF base attic.

[3] Please request files T01/AtticSim_WAM_Runs_Set02.xls and T01/RF_Check.xls for more details.

After comparisons were made between the Response Factors (RFs) provided by the input from Huang and Miller, the following observations:

- RFs sum to respective R-value used by Miller in AtticSim
- RFs do not sum to respective R-value specified by Huang in the DOE-2 and AtticSim interface

The conclusions from the two experiments were

- AtticSim in RSC should use the conduction transfer functions, which is the present setup using RFs.
- Huang's RFs appear to be incorrect and do not sum to the specified R-value of a given material layer.

Table 3. Response factors comparison (Part 1)

	W. Miller RF for 2 by 6 Rafter					W. Miller RF for R60 FGB Insulation				
	27.44	27.44	27.44			60.45	60.45	60.45	f	0.0625
									1-f	0.9375
	3.64E-02	3.64E-02	3.64E-02			1.65E-02	1.65E-02	1.65E-02		
0	22	3.64E-02	9.14E-01	27.44		12	1.65E-02	7.37E-01	60.45	
1	1.07E-01	2.65E-09	1.12E+00			1.06E-01	1.45E-06	6.30E-01		
2	-5.67E-02	1.52E-05	-7.16E-01			-6.21E-02	3.65E-04	-5.81E-01		
3	-3.84E-03	3.05E-04	-9.77E-02			-1.02E-02	1.99E-03	-1.31E-02		
4	-1.31E-03	1.08E-03	-4.90E-02			-5.29E-03	2.92E-03	-6.08E-03		
5	-8.82E-04	1.82E-03	-3.10E-02			-3.35E-03	2.71E-03	-3.71E-03		
6	-7.15E-04	2.21E-03	-2.22E-02			-2.31E-03	2.18E-03	-2.52E-03		
7	-6.14E-04	2.33E-03	-1.72E-02			-1.66E-03	1.66E-03	-1.80E-03		
8	-5.42E-04	2.29E-03	-1.42E-02			-1.21E-03	1.24E-03	-1.31E-03		
9	-4.86E-04	2.18E-03	-1.22E-02			-8.87E-04	9.15E-04	-9.56E-04		
10	-4.39E-04	2.04E-03	-1.07E-02			-6.52E-04	6.75E-04	-7.03E-04		
11	-3.98E-04	1.89E-03	-9.59E-03			-4.80E-04	4.98E-04	-5.18E-04		
12	-3.63E-04	1.74E-03	-8.66E-03			-3.54E-04	3.67E-04	-3.81E-04		
13	-3.31E-04	1.59E-03	-7.85E-03			-2.61E-04	2.70E-04	-2.81E-04		
14	-3.02E-04	1.46E-03	-7.14E-03			-1.92E-04	1.99E-04	-2.07E-04		
15	-2.76E-04	1.33E-03	-6.51E-03			-1.42E-04	1.47E-04	-1.53E-04		
16	-2.52E-04	1.22E-03	-5.94E-03			-1.04E-04	1.08E-04	-1.12E-04		
17	-2.30E-04	1.12E-03	-5.43E-03			-7.68E-05	7.97E-05	-8.28E-05		
18	-2.10E-04	1.02E-03	-4.96E-03			-5.66E-05	5.87E-05	-6.10E-05		
19	-1.92E-04	9.32E-04	-4.53E-03			-4.17E-05	4.33E-05	-4.50E-05		
20	-1.75E-04	8.52E-04	-4.14E-03			-3.07E-05	3.19E-05	-3.31E-05		
21	-1.60E-04	7.78E-04	-3.78E-03			-2.26E-05	2.35E-05	-2.44E-05		
22	-1.46E-04	7.11E-04	-3.45E-03			-1.67E-05	1.73E-05	-1.80E-05		
23	-1.34E-04	6.50E-04	-3.16E-03			-1.23E-05	1.28E-05	-1.32E-05		
24	-1.22E-04	5.94E-04	-2.88E-03			-9.06E-06	9.40E-06	-9.76E-06		
25	-1.12E-04	5.42E-04	-2.63E-03			-6.67E-06	6.93E-06	-7.19E-06		
26	-1.02E-04	4.96E-04	-2.41E-03			-4.92E-06	5.10E-06	-5.30E-06		
27	-9.33E-05	4.53E-04	-2.20E-03			-3.62E-06	3.76E-06	-3.90E-06		
28	-8.52E-05	4.14E-04	-2.01E-03			-2.67E-06	2.77E-06	-2.88E-06		
29	-7.79E-05	3.78E-04	-1.84E-03			-1.97E-06	2.04E-06	-2.12E-06		
30	-7.11E-05	3.45E-04	-1.68E-03			-1.45E-06	1.50E-06	-1.56E-06		
31	-6.50E-05	3.16E-04	-1.53E-03			-1.07E-06	1.11E-06	-1.15E-06		
32	-5.94E-05	2.88E-04	-1.40E-03			-7.87E-07	8.17E-07	-8.48E-07		
33	-5.43E-05	2.64E-04	-1.28E-03			-5.80E-07	6.02E-07	-6.25E-07		
34	-4.96E-05	2.41E-04	-1.17E-03			-4.27E-07	4.43E-07	-4.60E-07		
35	-4.53E-05	2.20E-04	-1.07E-03			-3.15E-07	3.27E-07	-3.39E-07		
36	-4.14E-05	2.01E-04	-9.77E-04			-2.32E-07	2.41E-07	-2.50E-07		
37	-3.78E-05	1.84E-04	-8.92E-04			-1.71E-07	1.77E-07	-1.84E-07		
38	-3.46E-05	1.68E-04	-8.15E-04			-1.26E-07	1.31E-07	-1.36E-07		
39	-3.16E-05	1.53E-04	-7.45E-04			-9.28E-08	9.63E-08	-1.00E-07		
40	-2.89E-05	1.40E-04	-6.81E-04			-6.84E-08	7.09E-08	-7.37E-08		

Table 4. Response factors comparison (Part 2)

	W. Miller RF for Parallel Path					J Huang RF for Parallel Path				
0.0625	56.22	56.22	56.22			41.88	54.08	52.88	√ Problem	
0.9375										
	1.78E-02	1.78E-02	1.78E-02			2.39E-02	1.85E-02	1.89E-02		
0				56.22		35	1.89E-02	9.25E-01	52.99	√
1	1.06E-01	1.36E-06	6.60E-01			1.58E+00	2.08E-11	8.75E-02		
2	-6.18E-02	3.43E-04	-5.89E-01			-9.24E-01	1.10E-06	-5.11E-02		
3	-9.83E-03	1.88E-03	-1.84E-02			-1.52E-01	4.70E-05	-8.01E-03		
4	-5.04E-03	2.81E-03	-8.76E-03			-7.93E-02	2.69E-04	-3.69E-03		
5	-3.19E-03	2.66E-03	-5.41E-03			-5.23E-02	6.12E-04	-1.95E-03		
6	-2.21E-03	2.18E-03	-3.75E-03			-3.94E-02	9.02E-04	-1.08E-03		
7	-1.59E-03	1.70E-03	-2.76E-03			-3.22E-02	1.07E-03	-6.31E-04		
8	-1.17E-03	1.30E-03	-2.11E-03			-2.76E-02	1.14E-03	-3.89E-04		
9	-8.62E-04	9.94E-04	-1.66E-03			-2.42E-02	1.13E-03	-2.56E-04		
10	-6.39E-04	7.61E-04	-1.33E-03			-2.14E-02	1.08E-03	-1.80E-04		
11	-4.75E-04	5.85E-04	-1.08E-03			-1.92E-02	1.02E-03	-1.36E-04		
12	-3.54E-04	4.53E-04	-8.98E-04			-1.72E-02	9.44E-04	-1.09E-04		
13	-2.65E-04	3.53E-04	-7.54E-04			-1.54E-02	8.68E-04	-9.16E-05		
14	-1.99E-04	2.78E-04	-6.41E-04			-1.39E-02	7.95E-04	-7.92E-05		
15	-1.50E-04	2.21E-04	-5.50E-04			-1.25E-02	7.27E-04	-6.99E-05		
16	-1.13E-04	1.78E-04	-4.77E-04			-1.13E-02	6.63E-04	-6.26E-05		
17	-8.64E-05	1.44E-04	-4.17E-04			-1.02E-02	6.05E-04	-5.65E-05		
18	-6.62E-05	1.19E-04	-3.67E-04			-9.17E-03	5.51E-04	-5.13E-05		
19	-5.11E-05	9.88E-05	-3.25E-04			-8.28E-03	5.02E-04	-4.68E-05		
20	-3.98E-05	8.31E-05	-2.90E-04			-7.48E-03	4.58E-04	-4.28E-05		
21	-3.12E-05	7.07E-05	-2.59E-04			-6.76E-03	4.18E-04	-3.93E-05		
22	-2.48E-05	6.07E-05	-2.33E-04			-6.11E-03	3.81E-04	-3.61E-05		
23	-1.99E-05	5.26E-05	-2.10E-04			-5.52E-03	3.48E-04	-3.32E-05		
24	-1.61E-05	4.59E-05	-1.89E-04			-5.00E-03	3.17E-04	-3.06E-05		
25	-1.32E-05	4.04E-05	-1.71E-04			-4.52E-03	2.90E-04	-2.82E-05		
26	-1.10E-05	3.58E-05	-1.55E-04			-4.10E-03	2.65E-04	-2.60E-05		
27	-9.23E-06	3.18E-05	-1.41E-04			-3.71E-03	2.43E-04	-2.41E-05		
28	-7.83E-06	2.85E-05	-1.28E-04			-3.36E-03	2.22E-04	-2.23E-05		
29	-6.71E-06	2.55E-05	-1.17E-04			-3.05E-03	2.03E-04	-2.07E-05		
30	-5.81E-06	2.30E-05	-1.06E-04			-2.77E-03	1.87E-04	-1.92E-05		
31	-5.06E-06	2.08E-05	-9.69E-05			-2.51E-03	1.71E-04	-1.78E-05		
32	-4.45E-06	1.88E-05	-8.84E-05			-2.28E-03	1.57E-04	-1.66E-05		
33	-3.94E-06	1.70E-05	-8.06E-05			-2.08E-03	1.45E-04	-1.55E-05		
34	-3.50E-06	1.55E-05	-7.35E-05			-1.89E-03	1.33E-04	-1.44E-05		
35	-3.13E-06	1.41E-05	-6.71E-05			-1.72E-03	1.22E-04	-1.35E-05		
36	-2.81E-06	1.28E-05	-6.13E-05			-1.59E-03	1.13E-04	-1.25E-05		
37	-2.52E-06	1.16E-05	-5.59E-05			-1.47E-03	1.05E-04	-1.15E-05		
38	-2.28E-06	1.06E-05	-5.11E-05			-1.36E-03	9.68E-05	-1.07E-05		
39	-2.06E-06	9.68E-06	-4.67E-05			-1.26E-03	8.95E-05	-9.86E-06		
40	-1.87E-06	8.83E-06	-4.26E-05			-1.16E-03	8.28E-05	-9.12E-06		

8 CORRECTION OF VALUE IN INPUT

During the study of RSC simulations, it was noticed that the thickness input for the tile and metal sheathing were left out, and were assigned by default to a thickness of 1 foot. This was corrected for the four template files (residential, mdoffice, retail, and warehouse). These changes are tracked with version updates and source control tracking of file updates of the building description language (*.bdl) template files template.resid, template.mdoffice, template.retail, and template.warehouse. The error in the RSC input files for tile and metal sheathing affects the following runs from the LBNL test series: 24588, 24589, 24591, 24592, 24594, 24595, 24612, 24613, 24615, and 24616. When those runs were recalculated, it was found that the performance results for the three roof types (asphalt, tile, and metal) were much closer. Even after this correction, nothing was seen that would invalidate or modify any of the conclusions drawn from earlier analysis. Figure 29 illustrates the heating penalties and cooling savings.[4] See Appendix B: Runs with roof layers corrected for tables of the values.

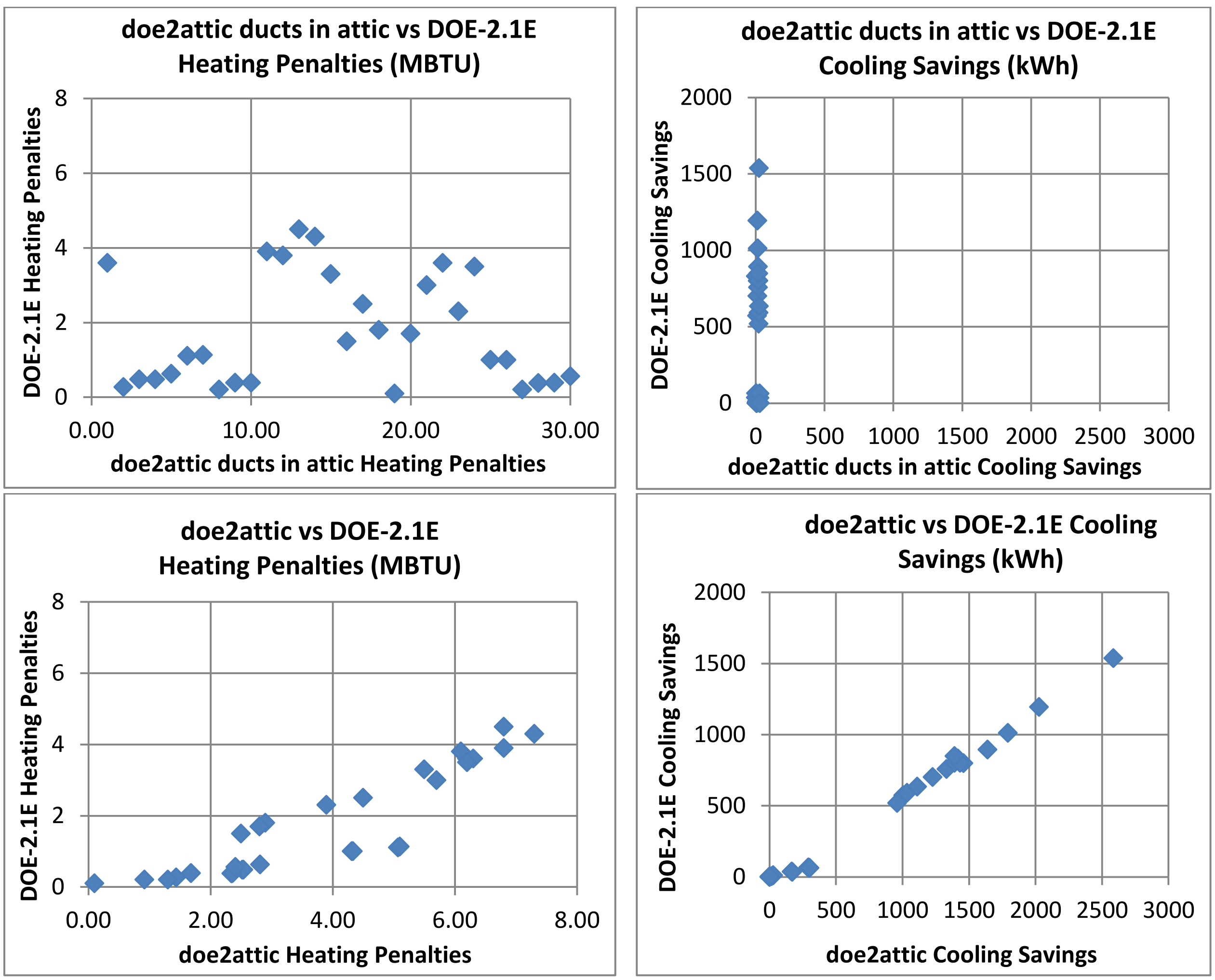


Figure 29: DOE-2.1E heating penalties and cooling savings.

[4] Please request the following files for more details:
T08/11_1213_doe2runs.log_cln
T08/12_0504_deltas.xlsx
T08/12_0504_doe2runs.log_cln
T08/12_0504_template_files.zip

9 DEBUGGING ATTICSIM

EnergyPlus models were prepared in order to isolate the heat flows between various rooms and through the attic floor for comparison. The findings diverged from what was expected. To allow for direct comparison, the EnergyPlus model was constrained to use boundary conditions calculated by doe2attic. Figure 30 confirms that all three boundary conditions used (outdoor air temperatures, room air temperatures, and attic ventilation rates) are essentially the same between doe2attic and EnergyPlus runs.

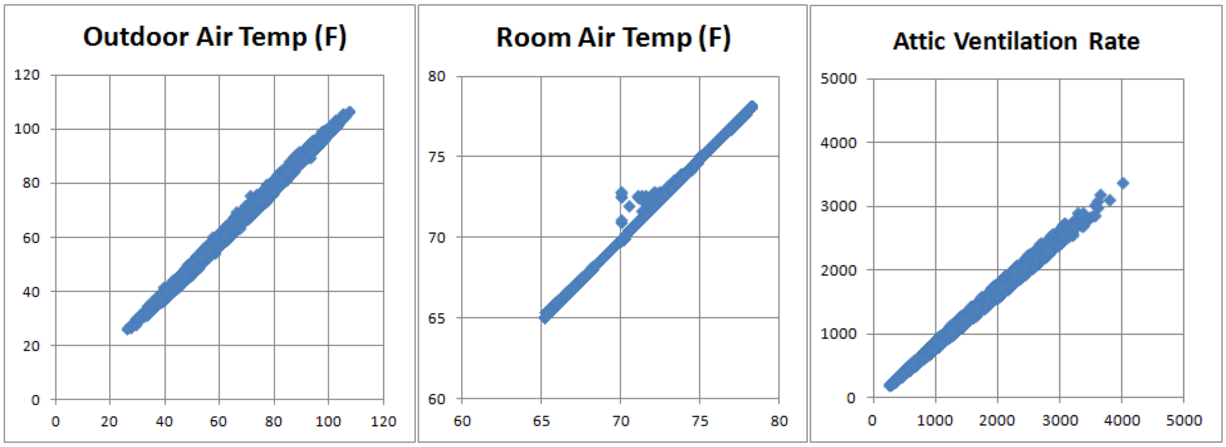


Figure 30. Comparison of outdoor air temperatures, room air temperatures, and attic ventilation rates between the doe2attic (x-axis) and EnergyPlus (y-axis) runs.

The congruence between doe2attic and EnergyPlus means all the boundary conditions for the attic are exactly the same with the exception of a few discrepancies in the room air temperature and ventilation rate. However, the differences in the simulation results for other variables were surprising. Figure 31 and Figure 32 show attic air temperatures calculated by doe2attic, EnergyPlus, and DOE-2.1E for January and July, respectively.

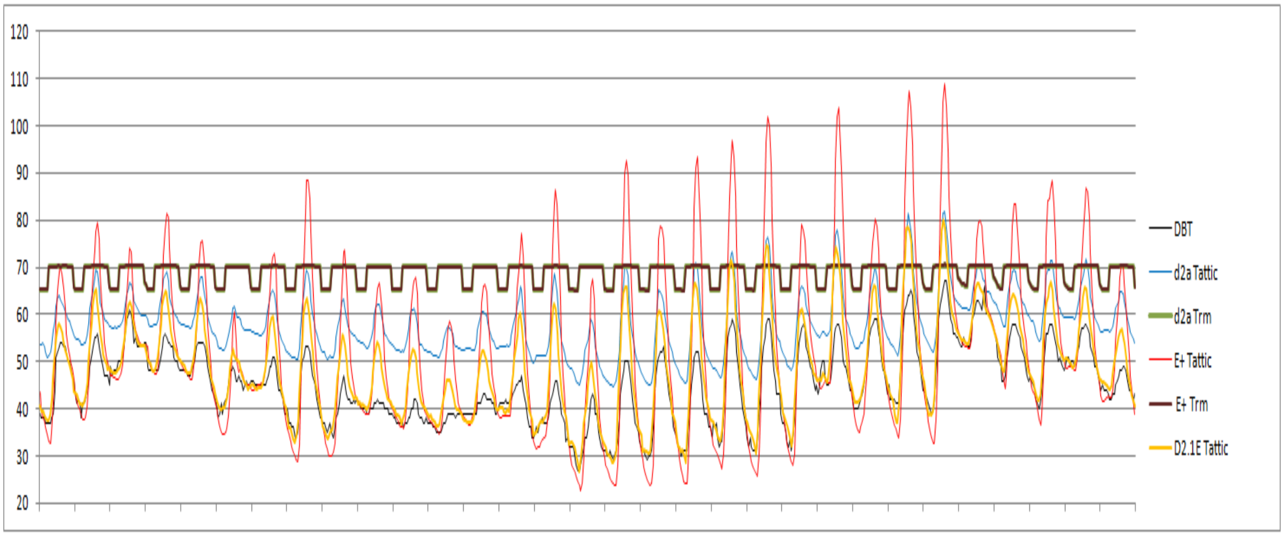


Figure 31. Attic air temperatures calculated by doe2attic, EnergyPlus, and DOE-2.1E for January. DBT is the outdoor air temperature, Tattic and Trm are the air temperatures of the attic and conditioned space below, respectively, as calculated by doe2attic (d2a), EnergyPlus (E+) and DOE-2.1E (D2.1E).

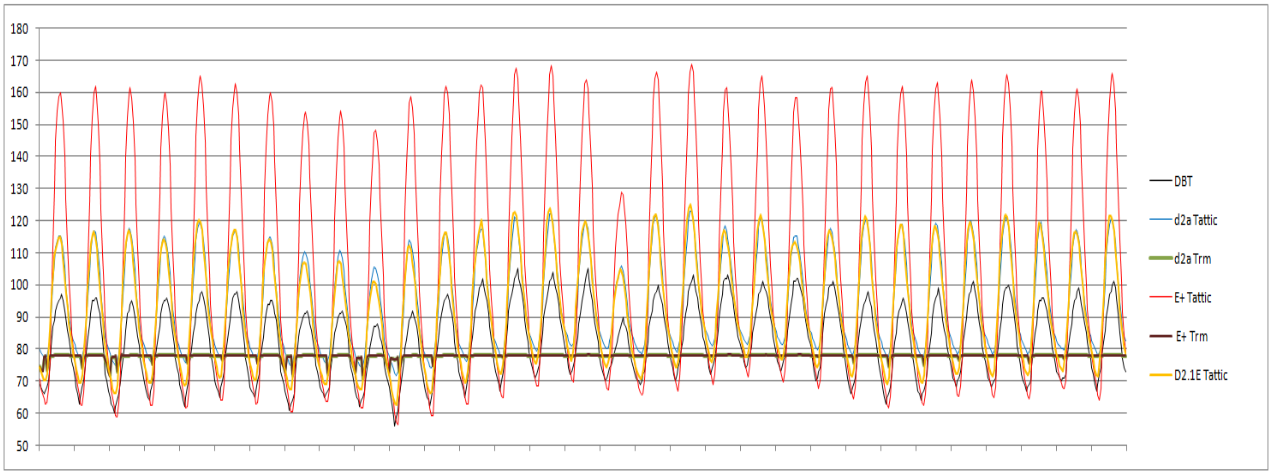


Figure 32. Attic air temperatures calculated by doe2attic, EnergyPlus, and DOE-2.1E for July. DBT is the outdoor air temperature, Tattic and Trm are the air temperatures of the attic and conditioned space below, respectively, as calculated by doe2attic (d2a), EnergyPlus (E+) and DOE-2.1E (D2.1E).

Doe2attic agrees with DOE-2.1E in the daytime peaks but predicts temperatures as much as 40°F lower than EnergyPlus predicts. On the other hand, DOE-2.1E agrees reasonably well with EnergyPlus on the nighttime valleys (although EnergyPlus results dip 5°F below the outdoor air temperature minima and DOE-2.1E results do not), whereas doe2attic shows a substantial dampening with nighttime temperatures being halfway between the outdoor and room air temperatures.

There was no immediate explanation for why these results should be so different, particularly between doe2attic and EnergyPlus (both of which are heat balance programs). The straight DOE-2.1E attic temperatures seem the most realistic (although DOE-2.1E is not necessarily calculating the change in heat fluxes correctly).

Figure 33 shows the dramatic difference between heat flux through the attic floor/ceiling as calculated by doe2attic (AtticSim) and EnergyPlus.

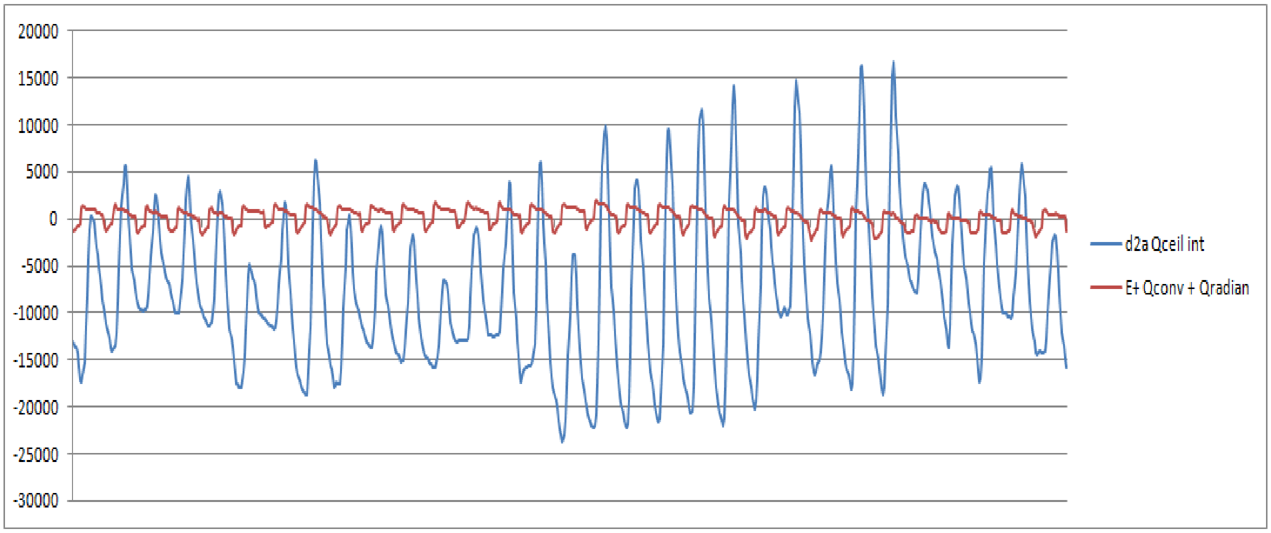


Figure 33. Heat flux (in BTUs/hour) through the attic floor/ceiling as calculated by doe2attic.

Diagnostic runs were made where the ceiling insulation was swapped from R-0 to R-50 with almost no effect on the attic air temperature as shown in Figure 34. At this point, the lack of effect on air temperature was conjectured to be due to an error in transferring the ceiling layer properties to AtticSim, or an error in the AtticSim program itself.

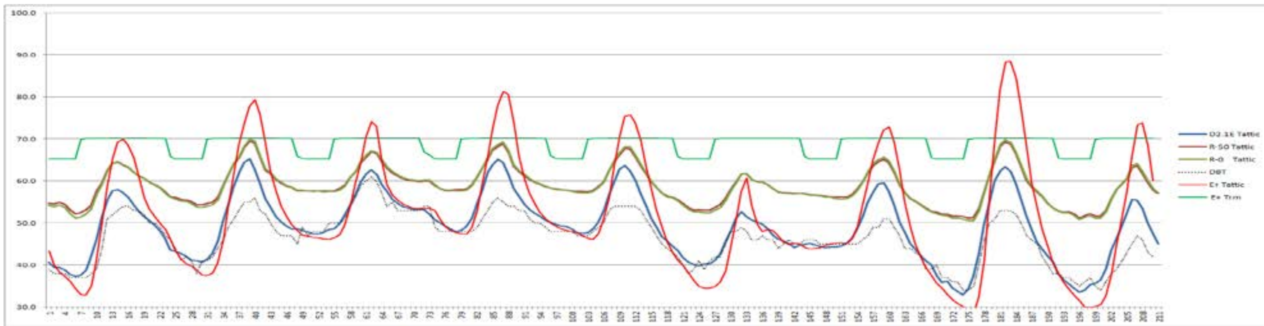


Figure 34. Heat flux through the attic floor/ceiling as calculated by doe2attic after toggling R-0 and R-50.

As part of the integration of DOE-2 and AtticSim, several temporary files are produced that serve as input files to AtticSim: ATIN.TMP, ATWEA.TMP, ATHVAC.TMP, etc. These files were renamed by removing the AT prefix and the AtticSim program crashed immediately upon being invoked. The duct inputs from an earlier file that ran were added in, and AtticSim restarted. It ran to Day 164 and then crashed, this time in reading HVAC. When day 164 of HVAC was inspected, it was found out that a formatting error in the integration code had let two numbers merge whenever the second number (temperature) was over 100. Memory space was added, and the AtticSim revision was able to run from beginning to end.

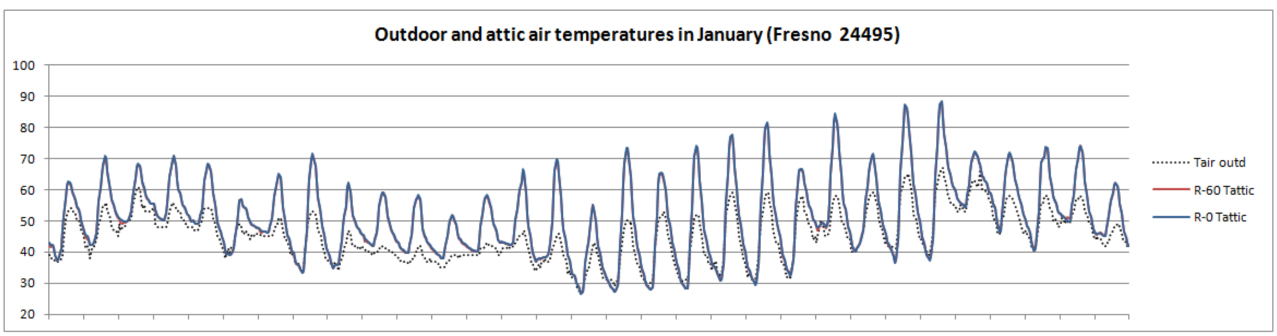


Figure 35. Outdoor air temperatures in January for Fresno, CA.

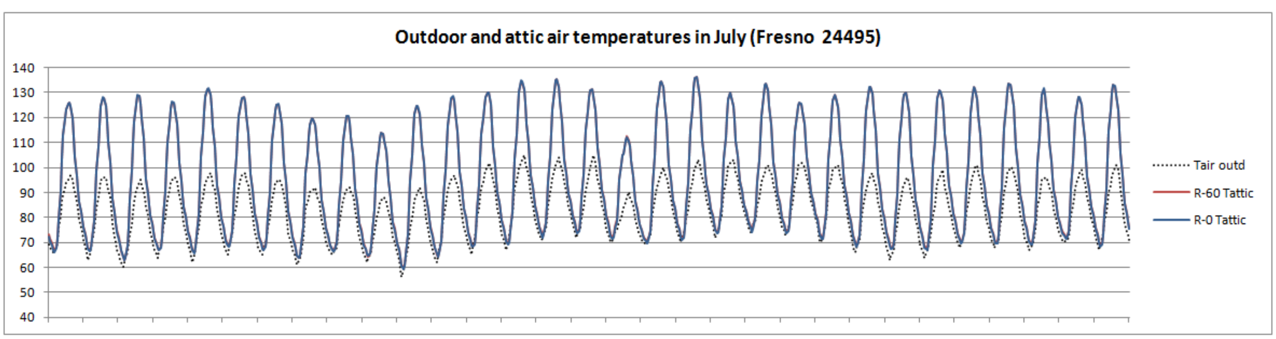


Figure 36. Outdoor air temperatures in July for Fresno, CA.

When the OUT files were inspected, it could be seen that the attic temperatures were not floating halfway between the outdoor and room air temperature but were very close to the outdoor minima at night (what one would expect from general physics). However, attic temperatures did not change at all whether the ceiling insulation was R-0 or R-60 as shown in Figure 35 and Figure 36. It is unlikely that ceiling insulation has no effect on the attic air temperature. Hypothesized causes included the integration routine's calculation of RFs with DOE-2 ***or*** their translation to the IN file.

While investigating why the doe2attic implementation comes out with very different and faulty results compared to EnergyPlus, an error was found and corrected in the ducts input of AtticSim. Formulation of the duct model is in the appendix of the ASTM C 1340 Protocol; however, it is not the current version used in AtticSim. The current version uses a transient finite difference analysis to compute the bulk air temperature along the length of the duct system. The duct can have up to 25 duct runs in any combination of supply and return ducts. Radiation from the attic surfaces to the duct and convection to the duct are accounted for in the finite differencing approach, allowing greater duct modeling accuracy than that originally defined in ASTM C 1340.

10 RESPONSE FACTORS AND CONDUCTION TRANSFER FUNCTIONS

The 2009 AtticSim version that was imported into the RSC reads an input file containing Conduction Transfer Functions (CTFs) that are calculated with a Fortran program called CTFwam.for. Furthermore, another, shorter program called Parctf.for combines CTFs for two sections of a surface, e.g., frame and non-frame portions of a wall or roof, into a single area-weighted CTF.

A comparison of the CTF with the RF generated by DOE-2.1E for the same layer found that they were almost exactly the same, except that the output from CTFwam.for (part of AtticSim) had a few more terms in the time series before resolving the Common Ratio (CR). Prof. Jeff Spitler at Oklahoma State University, the author of the CTF method, provided references to several methods [41][42][43] to convert RFs to CTFs.

An investigation indicated that RFs generated by DOE-2 are the same as CTFs calculated by AtticSim. It was initially decided that we did not need to incorporate CTFwam.for into doe2attic; rather, we could simply echo the DOE-2.1E RFs to AtticSim. Furthermore, a feature was also added to DOE-2.1E to combine two RFs into one, thus replicating what Partctf.for does and making that program also unnecessary.

10.1 VERIFICATION OF RESPONSE FACTORS

An exercise was conducted to compute the RF for an attic floor for comparison with output from DOE2 algorithms.[5] The simulation was for an attic floor having a parallel path heat flow between 2 by 6 rafters and blown insulation to RUS-19 specifications.

[5] Please request the following files for more details: T20/24495_ASstandalone_inps.zip, T20/ AtticSim_ASV.for, T20/ CeilR19_ctf.txt, T20/ CeilR19_ctfa, T20/ CeilR19_ctfb, T20/ CeilR19_ctfc, T20/ CTFwam.for, T20/ parctf.for, T20/ Qrpt-08Q4.pdf, and T20/ RF_09_0915_compare.xls.

Table 5: Computation of response factor for an attic floor for comparison with output from DOE-2 algorithms

Layer	Length (ft)	Conductivity (Btu/h·ft·°F)	Specific heat (Btu/lbm·°F)	Density (lbm/ft^3)	RUS-value (h·ft^2·°F/Btu)
FBG	0.726	0.038	0.17	2	19
GYP	0.042	0.093	0.26	50	0.45
FBG	0.267	0.038	0.17	2	7
6x2	0.458	0.069	0.289	33.75	6.614
GYP	0.042	0.093	0.26	50	0.45

1. CTFwam.for was run with property of materials input in inch-pound units, which produced two output files.
2. Then the Parctf.for code was used. The routine asks for the fraction of area for the two parallel paths. A value of 1.5/16 was used for the fraction of area, assuming 2 by 6 boards that are 16-in on center, which produced an output that could be used in in AtticSim for an RUS-19 attic floor.

AtticSim uses CTFs, and there is a simple conversion from RFs to CTFs; but RFs and CTFs are not equal and yield often slightly different but fundamentally incorrect results when used as replacements for one another. The conversion from RFs to CTFs could easily be made in AtticSim (approximately a dozen lines of code). Parctf.for can convert multiple CTFs into a single area-weighted CTF for use in AtticSim. The use of CTF in the input to AtticSim results in attic air temperatures that are very different for an R-0 and R-60 ceiling as previously discussed in Section 9. When doing so, two key issues arise:

1. AtticSim uses CTF, so a routine must either be added into Atticsim to convert the RFrs into a single set of CTFs or a pre-processing routine used to calculate the CTF as input to AtticSim.
2. The input file echoed from the DOE2 code shows for the specified test case show RFs to be wrong.
    a. The DOE-2 RFs should sum to the thermal resistance of the composite layer being modeled.
        i. X-terms are off 41.88 versus 52.99 (as seen previously in Table 4)
        ii. More terms are required than the number determined from other simulations.

At a quick glance, the results are according to expectations: Attic temperatures are more like the ambient temperature as insulation is added, thus decoupling the attic thermally from the space below. The previous set of runs were done using the AtticSim code modified by Huang to fit the Fortran structure of DOE-2, whereas this set was done using an old AtticSim code (circa 2009).

Work is ongoing to verify response factors and the role of improvements to the duct model for potential use in RSC. Specifically, four sets of AtticSim results for the same (or nearly the same) inputs are planned to be used:

1. From the RSC, i.e., doe2attic running a Fortran 77 version of AtticSim (modified by Ender Erdem)
2. From the latest Fortran 90 AtticSim (done by Ken Childs)
3. From Fortran 77 AtticSim standalone (modified by Ender Erdem)
4. From Fortran 77 AtticSim stand-alone

If sets 2 and 4 agree in showing significant changes in attic air temperatures with increased insulation, then the task would be to compare set 3 with set 4 to find out why set 3 is behaving differently. Then, for due diligence, improvements made in set 2 (e.g., better ventilation modeling) should be added to set 3 as well. Finally, any changes should be incorporated to set 1 (i.e., the doe2attic program in the RSC).

One caveat regarding the simulations is that the room air temperatures may be somewhat inaccurate, especially during hours when the HVAC system is not running, since those were by doe2attic before the latest duct modeling updates by Ken Childs to resolve this issue. The authors are unsure how duct interactions affect the change in space-conditioning energy use due to changes in the roof albedo, since to the first order the conductive heat flows through the ceiling are the same regardless of roof albedo. Ongoing analysis is further quantifying the role of ducts (e.g. a semi-conditioned attic) has on attic thermal flows in the roof and attic assembly.

10.2 ADDITIONAL RUNS

Additional runs were conducted involving hourly values from AtticSim not available through standard DOE-2.1E hourly reports. Shortened input file names were used with some slight changes (i.e., Roof_Type to Roof_Type_res or Roof_Type_com depending on the building type) and versioned for identification purposes. The list of the final input filenames and the batch procedure are available upon request. A summary hourly file was saved which reports hourly values from the AtticSim temporary files as well as the DOE-2 hourly reports for the room air temperature, heating and cooling energy use, and other values.[6]

In the output, field names include Month, Day, Hour, Qroof_ext, Qroof_int, Qatflr, Qceil, DBT, Troof_ext, Troof_int, Tattic, Tatflr, Tceil, At_Vent, Tattic, Troom, HeatE, and CoolE. All heat fluxes (Q) are in BTU/h, all temperatures (T) are in °F, HeatE is in BTU, CoolE is in kWh. The numbers for the office runs are very small because the offices have a central plant, so their HVAC energy consumption appears in a different HOURLY-REPORT.

Some additional notes regarding the simulations:

- Extracting and combining these hourly variables is not a standard tested procedure in DOE-2.1E and involves quite a bit of investigation and interpretation.
- All the results were not investigated, although the procedure was tested using the test runs from the previous year.
- Using the 136 parametrs in this study is likely overkill; certain parameters such as vintage and location variations would not yield significantly different results since building physics are similar in such cases.
- Substantial differences between DOE-2.1E, doe2attic, and EnergyPlus were observed, and in depth diagnostics were done in one run, such as taking out the duct system, varying the ceiling R-value, and roof absorptivity.

The differences in pre and post fix (using CTFs instead of RFs) to doe2attic were sorted. In addition to the repeat of all the previous runs, new runs were simulated for the “old office” identified as “wdroof” for which the roof was changed from 4 in. of concrete to residential wood frame construction.[7]

Summaries were made from the runs (old_office, old_office_wdroof, new_home), which revealed several interesting results that discussed in the following list. The office prototypes still exhibit substantial unmet

[6] Please request the following file for the output: T32/13_1010_Ronnen_runs_hrly.zip
[7] Please request the following file for the output: T32/ 13_1209_Ronnen_runs_hrly.zip

cooling loads, and the attic radiation effect (gauged by removing the radiant barrier) is less reliably predicted in these runs than in previous runs.

In the following observations, we refer to Summary A and B which are 380 and 552 pages, respectively. These documents consist primarily of R-generated analytical graphs for simulation data analysis and are too long to include in this report, but are available upon request.

1. Incorporating attic radiation (p.1 of Summary B)
Incorporating attic radiation (by removing the radiant barrier) has minimal effect on the cooling savings in old_office; in old_office_wdroof, it reduces the cooling energy savings by ~10% and reduces the heating penalty by up to 60% as seen in Figure 37.

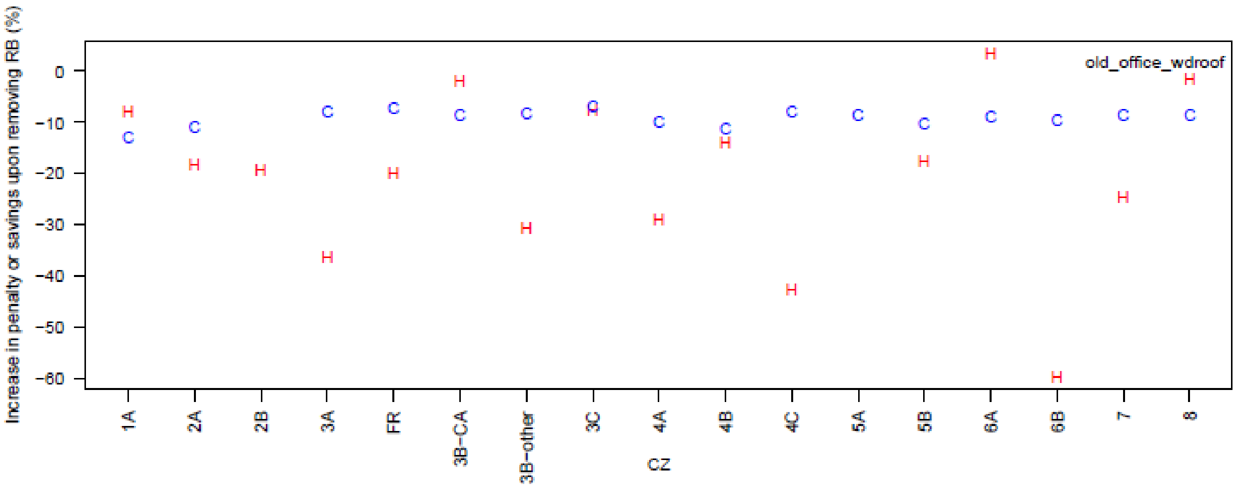


Figure 37. Simulation effects of removing a radiant barrier from old office with wood roof

In new_home, incorporating attic radiation increases both the cooling savings and the heating penalty as seen in Figure 38. Fractional increases in cooling energy savings are still substantially higher than fractional increases in heating energy penalties, although the fractional increases are roughly half those in Summary A (October runs).

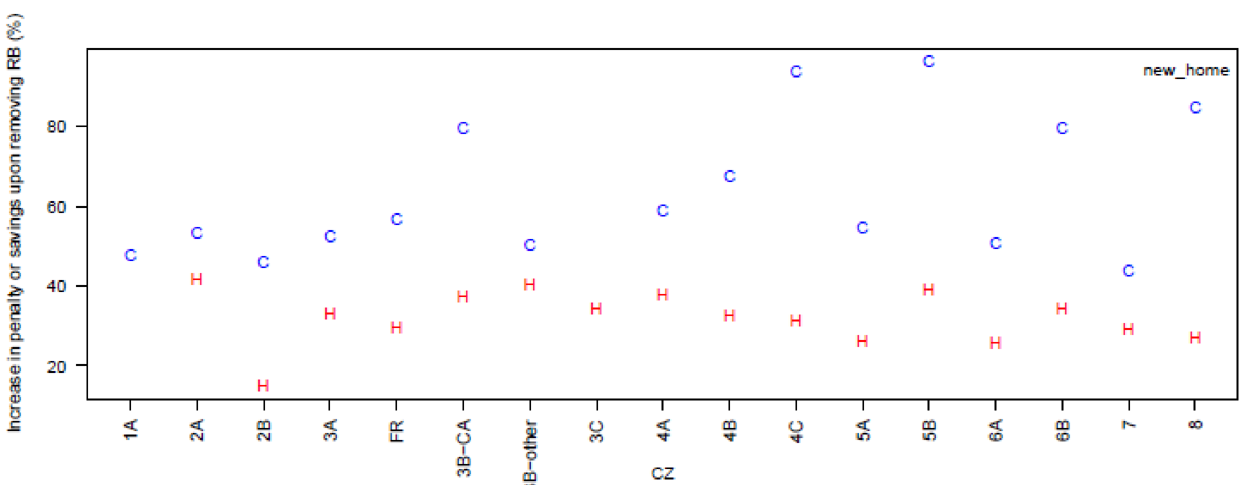
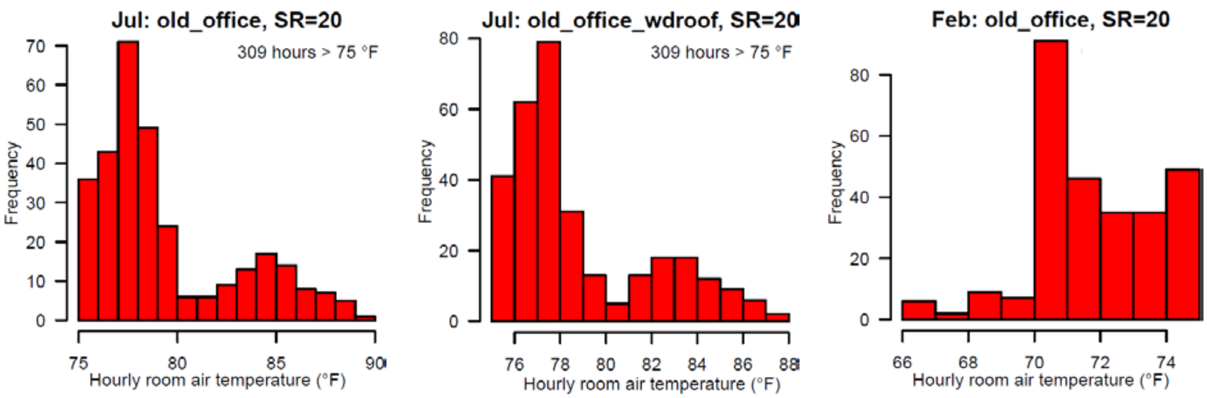


Figure 38. Simulation effects of removing a radiant barrier from a new home.

Simulation results for the month of December for old_office and old_office_wdroof appear not to make physical sense. Further analysis would be needed to determine whether simulations for December for new_home are more or less accurate than those for October.

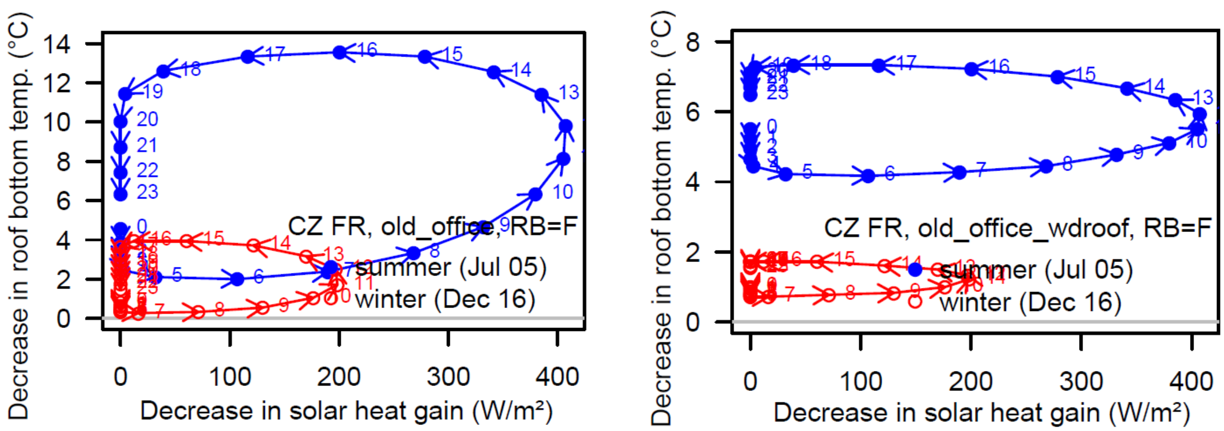
2. Unmet cooling loads in summer (pp. 13, 16 of Summary B)
In summer months, there are as many as 309 hours of scheduled HVAC operation during which the air temperatures inside old_office and old_office_wdroof exceed the setpoint of 75°F as shown in Figure 39 (a) and (b). Thus the reflective roof reduces inside air temperature instead of saving cooling energy. Unmet hours were also observed for the old_office in winter month as shown for February in Figure 39 (c). This analysis assesses HVAC operation from local (clock) time. While DOE-2 holidays were not excluded, there are no such holidays in June or August.



(a) (b) (c)

Figure 39. Simulation results of varying unmet hours complicate comparison of RSC results.

3. Wood roof deck exhibits less thermal mass (p. 39 of Summary B)
As expected, the 3/4 in. wooden roof deck in old_office_wdroof, as shown in Figure 40 (a), exhibits less thermal mass than the 4in. concrete roof deck in old_office as shown in Figure 40 (b).



(a) (b)

Figure 40. Hourly variance of roof bottom temperatures for summer and winter days.

The many graph types are shown in Section 12, but the domain-specific analysis of this data and the extent to which it was used to update RSC extends beyond the scope of this work.

10.3 CHANGE IN SIZING RATIO

Simulations of office were conducted increasing the SIZING-RATIO to 1.667 to eliminate the underheated and undercooled hours. The number of unmet hours is large due to the way DOE-2 performs its autosizing. It does not know the interzone heat transfer; therefore, the office spaces have all been sized assuming no heat transfer through the ceiling (nor any effects from pick-up loads), which was why the equipment was undersized.[8]

The radiant component was shown to be more prominent in simulations specifically for October and December. Use of Response Factors in lieu of Conduction Transfer Functions in earlier October simulations resulted in large amounts of ceiling heat transfer (in reference to the discussion about the attic temperatures being too high and not changing with ceiling R-value), unrealistically accentuated radiant (as well as convective) heat transfer.

10.4 CORRECTION OF CALCULATION OF THE COMPOSITE RESPONSE FACTORS

The calculation of the composite response factors was corrected after conversion of the attic response factors to conduction transfer functions. Reasonable changes in the attic air temperatures between R-0 and R-53 test cases were observed in the new version of AtticSim. This modification was complicated by the nomenclature differences for CTFs between doe2attic (X, Y, and Z) to that used by DOE-2 (XX, YY, and ZZ) when DOE-2 uses the same X, Y, Z terminology for response factors. AtticSim additionally uses the same X and Y variables for other purposes in the configuration algebra for view factors.

There were mistakes in the material thicknesses that was found and corrected to enable correct computation and formatting of RFs and CTFs:

- Gypsum board changed to 0.04167 feet thick
- There is a dimensional discrepancy in thickness of FG insulation.
  - Total FG Thickness = 1.315000057 feet (from 0.815300047)
  - 2 by 6 Thickness = 0.4583 feet
  - FG above 2 by 6 = 0.8567 feet (from 0.8153)

```
CEILJL = LAYERS
MATERIAL=(DRYWALL,WOOD,INSUL)
SPECIFIC-HEAT=(.26,.29,.20)
CONDUCTIVITY=(0.0925,0.0667,0.0263)
DENSITY=(50,34, 1.15)
THICKNESS=(.4167,.4583,0.815300047)
INSIDE-FILM-RES=.765 ..

CEILNJL = LAYERS
MATERIAL=(DRYWALL,INSUL)
SPECIFIC-HEAT=(.26,.20)
CONDUCTIVITY=(0.0925,0.0263)
DENSITY=(50,1.15)
THICKNESS=(.4167,1.315000057)
INSIDE-FILM-RES=.765 ..
```

[8] Please request the output file: T32/13_1221_Ronnen_runs_hrly.zip

After modifying doe2attic to use the composite parallel CTFs rather than the RFs, many results (outlined throughout this report) have become more aligned with expected patterns. A rough model of the ORNL-Charleston Facility was created and simulations made that generally match the results shown earlier, with the exception that simulated peak daytime temperatures are low by several degrees C.

Comparing results for houses in Fresno, CA

A project lead by Levinson recently concluded a study which measured temperatures, heat flows, and energy uses for 12 months in two adjacent homes in Fresno, CA. One home had a low-albedo asphalt shingle roof, while the other had a higher-albedo concrete tile roof; the two buildings were otherwise quite similar. For details on house properties (Table 1 and Figure 1) or building operation (Section 3.5), the interested reader is referred to [36]

Pablo Rosado and Ronnen Levinson assembled a TMY2-format weather file in which the Fresno TMY2 hourly values of solar irradiation, outside air temperature, and outside air humidity are replaced with values measured at the site, and replace wind speeds with values reported by the nearest CIMIS station. Data from the onsite anemometer is missing. As part of the RSC validation effort, these two houses were simulated and compared for hourly temperatures, heat flows, and (possibly) energy uses. This study is ongoing and beyond the scope of this work.

11 MODIFICATIONS FOR ATTICSIM/DOE2.1E

The errors that were discovered in the summer of 2013 while simulating radiant barriers with and without ducts and trusses in the attic were reviewed and verified[9]. The following are a few of the changes that were made to the source code of the DOE2.1E/Atticsim workspace as a direct result of the radiant barrier study:

1. **Subroutine Vent**
   - **Comment out the following algorithm**

```
C CALCULATE THE EFFECTS OF WIND DIRECTION ON WIND AT VENT
c   Arg = DABS(DSIN((DIR + 90.0D0)*3.14159265/180.0D0))
c          if (Arg .eq. 0.0) then
c          WSi = 0.087*WS
c          else
c          WSi = 0.45*WS*(0.087 +
c  &         0.130*Arg**2.5)
c     end if
```

   - Rename WSi to WS in equation for QWIND

```
C CALCULATE FLOW DUE TO WIND PRESSURE, SEE ASHRAE PG. 22.6
  QWIND = 5280.0*0.6*AMIN*WS
```

2. **Check and correct dimension for G array**
   - **Make G array G(33,33) in main and all subsequent subroutines**
   - **Subroutine View2D make B, E, Emit, CHI, F and PSI arrays 33 by 33**

```
DIMENSION F(33,33),CHI(33,33),PSI(33,33),E(33)
DIMENSION B(33),EI(7),G(33,33),A(K),EMIT(33)
```

[9] Please request T09/HCONRoof.for for more details.

3. **Subroutine HCON**
   - **Modify routine to make convection coefficients zero for small eaves**
     Note: AtticSim input calls for eave height. If height "AL" made small then convection coefficient goes high which is not consistent with intent of eliminating eave.

```
1000 CONTINUE
  if (AL .GT. 0.0625) THEN
  HCN = NUS*K/AL
        ELSE
        HCN = 0.0
        END IF
2000 continue
  if (AL .GT. 0.0625) THEN
  HCF = NUSf*K/AL
        ELSE
        HCF = 0.0
        END IF
```

4. **Call to Subroutine SOLVP**
   - **In subroutine view2d**

```
 300 IF(I.EQ.L) E(I) = 1.0
   CALL SOLVP(NTOT1,CHI,E,B,33)
```

   - **In subroutine view2t**

```
1000 IF(I.EQ.L) E(I) = 1.0
  CALL SOLVP(NTOT1,CHI,E,B,33)
```

5. **Subroutine HCONRoof**
   - **Add the attached subroutine for computing the external roof heat transfer coefficient Routine attached in Fortran code**

   - **Modify main body of code to call HCONRoof where exterior conv coefficient required Places in main code requiring modified call**

```
C CALCULATE CONVECTION COEFFICIENTS AT OUTSIDE SURFACES
  WS1 = WS*5280. ! WIND VELOCITY FT PER HR (POINT FOR TMY2 ADJUSTMENT)
C
  CALL HCON(TOS(1,1),TI,0.0D0,AL1,2,1,0.0D0,HCO(1))
C
  IF (LFLAG(1) .eq. 0) then
  CALL HCONRoof(TOS(2,1),TO,PITCH1,AL2,1,ISURF,WS1,HCO(2))
  if (IVFLAG .eq. 0) CALL HCONRoof(TOS(3,1),TO,PITCH2,AL3,1,ISURF,
 &                 WS1, HCO(3))
    go to 150
    END IF
    IF (LFLAG(1) .eq. 1 .and. LFLAG(3) .eq. 1) then
  CALL HGapOpn(TIS(8,1),TASV(1,1),TOS(2,1),TO,EO(2),PITCH1,AL,AL2,
 &        GAP,1,0.0D0,HCO(2),AMDOT2,NUS(2))
  CALL HCONRoof(TOS(8,1),TO,PITCH1,AL2,1,ISURF,WS1,HCO(8))
    if (IVFLAG .eq. 0)
 &CALL HGapOpn(TIS(9,1),TASV(2,1),TOS(3,1),TO,EO(3),PITCH2,AL,AL3,
 &        GAP,1,0.0D0,HCO(3),AMDOT3,NUS(3))
  if (IVFLAG .eq. 0) CALL HCONRoof(TOS(9,1),TO,PITCH2,AL3,1,ISURF,
 &                 WS1, HCO(9))
    go to 150
```

```
 END IF
    IF (LFLAG(1) .eq. 1 .and. LFLAG(3) .eq. 0) then
 CALL HGapCld(TIS(8,1),TASV(1,1),TOS(2,1),TO,PITCH1,AL,AL2,GAP,1,
&        0.0D0,HCO(2),AMDOT2,NUS(2))
 CALL HCONRoof(TOS(8,1),TO,PITCH1,AL2,1,ISURF,WS1,HCO(8))
    if (IVFLAG .eq. 0)
&CALL HGapCld(TIS(9,1),TASV(2,1),TOS(3,1),TO,PITCH2,AL,AL3,GAP,1,
&        0.0D0,HCO(3),AMDOT3,NUS(3))
 if (IVFLAG .eq. 0) CALL HCONRoof(TOS(9,1),TO,PITCH2,AL3,1,ISURF,
&                 WS1, HCO(9))
 END IF

150 CALL HCON(TOS(4,1),TO,90.0D0,AL4,1,1,WS1,HCO(4))
    CALL HCON(TOS(5,1),TO,90.0D0,AL5,1,1,WS1,HCO(5))
         CALL HCON(TOS(6,1),TO,90.0D0,AL6,1,1,WS1,HCO(6))
         CALL HCON(TOS(7,1),TO,90.0D0,AL7,1,1,WS1,HCO(7))
```

6. **Subroutine HCONRoof and HCON**
    - **Declare variable NUSF as REAL*8**

7. **Subroutine DUCTTR**
    - **Search for QRAD(8) and substitute dx(I) for ALD(I)**

```
 DO 350 J = 1,7
 DO 350 I = 1,NTOT
 DO 350 JJ = 1,NSEC(I)
 QRAD(J) = QRAD(J) +
&  HR(I,J)*PO(I)*DX(I)*(TWOD(I,JJ) - TIS(J,1))*DT
350 CONTINUE
  IF(ITRUS.NE.0) THEN
  DO 360 I = 1,NTOT
  DO 360 JJ = 1,NSEC(I)
  QRAD(8) = QRAD(8)
&  + HR(I,8)*PO(I)*DX(I)*(TWOD(I,JJ) - TTRUS(1))*DT
360 CONTINUE
```

12 ANALYSIS AND COMPARISON OF RSC RESULTS

The graphs[10] in this section (Figure 41-Figure 53) illustrate the analysis of the RSC results, and some are compared with Akbari and Konopacki 2005 [23].

The following are some property values used in the nomenclature of the following analysis and figures:

- HHI18C [kWh/m2] = heating hour insolation, base 18C = insolation received during hours when outside air temperature <= 18°C.
- CHI18C [kWh/m2] = cooling hour insolation, base 18C = insolation received during hours when outside air temperature > 18°C.
- Heating load = heat added by HVAC = heating energy use · COP_heating.
- Cooling load = heat removed by HVAC = cooling energy use · COP_cooling.
- FR = Fresno.
- RB=(T,F) ≥ radiant barrier (present, absent).

[10] Please request T05/summary 2013-11-11b.pdf for comparison graphs for all cities.

- AKBARI refers to Akbari and Konopacki 2005 [23].
- RSC old_office prototype very closely matches that in AKBARI.
- RSC new_home prototype is styled after that in AKBARI, but it has an SR gain of 0.15, rather than 0.30, has a 10% higher COP_cooling (3.3 vs 2.9), and is smaller.

For comparison with RSC, the ABKARI new_home savings and penalties were scaled to match the SR gain and cooling COP used in RSC (i.e., multiplied by 0.15 / 0.30, and then by 2.9 / 3.3). All savings and penalties are per unit of roof area. This is slightly ambiguous for the new home, but roof area difference is minimal at 6% greater than ceiling area for a 20° roof.

The design HVAC temperatures and schedule in each prototype (old_office, new_home) are as follows from doe2.out:

```
old_office
   *2435 * $ Schedules
   #2436 # ##set1 wd_start 7
   #2437 # ##set1 wd_stop 18
   #2438 # ##set1 we_start 8
   #2439 # ##set1 we_stop 12
  $ HVAC schedules
  .1*2538 *  $ no ramping, on 1 hour early, off 1 hour late
   *2713 * SPACE-1 SPACE-CONDITIONS
   *2714 *     ZONE-TYPE    = CONDITIONED
   *2715 *     TEMPERATURE   = (73)

new_home
   *3065 *  HEATSET=70  SETBACK=65  $ moderate night setback
   *3066 *  COOLSET=78  SETUP=78   $ no day setup
   *3067 *
   *3068 *  VTYPE=-1          $ enthalpic venting
   *3143 * HTSCH  SCHEDULE $ heat temperature schedule, 7 hour night setback
   *3144 *          THRU DEC 31 (ALL) (1,6) (SETBACK)
   *3145 *                   (7,23) (HEATSET)
   *3146 *                   (24)  (SETBACK) ..
   *3147 * CTSCH  SCHEDULE $ cool temperature schedule, 7 hour day setup
   *3148 *          THRU DEC 31 (ALL) (1,9) (COOLSET)
   *3149 *                   (10,16) (SETUP)
   *3150 *                   (17,24) (COOLSET) ..
```

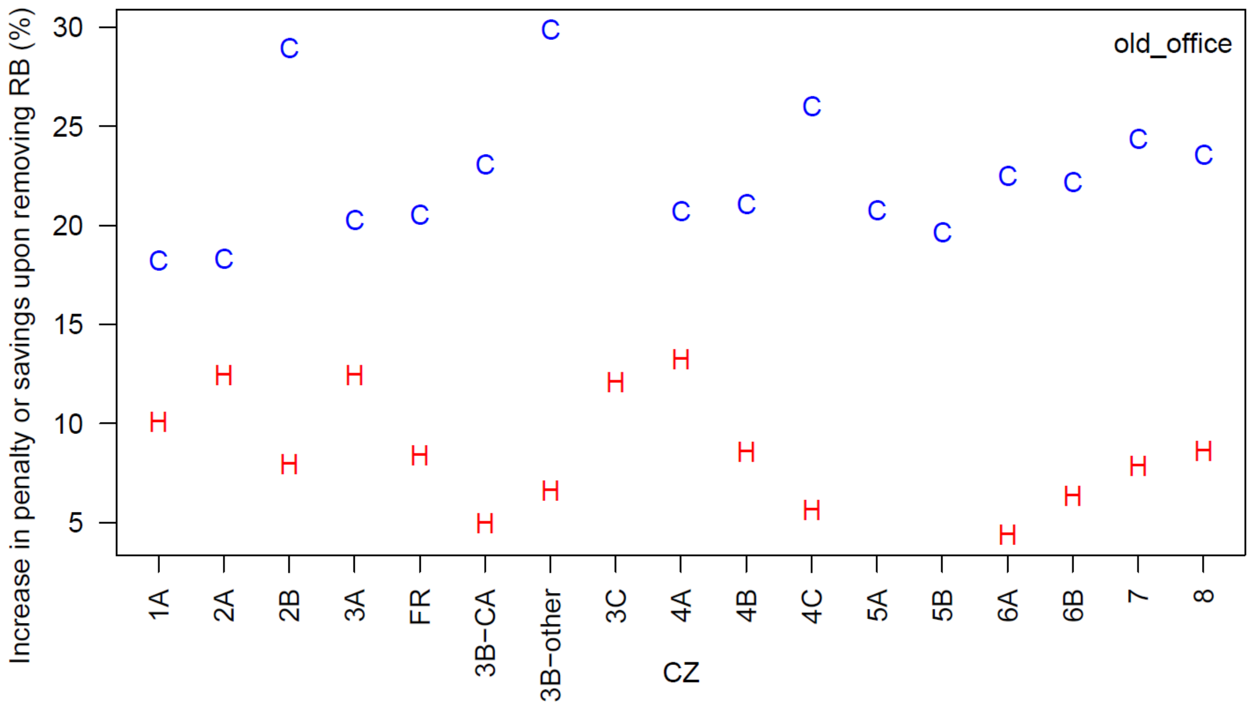


Figure 41. For old office, attic radiation boosts cooling savings more than heating penalty.

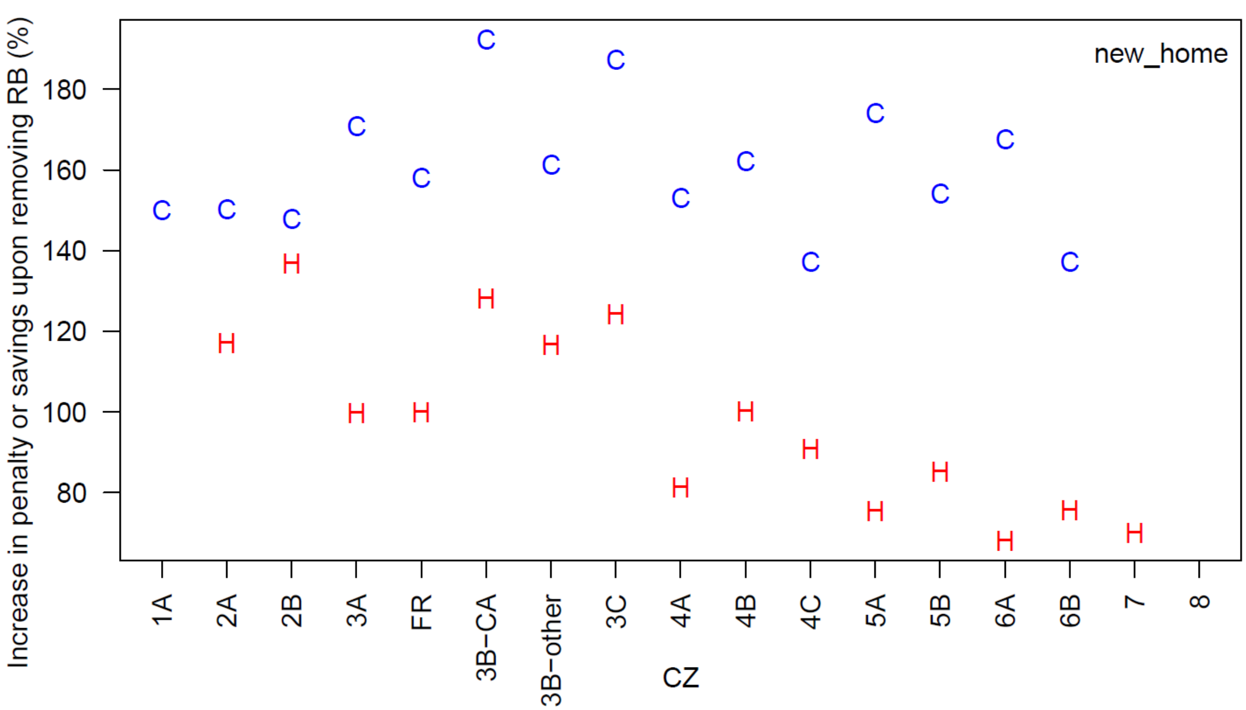


Figure 42. For new home, attic radiation boosts cooling savings more than heating penalty.

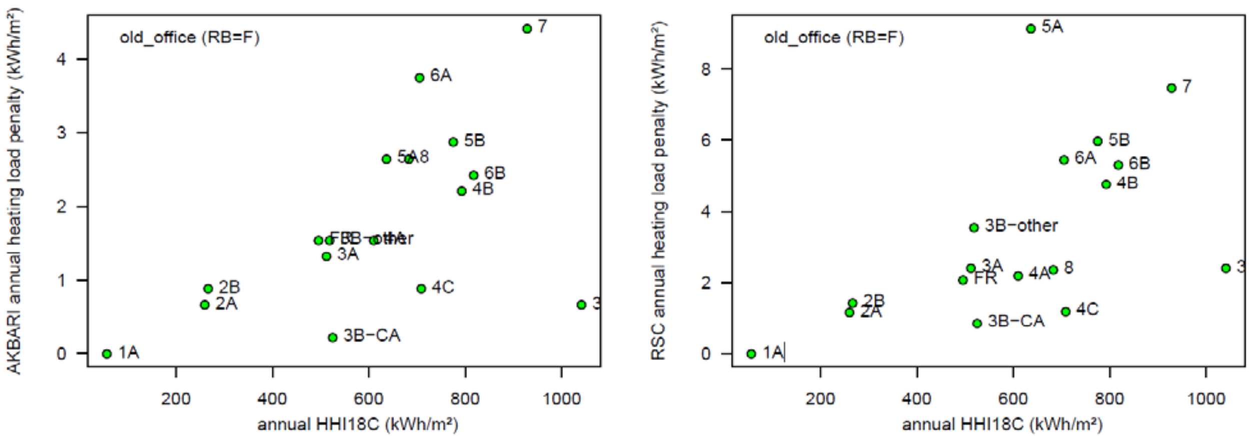


Figure 43. Annual heating load penalty (AKBARI vs RSC) for old office.[11]

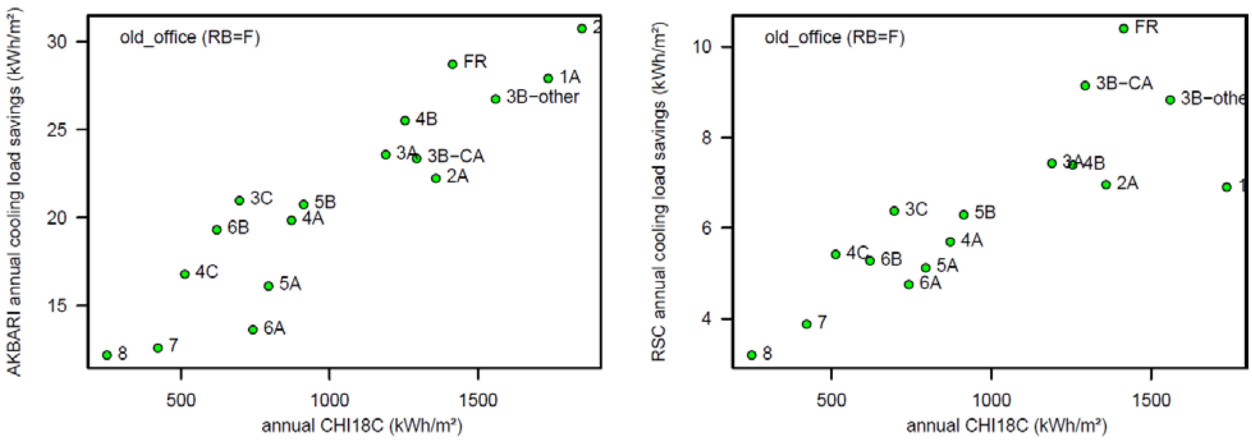


Figure 44. Annual cooling load savings (AKBARI vs RSC) for old_office.

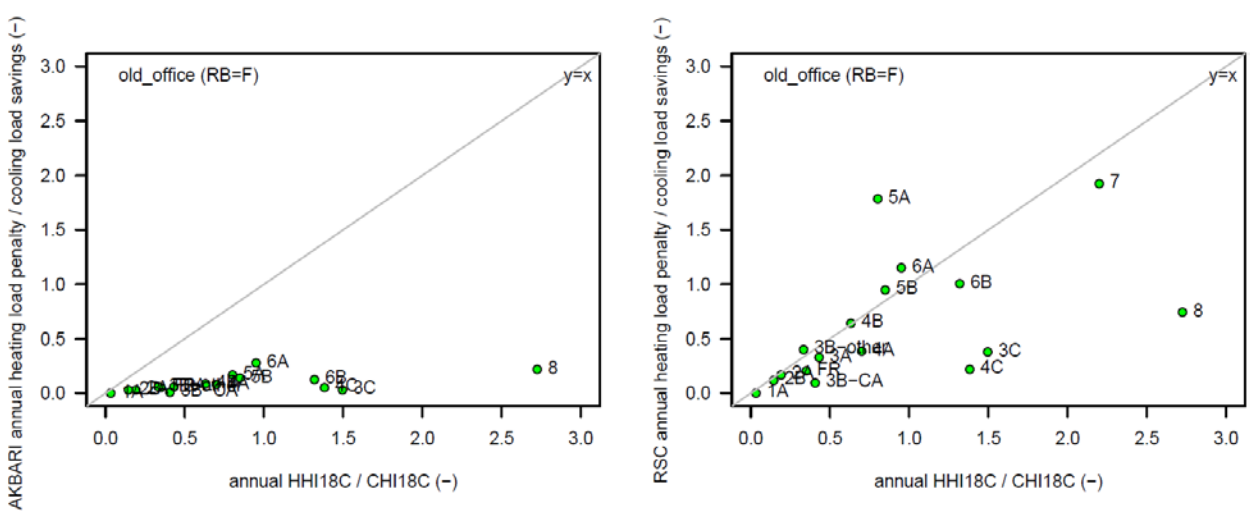


Figure 45. Annual heating load penalty / annual cooling load savings (AKBARI vs RSC) for old office.

[11] Please request T05/summary 2013-11-11b.pdf for comparison graphs for all cities.

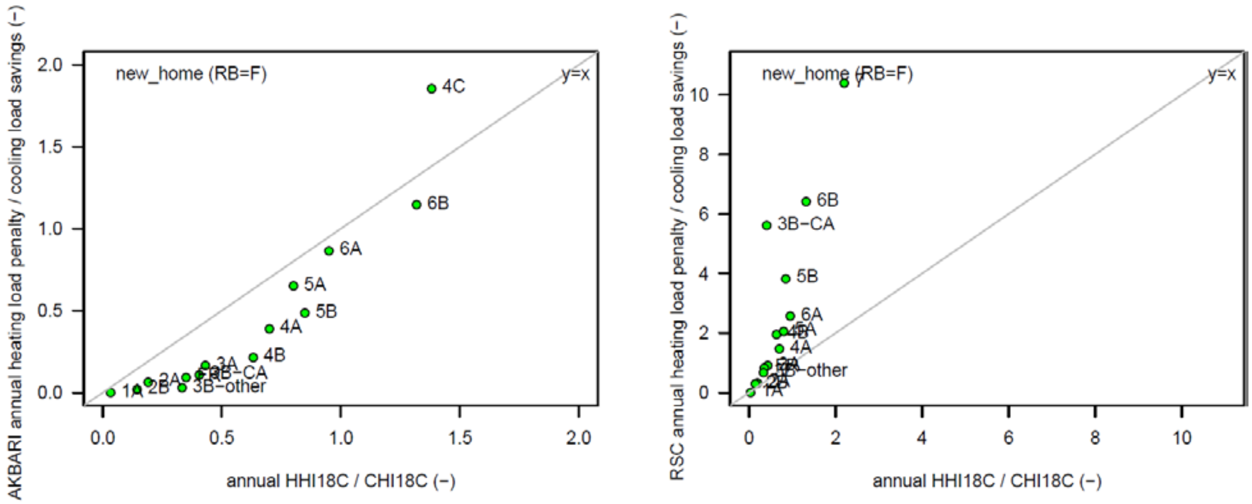


Figure 46. Annual heating load penalty / annual cooling load savings (AKBARI vs RSC) for new home.

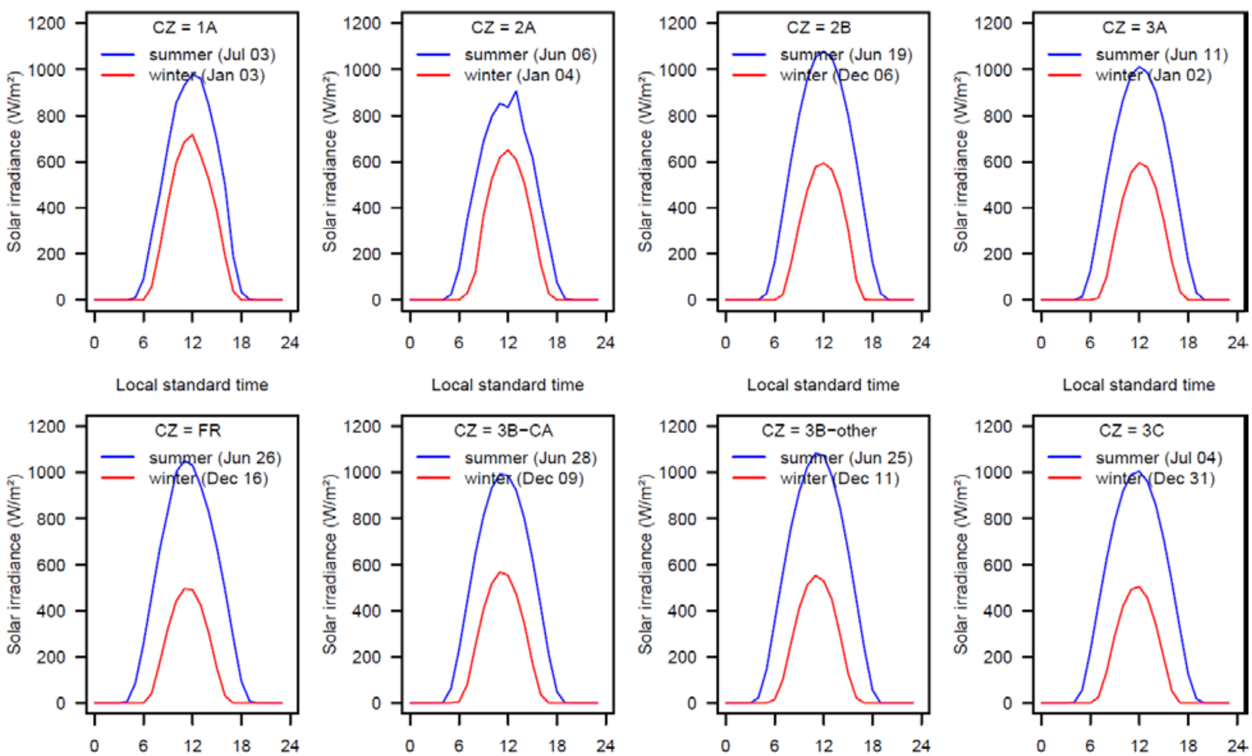


Figure 47. Global solar horizontal irradiance on sunny weekdays in summer and winter.[12]

[12] Please request T05/summary 2013-11-11b.pdf for comparison graphs for all cities.

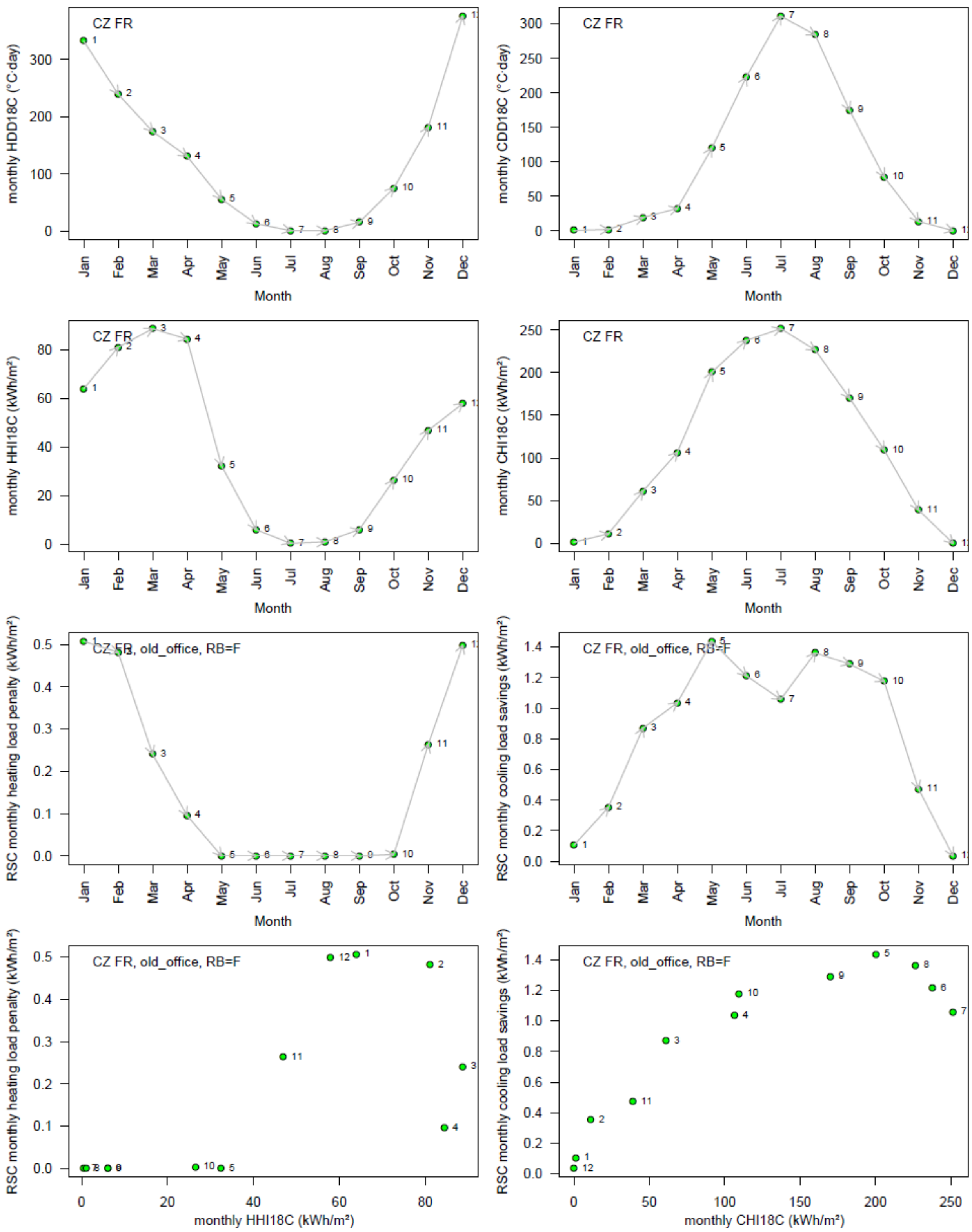


Figure 48. Monthly cooling savings and heating penalties for old office in Fresno, CA.

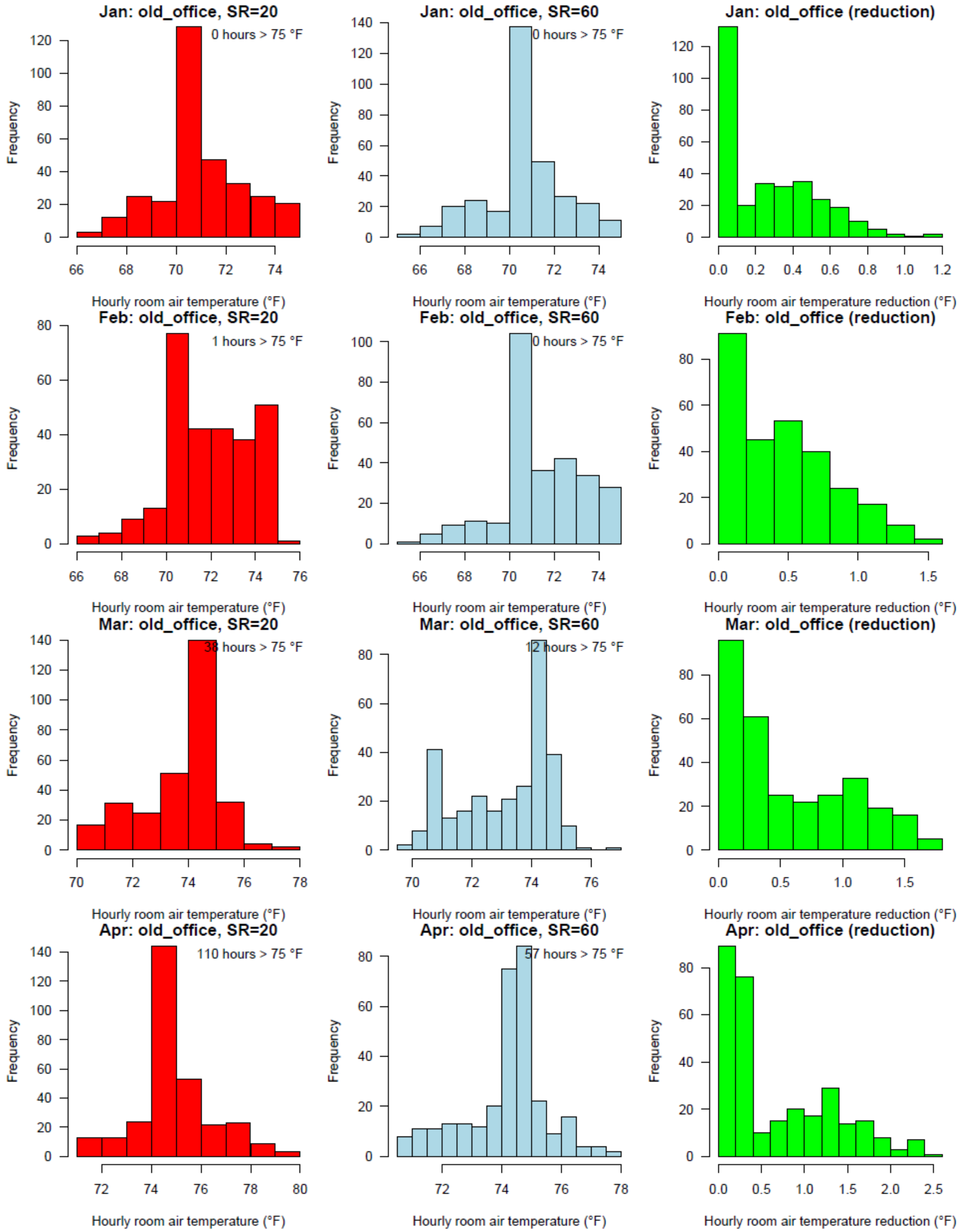


Figure 49. Old office room air temperatures in Fresno, CA for Jan, Feb, Mar, and Apr.[13]

[13] Please request T05/summary 2013-11-11b.pdf for comparison graphs for all cities.

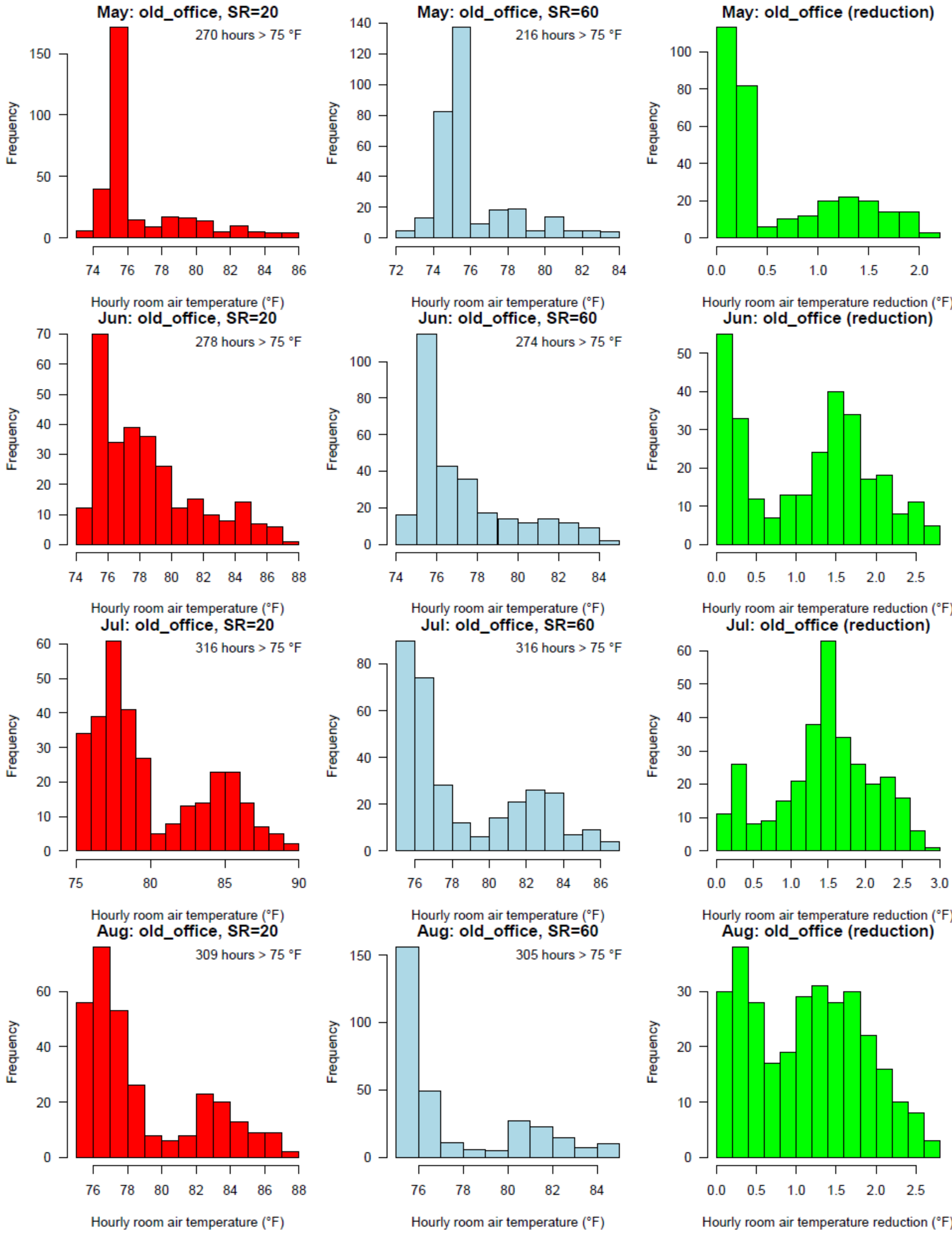


Figure 50. Old office room air temperatures in Fresno, CA for May, Jun, Jul, and Aug.

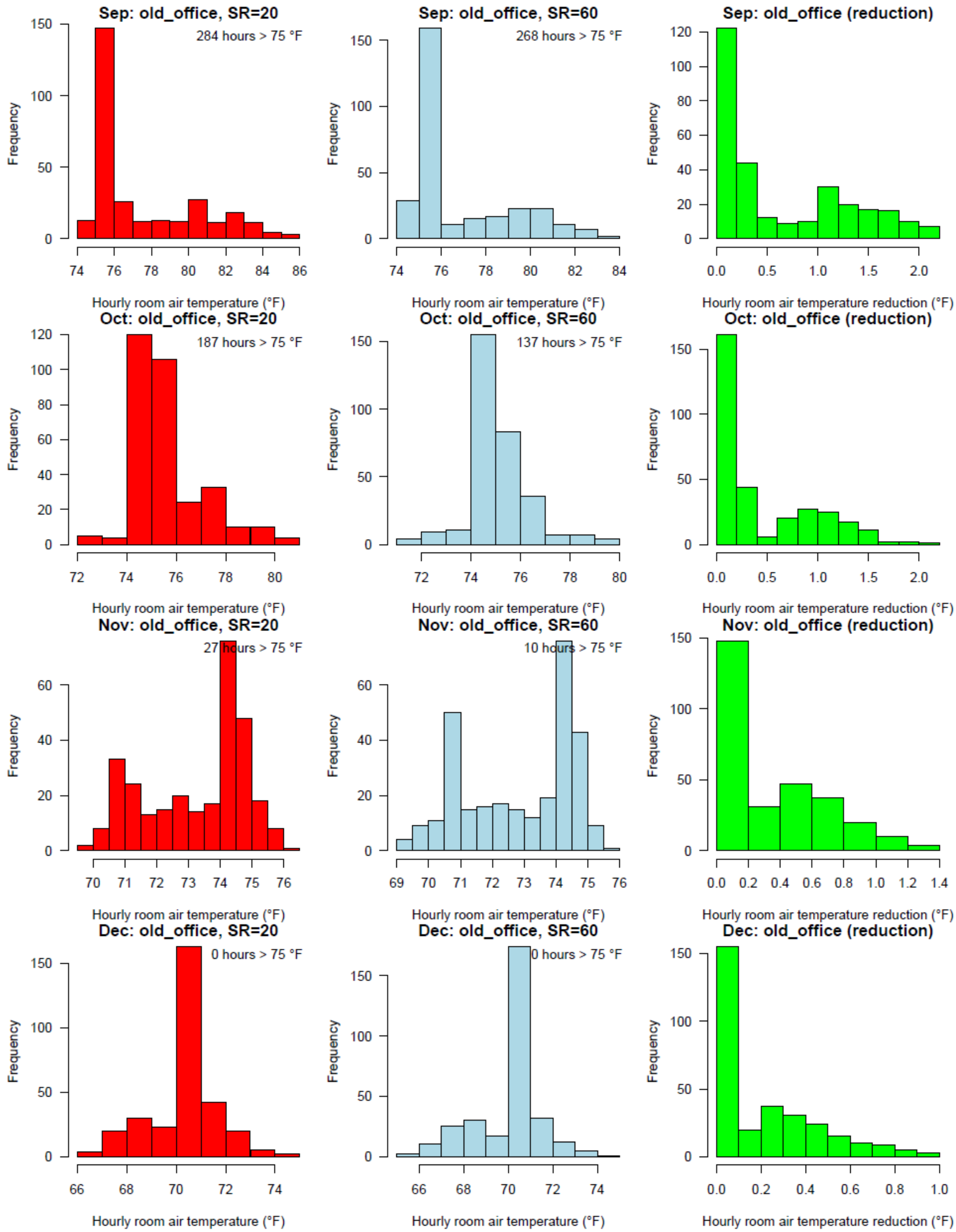


Figure 51. Old office room air temperatures in Fresno, CA for Sep, Oct, Nov, and Dec.

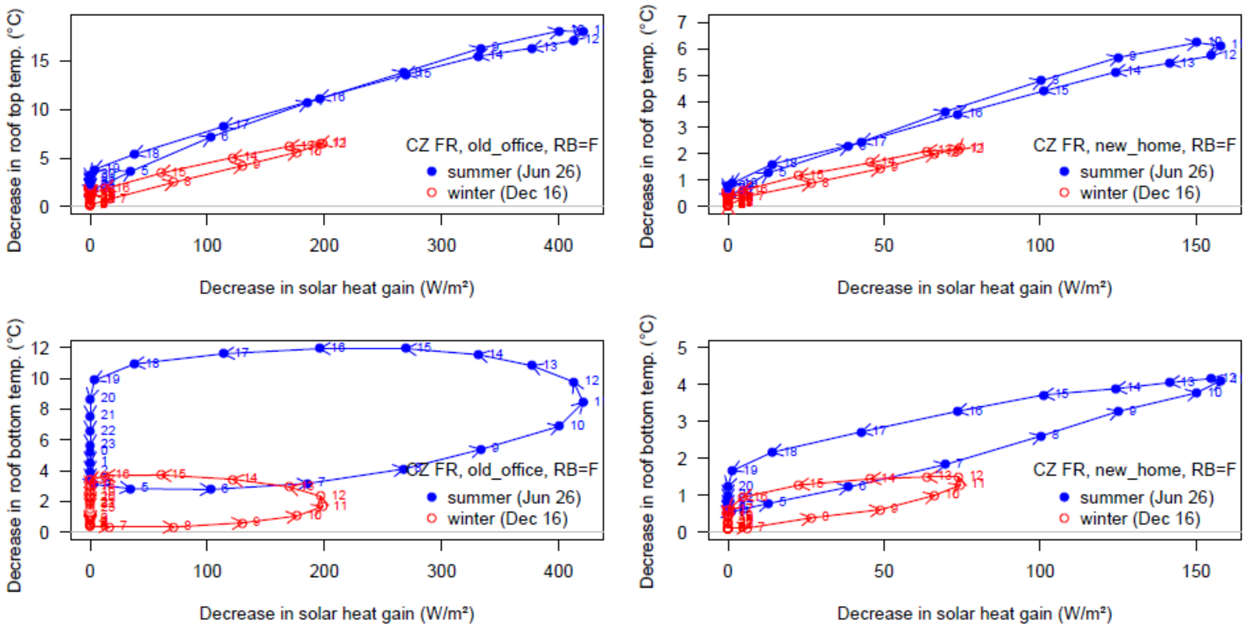


Figure 52. Decreases in hourly temperatures in Fresno, CA.

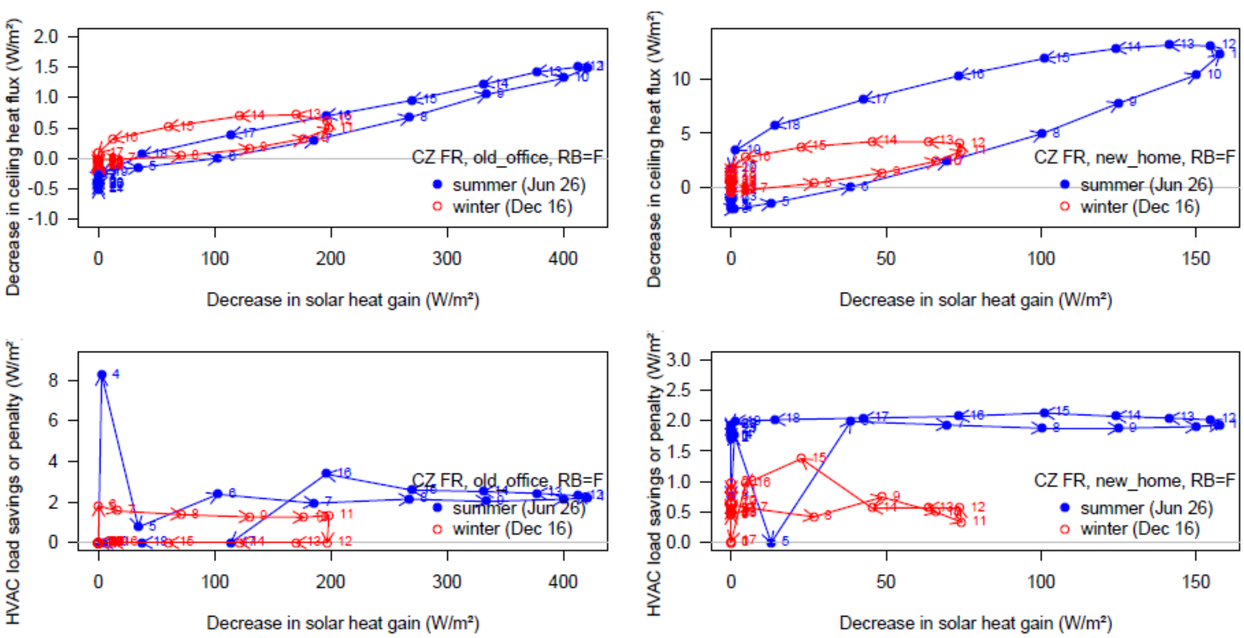


Figure 53. Decreases in hourly heat flux in Fresno, CA.[14]

[14] Please request T05/summary 2013-11-11b.pdf for comparison graphs for all cities.

13 CONCLUSION AND FUTURE WORK

This report summarizes and provides some of the analysis methods used to compare simulation calculations inside DOE's Roof Savings Calculator to other software engines, known physical processes, and measured data. The data and results from this analysis extend beyond the current report and are available upon request. This report extends a previous 63-page internal report made available in November, 2013 titled "Analysis of DOE's Roof Savings Calculator with Comparison to other Simulation Engines" by adding detailed investigations of software comparisons as well as empirical validation comparing RSC to measured data from ORNL's Charleston, SC NET facility and LBNL's Fresno, CA homes. A few specific changes of the many source code changes to RSC have been outlined in this report describing an updated and improved version of RSC.

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APPENDIX A: NOMENCLATURE

AJAX	Asynchronous JavaScript and XML
API	application programming interface
CSS	Cascading Style Sheets
DHTML	Dynamic HyperText Markup Language
DOE	Department of Energy
DOM	Document Object Model
EPA	Environmental Protection Agency
HVAC	Heating Ventilation and Air Conditioning
JSON	JavaScript Object Notation
PHP	Personal Home Page
PVC	PolyVinylChloride thermoplastic membranes
PIER	Public Interest Energy Research
RSC	Roof Savings Calculator
SR	solar reflectance
TE	thermal emittance
R_{US}	Thermal resistance (hr ft^2 ^{o}F / Btu)
R_{SI}	Thermal resistance (m^2 K / W)

APPENDIX B: RUNS WITH ROOF LAYERS CORRECTED

Run	Location	Bldg Type	Roof Type	doe2attic_Ducts_in_Attic HE (MBTU)	HE Penalty	% HE Penalty	CE (kWh)	CE Savings	% CE Savings
24491	GA_Atlanta	mdoffice	bur	74.10	6.00	8.1	15584	1324	8.5
24495	CA_Fresno	resid	Asphalt	26.96	1.82	6.8	1552	160	10.3
24588	CA_Fresno	resid*	Tile	27.39	3.20	11.7	1575	272	17.3
24589	CA_Fresno	resid*	Metal	27.42	3.22	11.7	1577	273	17.3
24590	CA_Arcata	resid	Asphalt	39.07	3.64	9.3	0	0	0.0
24591	CA_Arcata	resid*	TIle	39.81	6.54	16.4	0	0	0.0
24592	CA_Arcata	resid*	Metal	39.85	6.57	16.5	0	0	0.0
24593	CA_Los-Angeles	resid	Asphalt	7.23	1.25	17.3	56	15	26.8
24594	CA_Los-Angeles	resid*	TIle	7.47	2.25	30.1	57	27	47.4
24595	CA_Los-Angeles	resid*	Metal	7.49	2.26	30.2	57	27	47.4
24598	IL_Chicago	mdoffice	bur	157.60	4.00	2.5	10469	954	9.1
24600	CA_Fresno	mdoffice	bur	47.10	5.80	12.3	17501	1865	10.7
24600	CA_Arcata	mdoffice	bur	39.60	4.80	12.1	4803	1147	23.9
24600	CA_Santa-Maria	mdoffice	bur	47.40	4.90	10.3	6098	1356	22.2
24600	CA_Daggett	mdoffice	bur	36.00	8.10	22.5	22012	1624	7.4
24600	CA_Los-Angeles	mdoffice	bur	15.30	2.40	15.7	11204	1532	13.7
24601	TX_Fort-Worth	mdoffice	bur	52.90	1.40	2.6	20187	1261	6.2
24602	TX_Houston	mdoffice	bur	30.90	2.70	8.7	23350	1325	5.7
24603	FL_Miami	mdoffice	bur	7.30	0.10	1.4	31816	1391	4.4
24604	LA_New-Orleans	mdoffice	bur	29.50	1.60	5.4	22346	1359	6.1
24605	NY_New-York	mdoffice	bur	98.50	5.00	5.1	11500	911	7.9
24606	PA_Philadelphia	mdoffice	bur	107.70	26.20	24.3	12002	983	8.2
24607	AZ_Phoenix	mdoffice	bur	21.70	3.50	16.1	28817	2274	7.9
24608	MD_Baltimore	mdoffice	bur	90.40	5.30	5.9	12823	1050	8.2
24612	CA_Santa-Maria	resid*	TIle	26.27	5.56	21.2	3	2	66.7
24613	CA_Santa-Maria	resid*	Metal	26.29	5.59	21.3	3	2	66.7
24614	CA_Daggett	resid	Asphalt	15.40	1.67	10.8	2415	163	6.7
24615	CA_Daggett	resid*	TIle	15.72	2.99	19.0	2449	286	11.7
24616	CA_Daggett	resid*	Metal	15.73	3.01	19.1	2450	284	11.6
24621	CA_Santa-Maria	resid	Asphalt	25.68	3.10	12.1	3	1	33.3

Run	Location	Bldg Type	Roof Type	doe2attic_Ducts_in_Space HE (MBTU)	HE Penalty	% HE Penalty	CE (kWh)	CE Savings	% CE Savings
24491	GA_Atlanta	mdoffice	bur	73.90	6.20	8.4	16088	1416	8.8
24495	CA_Fresno	resid	Asphalt	21.27	1.44	6.8	1613	167	10.4
24588	CA_Fresno	resid*	Tile	21.58	2.52	11.7	1641	292	17.8
24589	CA_Fresno	resid*	Metal	21.60	2.54	11.8	1643	292	17.8
24590	CA_Arcata	resid	Asphalt	30.31	2.81	9.3	0	0	0.0
24591	CA_Arcata	resid*	TIle	30.86	5.07	16.4	0	0	0.0
24592	CA_Arcata	resid*	Metal	30.88	5.10	16.5	0	0	0.0
24593	CA_Los-Angeles	resid	Asphalt	5.03	0.92	18.3	58	16	27.6
24594	CA_Los-Angeles	resid*	TIle	5.19	1.68	32.4	58	28	48.3
24595	CA_Los-Angeles	resid*	Metal	5.21	1.68	32.2	58	28	48.3
24598	IL_Chicago	mdoffice	bur	136.80	6.80	5.0	10740	1006	9.4
24600	CA_Fresno	mdoffice	bur	46.50	6.10	13.1	18134	2027	11.2
24600	CA_Arcata	mdoffice	bur	37.10	6.80	18.3	4947	1227	24.8
24600	CA_Santa-Maria	mdoffice	bur	42.60	7.30	17.1	6356	1459	23.0
24600	CA_Daggett	mdoffice	bur	34.00	5.50	16.2	22683	1793	7.9
24600	CA_Los-Angeles	mdoffice	bur	14.30	2.50	17.5	11573	1639	14.2
24601	TX_Fort-Worth	mdoffice	bur	49.80	4.50	9.0	20702	1331	6.4
24602	TX_Houston	mdoffice	bur	30.30	2.90	9.6	23970	1392	5.8
24603	FL_Miami	mdoffice	bur	7.30	0.10	1.4	32576	1432	4.4
24604	LA_New-Orleans	mdoffice	bur	26.40	2.80	10.6	22881	1391	6.1
24605	NY_New-York	mdoffice	bur	100.90	5.70	5.6	11792	959	8.1
24606	PA_Philadelphia	mdoffice	bur	102.70	6.30	6.1	12310	1033	8.4
24607	AZ_Phoenix	mdoffice	bur	20.50	3.90	19.0	29868	2586	8.7
24608	MD_Baltimore	mdoffice	bur	90.70	6.20	6.8	13165	1111	8.4
24612	CA_Santa-Maria	resid*	TIle	19.86	4.31	21.7	3	2	66.7
24613	CA_Santa-Maria	resid*	Metal	19.87	4.33	21.8	3	2	66.7
24614	CA_Daggett	resid	Asphalt	11.45	1.30	11.4	2499	172	6.9
24615	CA_Daggett	resid*	TIle	11.66	2.34	20.1	2532	300	11.8
24616	CA_Daggett	resid*	Metal	11.66	2.36	20.2	2535	301	11.9
24621	CA_Santa-Maria	resid	Asphalt	19.43	2.41	12.4	3	1	33.3

Run	Location	Bldg Type	Roof Type	DOE-2.1E HE (MBTU)	HE Penalty	% HE Penalty	CE (kWh)	CE Savings	% CE Savings
24491	GA_Atlanta	mdoffice	bur	77.30	3.60	4.7	15308	831	5.4
24495	CA_Fresno	resid	Asphalt	20.08	0.27	1.3	1248	37	3.0
24588	CA_Fresno	resid*	Tile	20.08	0.48	2.4	1262	65	5.2
24589	CA_Fresno	resid*	Metal	20.08	0.48	2.4	1263	65	5.1
24590	CA_Arcata	resid	Asphalt	30.68	0.63	2.1	0	0	0.0
24591	CA_Arcata	resid*	TIle	30.61	1.11	3.6	0	0	0.0
24592	CA_Arcata	resid*	Metal	30.59	1.13	3.7	0	0	0.0
24593	CA_Los-Angeles	resid	Asphalt	6.75	0.21	3.1	55	6	10.9
24594	CA_Los-Angeles	resid*	TIle	6.75	0.39	5.8	60	12	20.0
24595	CA_Los-Angeles	resid*	Metal	6.75	0.39	5.8	60	12	20.0
24598	IL_Chicago	mdoffice	bur	141.90	3.90	2.7	10188	573	5.6
24600	CA_Fresno	mdoffice	bur	49.80	3.80	7.6	17307	1195	6.9
24600	CA_Arcata	mdoffice	bur	41.00	4.50	11.0	4149	701	16.9
24600	CA_Santa-Maria	mdoffice	bur	47.20	4.30	9.1	5430	800	14.7
24600	CA_Daggett	mdoffice	bur	35.20	3.30	9.4	22101	1013	4.6
24600	CA_Los-Angeles	mdoffice	bur	15.40	1.50	9.7	10623	894	8.4
24601	TX_Fort-Worth	mdoffice	bur	52.50	2.50	4.8	19973	759	3.8
24602	TX_Houston	mdoffice	bur	32.50	1.80	5.5	23154	801	3.5
24603	FL_Miami	mdoffice	bur	7.40	0.10	1.4	31673	802	2.5
24604	LA_New-Orleans	mdoffice	bur	28.10	1.70	6.0	22116	849	3.8
24605	NY_New-York	mdoffice	bur	104.60	3.00	2.9	11198	519	4.6
24606	PA_Philadelphia	mdoffice	bur	106.50	3.60	3.4	11729	592	5.0
24607	AZ_Phoenix	mdoffice	bur	21.50	2.30	10.7	29133	1538	5.3
24608	MD_Baltimore	mdoffice	bur	94.40	3.50	3.7	12575	634	5.0
24612	CA_Santa-Maria	resid*	TIle	23.53	1.00	4.2	7	2	28.6
24613	CA_Santa-Maria	resid*	Metal	23.52	1.00	4.3	7	2	28.6
24614	CA_Daggett	resid	Asphalt	10.82	0.21	1.9	1981	35	1.8
24615	CA_Daggett	resid*	TIle	10.82	0.38	3.5	1997	63	3.2
24616	CA_Daggett	resid*	Metal	10.81	0.39	3.6	1998	63	3.2
24621	CA_Santa-Maria	resid	Asphalt	23.56	0.56	2.4	6	0	0.0

APPENDIX C: SUMMARY OF ATTICSIM INPUT AND DATA REQUIREMENTS

At least two input files are needed to run the model. The first is a file that contains a description of the geometry of the attic and its thermal characteristics, along with a few other parameters that are fixed for a particular run. The second file is an hourly listing of weather data. A third optional file consists of hourly values of specified boundary temperatures and attic ventilation rates.

Geometry/Thermal Characteristics Input File

An example of the file for geometry/thermal characteristics is given in Figure 1. To clarify each input, line numbers have been added as a righthand column in this figure. In the real input file, these line numbers should not appear. It is suggested that the file in Figure 1 be used as a complete set of default inputs. The user may find the easiest route to generating an input file is to use this file and modify it as needed to suit his/her own particular needs.

Line 1. This contains seven integers, having values of either 0 or 1. These are flags that instruct the computer program on how to handle the temperatures of the seven surfaces that face the attic space. A 0 indicates that the temperature is unknown and is to be calculated in the simulation. A 1 indicates that the temperature is known and the simulation should use this known value. If any one of the seven variables on Line 1 is a 1, the third input file giving the specified boundary temperatures must be furnished. These seven inputs are called KFLAG(I), with 1=1,7. The index identifies a particular attic surface as follows:

1 = top surface of the attic floor
2 = bottom surface of the east side of the roof (for a north-south oriented ridge)
3 = bottom surface of the west side of the roof (for a north-south oriented ridge)
4 = inside surface of the south gable (for a north-south oriented ridge)
5 = inside surface of the north gable (for a north-south oriented ridge)
6 = inside surface of the east eave wall (for a north-south oriented ridge),
7 = inside surface of the west eave wall (for a north-south oriented ridge)

Note 1-1: the attic model is set up to include vertical walls at the eaves. If there are-mo vertical walls in the attic to be simulated, it is suggested that a fictitious wall about 1 inch high be added. This should not affect the simulation to any appreciable extent, and may correspond to a gap that is left for ventilation.

Note 1-2: if the ridge is not oriented in a north-south direction, setup the first inputs as if it were, and then later in the input, a parameter will be entered that will rotate the house to the desired orientation.

Line 2. This also contains seven integers that have values of either 0 or 1. Whereas Line 1 refers to the temperatures on the surfaces facing the attic air space, the variables on Line 2 refer to the temperatures on the outside of the attic.

A 0 indicates that the temperature is unknown and is to be calculated in the simulation. A 1 indicates that the temperature is known and the simulation should use this known value. If any one of the seven variables on Line 2 is a 1, the third input file giving the specified boundary temperatures must be furnished. These seven inputs are called KFLAG(I), with 1=8,14. The index identifies a particular attic surface as follows:

8 = surface of the ceiling below the attic
9 = top surface of the east side of the roof (for a north-south oriented ridge)
10 = top surface of the west side of the roof (for a north-south oriented ridge)

11 = outside surface of the south gable (for a north-south oriented ridge)
12 = outside surface of the north gable (for a north-south oriented ridge)
13 = outside surface of the east eave wall (for a north-south oriented ridge)
14 = outside surface of the west eave wall (for a north-south oriented ridge)

Note 2-1: the attic model is set up to include vertical walls at the eaves. If there are no vertical walls in the attic to be simulated, it is suggested that a fictitious wall about 1 inch high be added. This should not affect the simulation to any appreciable extent, and may correspond to a gap that is left for ventilation.

Note 2-2: if the ridge is not oriented in a north-south direction, set up the first inputs as if it were, and then later in the input, a parameter will be entered that will rotate the house to, the desired orientation.

Line 3. This contains two integers, called KFLAG(15) and KFLAG(16), having a value of either 0 or 1. If either is set to 1, or if any of the previous 14 KFLAG values is 1, an auxiliary input file is needed with values for all 16 parameters. They can be 0 or any dummy value, but 16 columns of data are needed for every time step. KFLAG(15) refers to the rate of flow of ventilation air through the attic. If the ventilation rate is to be calculated by the simulation, this flag is set to 0. If the ventilation rate is supplied, this flag is set to 1 and the proper values (in cubic feet per hour) must be found in the auxiliary data file. KFLAG(16) refers to the ventilation air temperature. If the ventilation air temperature is to be the outside air temperature this flag is set to 0. If the ventilation air temperature is to be supplied, this flag is set to 1 and the proper values (in °F) must be found in the auxiliary data file.

Lines 4-17. These lines contain information on the thermal characteristics of the ceiling and ceiling insulation system. The first entry in Line 4 is an integer that identifies the number of following lines that pertain to the ceiling/insulation (here, this number is 13, corresponding to Lines 5 through 17). The second entry is the surface-to-surface thermal conductance of the ceiling/insulation, in Btu/h.ft$^{2}\cdot$°F. The third entry on Line 4 is the common ratio of the conduction transfer functions. The last entry on Line 4 is the temperature coefficient of the thermal conductance. Lines 5 through 17 contain the conduction transfer functions for the ceiling/insulation, with the first, second, and third columns containing the X, Y and Z conduction transfer functions. Units for the conduction transfer functions are Btu/h.ft$^{2}\cdot$°F. See Chapter x for an explanation of the conduction transfer functions.

Note 4-1: the conduction transfer functions given in Figure 1 were calculated using a computer program supplied by George Walton of NIST. For input to Walton's program, it is necessary to describe the layers of an attic envelope component in order from the outside of the wall towards the inside of the wall. For Walton's program, "inside" means closer to the interior of the house. For the attic model, "<u>inside" means facing the attic air space.</u> The implication of this is that Walton's program (or an equivalent program) should be used to calculate the conduction transfer functions, with Walton's definition of "inside." Inside the attic model program, .these conduction transfer functions are converted to fit the
Convention used in the attic model (basically, this means that for the ceiling only, the Xs and Zs are interchanged).

Lines 18-29. These lines are similar to Lines 4-17, except that they apply to the east side of the roof (for a north-south ridge).

Lines 30-41. These lines are similar to Lines 4-17, except that they apply to the west side of the roof (for a north-south ridge).

Lines 42-46. These lines are similar to Lines 4-17, except that they apply to the south gable (for a north-south ridge).

Lines 47-51. These lines are similar to Lines 4-17, except that they apply to the north gable (for a north-south ridge).

Lines 52-55. These lines are similar to Lines 4-17, except that they apply to the east eave wall (for a north-south ridge).

Lines 56-59. These lines are similar to Lines 4-17, except that they apply to the west eave wall (for a north-south ridge).

Line 60. This line contains seven entries for the solar absorptances of the exterior surfaces of the seven components of the attic envelope. The first entry is the exterior surface of the ceiling/insulation, which corresponds to the bottom side of the ceiling. This particular value is not used in any calculations, since it is assumed that the sun does not shine on the bottom of the ceiling. Instead, the value for the ceiling is used as a placeholder in the input. The other six entries are used in the model. The seven entries correspond, in order to:

- the ceiling/insulation
- the east side of the roof (for a north-south ridge)
- the west side of the roof (for a north-south ridge)
- the south gable (for a north-south ridge)
- the north gable (for a north-south ridge)
- the east eave wall (for a north-south ridge)
- the west eave wall (for a north-south ridge)

Note 60-1: the above order of input is also used for Lines 61, 62, 65, 66, 67, and 68.

Line 61. This line contains seven entries for the infrared emittance of the outside surface of each of the components of the attic envelope.

Line 62. This line contains seven entries for the infrared emittance of the inside (i.e., facing the attic air space) surface of the components of the attic envelope.

Line 63. This line contains six entries that deal with the geometry of the attic. In order, they are:

- the length of the attic, feet
- the width of the attic, feet
- the pitch of the east side of the roof (for a north-south ridge), degrees
- the pitch of the west side of the roof (for a north-south ridge), degrees
- the orientation of the house. This is the angle (in degrees) that the ridge line makes with the north direction, measured in a clockwise fashion. For example, the entry for an attic with its ridge running in a north-south direction is 0.0. If the ridge runs in the east-west direction, such that what we originally called the east roof is now facing south, the entry is 90.0.
- the height of the eave walls, feet

Line 64. This line contains three entries that deal with the attic vents. The entries are, in order:

- the area of the inlet vents, ft^2
- the area of the outlet vents, ft^2
- an integer that takes on the following values:
  1 = soffit and ridge vents
  2 = soffit and gable vents
  3 = soffit vents only

Line 65. This line contains seven entries for the water vapor permeances of the components of the attic envelope, in perms.

Line 66. These seven entries are the ratios of the total area of exposed wood to the projected area of the inside surface of each of the components of the attic envelope. These values are used in the moisture balances, and account for the fact that the exposed area of wood may be larger or smaller than the geometrical projection of the area. (Note, the geometrical projection is used for the thermal balances). For example, suppose that insulation fills the cavities between ceiling joists to a depth that equals the height of the joists. Further, suppose that the joists are 1.5 inches wide and are 24 inches apart. The entry for the attic floor would then be 1.5/24 = 0.063.

As another example, suppose that the roof rafters are 2×4s spaced 24 inches apart. Then each two square feet of the projected area of the inside surface of the roof will contain 12×(24-1.5) = 270 square inches of exposed roof sheathing, and 12×(3.5+1.5+3.5) = 102 square inches of exposed rafter wood. The entry on Line 66 for this roof would then be (270+102)/288 = 1.29.

Line 67. This line contains seven entries also pertain to the moisture sorption/desorption calculations, and apply to the inside surfaces of each of the attic envelope components. The entries are the mass of wood that is considered to participate in moisture transfer, per projected unit surface area, in lb/ft^2. It is expected that, over the course of a daily cycle, moisture levels in the wood will only change within a fraction of an inch of the surface, and the moisture content of the inner core of the wood will not change appreciably on an hour-by-hour, or even daily, basis. This is clearly a simplification, but the intent was to incorporate moisture effects to the extent that they influence the hourly attic heat flows. This penetration distance must be supplied by the user.

For the examples given here, the penetration distance has been taken to be 0.25 inches. For the insulation/ceiling joist described as an example for Line 66, with a wood density of 28 lb/ft^3, the entry would be (12×1.5×0.25×28)/(12×12×24) = 0.0365 lb/ft^2. (For each 12 inch by 24 inch area of attic floor, the area of exposed wood is 12×1.5 = 18 square inches; the extra factor of 12 in the denominator is a unit conversion from inches to feet.)

Line 68. The seven entries are the initial moisture contents by weight of the wood in the inside surfaces of the components of the attic envelope, expressed as a decimal fraction. For example, an initial moisture content of 9.0% would be entered as 0.09.

Line 69. There is only one entry on this line. This value is the latent heat of vaporization of water, in Btu/lb. For average building conditions, this value may be taken to be 1060 Btu/lb. The reason for providing an input for this number is to allow it to also act as a flag. If the user desires to bypass all the moisture calculations in the model, a value of 0.0 should be entered on this line.

Line 70. There is only one entry on this line. This is the exfiltration air flow from the house into the attic space, in lb/h. It is expected that later implementations of this model may add a subroutine to calculate the exfiltration rate on an hourly basis, but for the present version, a fixed value may be input, here.

Line 71. This line contains two integer entries. Both of these are flags that deal with the duct system in the attic. The first is a flag to determine whether ducts are to be included in the model. A value of 0 indicates that ducts are not considered, while a value of 1 indicates that ducts are included. The second entry allows of choice of duct models: a value of 0 indicates that the steady-state duct model should be used, and a value of 1 indicates that the transient duct model should be used.

If the first entry in Line 71 is 0, the other lines that deal with ducts (Lines 72-103 in this example) should not appear in the input.

Line 72. This line contains two integer entries. The first is the total number of supply duct runs in the attic, and the second is the total number of return duct runs.

Line 73. This line contains one real entry, which corresponds to the temperature of the air as it leaves the conditioning equipment. For this example, it is assumed that air-conditioning is being simulated, and that the temperature of the air leaving the evaporator is at 55°F. A later version of the model might provide two values, one for cooling and another for heating, or it might provide hourly values.

Lines 74-103. These lines are grouped into sets of three lines, with one set for each of the supply and return ducts. Inputs for the supply ducts are listed first, followed by input for the return ducts. The number of lines in this total group should equal three times the sum of the two entries on Line 73. Lines 74, 75, and 76 will now be described. Lines 77-103 follow the same pattern.

Line 74. The first entry is an integer that is unique to each duct run. It is suggested that the ducts should be numbered sequentially, starting with the run nearest the air-handling equipment.

> The second and third entries are also integers. These identify node numbers for the inlet and exit of each duct run. The node numbers identify how the duct runs are connected to each other. The exit for one duct run will be the inlet for one or more duct runs next downstream, and the junction will occur at a particular node. See Figure 2 for an example of the duct and node numbering scheme.
> The fourth entry is an integer that identifies the shape of the duct. An entry of 0 indicates a round duct, and an entry of 1 indicates a rectangular duct. All ducts do not have to have the same shape. However, there is nothing in the model that calculates any flow disturbance due to a change in size or shape of the ducts.
> The fifth and sixth entries are thermal conductivities (Btu/h.ft.^{0}F) for an inner and an outer layer of duct insulation. Two values for thermal conductivity are allowed in order to handle several different insulation strategies. For example, the ducts may be sheet metal with insulation on the outside, or on the inside, or on both sides. Even if only one layer of insulation is to be modeled, non-zero values for both conductivities must be entered as input, in order to avoid a divide-check.
> The seventh entry is the heat capacity per unit length of the duct materials (including the duct wall and insulation), in Btu/ft.°F.
> The last entry oil Line 74 is the length of the duct run, hi feet.

Line 75. There are four entries on this line.

> The first entry is the mass flow rate of air that enters the duct length, hi lb/h.
> The second entry is the rate of mass leakage to or from the duct per unit of length, in lb/h.ft.
> The third entry is the emittance of the external surface of the duct, dimensionless.
> The last entry on Line 75 is an integer that was intended to identify the zone of the house that the duct supplies ah to. At present, this parameter is not used in the program

Line 76. If the duct run is round, Line 76 will contain three entries:

> The inside diameter of the inner layer of the duct insulation system, feet.
> The outside diameter of the inner layer of the duct insulation system, feet (Note, this will also be in inside diameter of the outer layer of duct insulation.)
> The outside diameter of the outer layer of duct insulation, feet.

If the duct run is rectangular, Line 76 will contain six entries:

> The inside width of the inner layer of the duct insulation system, feet.
> The inside height of the inner layer of the duct insulation system, feet.
> The outside width of the inner layer of the duct insulation system, feet.

The outside height of the inner layer of the duct insulation system, feet.
The outside width of the outer layer of the duct insulation system, feet.
The outside height of the outer layer of the duct insulation system, feet.

Lines 73 to 76 are repeated for each of the duct runs in the duct system. Note that the program is dimensioned to allow up to 25 duct runs, in any combination of supply and return ducts.

Line 104. This line has one integer entry, which is a flag to determine whether or not the trusses are to be modeled. If the entry is 0, then trusses are not to be modeled, and no more input for the trusses is needed. If the entry is 1, then trusses are to be modeled, and two more lines of input are needed.

Line 105. This line has seven entries that deal with the trusses framing.

The first entry is the dimensionless fraction of the attic cross sectional area at a truss that is open.
The second entry is the total exposed surface area of all the trusses framing members, in ft^2. This would include the areas on all sides of the truss members that are not in contact with other materials. If the bottom chords of the trusses are covered with insulation, then surface areas would not be included in the total exposed surface area.
The third entry is the total volume of the truss framing members exposed to the attic air space, ft^3. If the bottom chords of the trusses are covered with insulation, their volumes are not included.
The fourth entry is a characteristic length of the truss framing for use in calculating convection heat transfer coefficients, feet. For example, this characteristic length might be taken as the average height of the attic.
The fifth entry is the emittance of the surface of the truss framing members, dimensionless. The sixth entry is the specific heat of the truss framing material, Btu/lb.^{0}F. The seventh entry is the density of the truss framing material, lb/ft^3.

Line 106. There are two entries on this line:

The first entry is the mass of truss framing that participates in moisture transfer, per unit of exposed surface area of the truss framing, lb/ft^2. This is calculated in the same way on Line 67.
The second entry is the initial moisture content of the truss framing, as a weight fraction.

Line 107. This line contains six entries:

The first is the latitude of the house, degrees.
The second is the longitude of the house, degrees.
The third is an integer to indicate the time zone: 5 indicates the Eastern time zone, 6 indicates the Central time zone, 7 indicates the Mountain time zone, and 8 indicates the Pacific time zone.
The fourth is the solar reflectance of the ground surrounding the house, dimensionless.
The fifth is an integer to indicate the type of solar radiation data that are to be used:
1 indicates that both total horizontal and direct solar radiations are to be input,
2 indicates that only total horizontal radiation is available, and
3 indicates that no solar data are available, but that the cloud cover is available.
Note: Option 1 is preferred; TMY weather data correspond to option 1.

Line 108. This line has four entries:

The first is the fixed temperature inside the house, °F.
The second is the fixed relative humidity inside the house, percent.
The third is an integer to that deals with the ventilation flow through the attic. If this entry is 0, then the ventilation flow is assumed to flow through both sides of the attic. <u>If the attic is a shed roof design, where ventilation flows in only at one eave, then this entry</u> should be 1.

The last entry is the fraction of the hour that the equipment is running, dimensionless.
Note: the values read in the last line of input are fixed for the entire simulation. If there is a need to have these values change on an hourly basis, then a means needs to be incorporated within the hourly loop of the main program to obtain these values from an external source.

Hourly Weather Input File

A short example of an hourly weather input file is given in Figure 3. Each row of the file corresponds to one hour of data. The file has 12 columns of data, which are as follows:

Column 1. This is an integer that identifies the day of the year. January 1 is identified as 1. In this example, the first entry is 182, which corresponds to July 1.
Column 2. This is an integer that identifies the hour of the day. Hour 1 is 1:00 am, etc.
Column 3. This is the outdoor dry-bulb temperature, °F.
Column 4. This is the outdoor atmospheric pressure, lb/in^2.
Column 5. This is the cloud amount, and is a number ranging from 0 for cloudless to 10 for complete cloud cover.
Column 6. This is the wind direction, measured clockwise from the north, in degrees.
Column 7. This is the outdoor humidity ratio, pounds of water per pound of dry air.
Column 8. This is the total horizontal solar radiation, Btu/h.ft^2.
Column 9. This is the direct solar radiation, Btu/h*ft.
Column 10. This is the cloud type.
Column 11. This is the wind speed, miles per hour.
Column 12. This is the atmospheric clearness number, dimensionless.

Optional Hourly File for Specified Temperatures

If anyone of the entries on Lines 1, 2, or 3 is other than 0, then an hourly file for specified temperatures and ventilation rate needs to be supplied. For each hour, the following data need to be supplied, in order:

- temperatures for: attic floor, bottom of east *roof,* bottom of west roof, inside of south gable, inside of north gable, inside of east eave wall, inside of west eave wall
- temperatures for : ceiling, top of east roof, top of west roof, outside of south gable, outside of north gable, outside of east eave wall, outside of west eave wall
- ventilation rate through attic
- Note: an entry must be supplied for each of the 15 variables. If a particular variable is identified as not being specified (i.e., the corresponding entry on Lines 1, 2, or 3 is 0), then put a 0.0 in this file for that variable, and the program will subsequently ignore it. The program only uses input variables for variables that have an entry of 1 on Lines 1, 2, or 3. If you put a 1 on Lines 1, 2, or 3 for a variable, and then put 0.0 in this file for that variable, then the program will use the 0.0 value in the calculations.

Instructions on Running the Program

The program is run by entering the following at the DOS prompt:
ATTICSIM1 *filename1 filename2 filename3 filename4*

where *filename1* is the filename of the geometry/thermal characteristics input file,
filename2 is the filename of the hourly weather data input file,
filename3 is the filename of the output file, and
filename4 is the filename of the [optional] file for specified surface temperatures or ventilation rate.

APPENDIX D: ADDITIONAL RELATED PUBLICATIONS

Other publications showing development of the calculator, validation of portions to field demonstration data, and visual analysis (in reverse chronological order):

Jones, Chad, New, Joshua R., Sanyal, Jibonananda, and Ma, Kwan-Liu (2012). "Visual Analytics for Roof Savings Calculator Ensembles." In *Proceedings of the 2nd Energy Informatics Conference*, Atlanta, GA, Oct. 6, 2012. [PDF] [PPT]

Cheng, Mengdawn, Miller, William (Bill), New, Joshua R., and Berdahl, Paul (2011). "Understanding the Long-Term Effects of Environmental Exposure on Roof Reflectance in California." In *Journal of Construction and Building Materials*, Volume 26, Issue 1, pages 516-26, August 2011. [PDF]

New, Joshua R., Jones, Chad, Miller, William A., Desjarlais, Andre, Huang, Yu Joe, and Erdem, Ender (2011). "Poster: Roof Savings Calculator." In *Proceedings of the International Conference on Advances in Cool Roof Research*, Berkeley, CA, July 2011. [PDF]

New, Joshua R., Miller, William (Bill), Desjarlais, A., Huang, Yu Joe, and Erdem, E. (2011). "Development of a Roof Savings Calculator." In *Proceedings of the RCI 26th International Convention and Trade Show*, Reno, NV, April 2011. [PDF] [PPT]

Miller, William A., New, Joshua R., Desjarlais, Andre O., Huang, Yu (Joe), Erdem, Ender, and Levinson, Ronnen (2010). "Task 2.5.4 - Development of an Energy Savings Calculator." California Energy Commissions (CEC) PIER Project, ORNL internal report ORNL/TM-2010/111, March 2010, 32 pages.

Miller, William A., Cheng, Mengdawn, New, Joshua R., Levinson, Ronnen, Akbari, Hashem, and Berdahl, Paul (2010). "Task 2.5.5 - Natural Exposure Testing in California." California Energy Commissions (CEC) PIER Project, ORNL internal report ORNL/TM-2010/112, March 2010, 56 pages.