UZM Model

PIER Research for the 2008 Residential Building Standards
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ACKNOWLEDGEMENT

Bruce Wilcox was the project director and prime contractor for the UZM development, designed the UZM model and carried out the comparisons with field data. Ken Nittler of Enercomp, Inc. was lead programmer, integrated UZM with Micropas and carried out the comparison with 2005 ACM and the impact analyses. Phil Niles, chief engineer, developed, tested and documented the UZM attic model. Larry Palmiter of Ecotope, chief theoretician developed the UZM duct model and provided essential perspective. Danny Parker of Florida Solar Energy Center provided measured attic data, algorithms and advice. Mark Modera of Carrier Aeroseal, Iain Walker of Lawrence Berkeley National Laboratory and John Proctor of Proctor Engineering provided algorithms and reality checking. Martha Brook of the California Energy Commission Public Interest Energy Research (PIER) program provided solid support and perspective.

Summary

UZM (Unconditioned Zone Model) is a new computer model designed to simulate the thermal performance of an unconditioned attic containing an air conditioning duct system. UZM is designed to be integrated into the computer programs used for compliance calculations for the 2008 version of the residential energy code in California. UZM has been tested and is available to be used in calculations now underway to develop the 2008 standards.

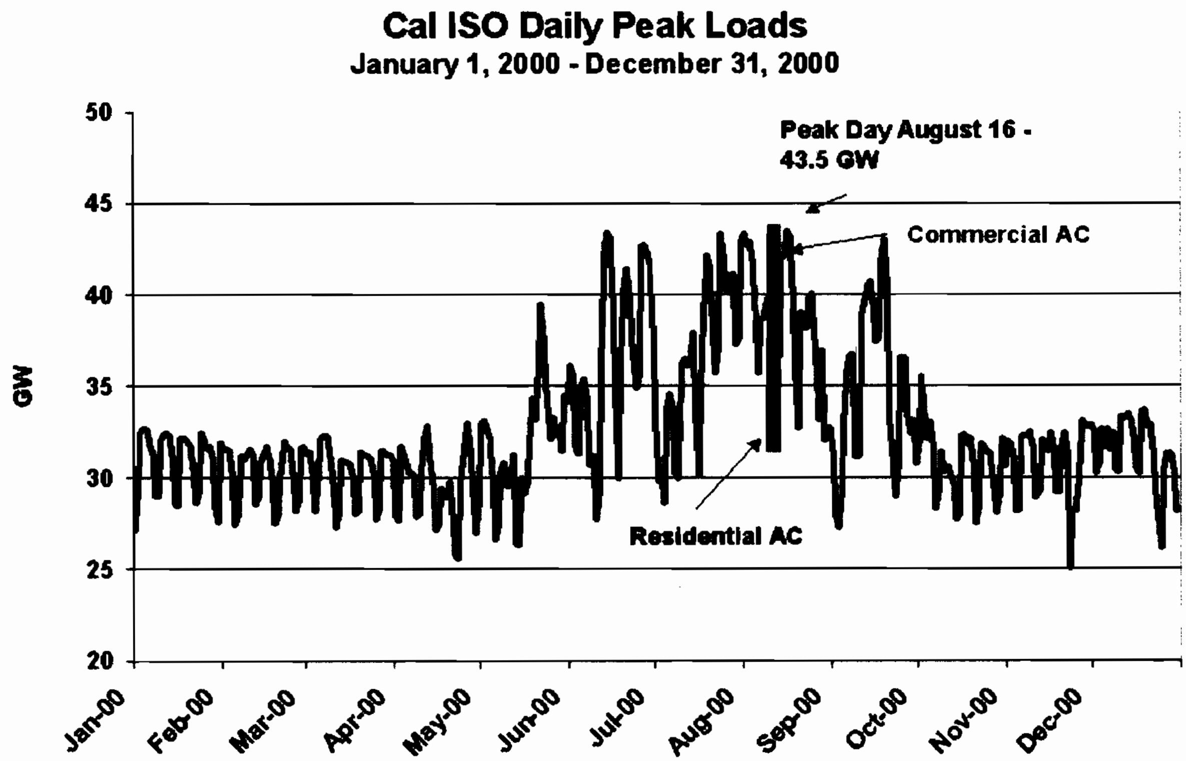

Figure 1. Residential AC and California's Peak Electricity Demand Problem

Background

Air conditioning on peak efficiency is of great interest in California because it has a significant impact on the state's ongoing peak electricity supply problem. Figure 1 shows the daily peak electric demand for the states Independent System Operator in the year 2000 with an estimate of air conditioning peak demand overlaid[1]. About 30% of the total peak demand was caused by air conditioning, but more importantly, about 30% of the summer peak above baseline was caused by residential air conditioning alone.

Figure 2 shows the calculated performance of 2 residential duct systems in Palm Springs attics under summer peak conditions. The system shown on the left is a "typical" California production house air conditioning system built in 2000. The system on the right shows the same system built according to the

[1] Borenstein, S., Jaske, M., and Rosenfeld, A. 2002. "Dynamic Pricing, Advanced Metering and Demand Response in Electricity Markets," The Hewlett Foundation Energy Series Foundation monograph. http://www.ef.org/energyseries_dynamic.cfm

requirements in the 2005 version of the California's energy efficiency standards for low-rise residential buildings. Efficiency measures including air sealed and tested ducts, R-8 duct insulation and a radiant barrier reduce the on peak energy losses by about half, from almost 40% to less than 20% of system output.

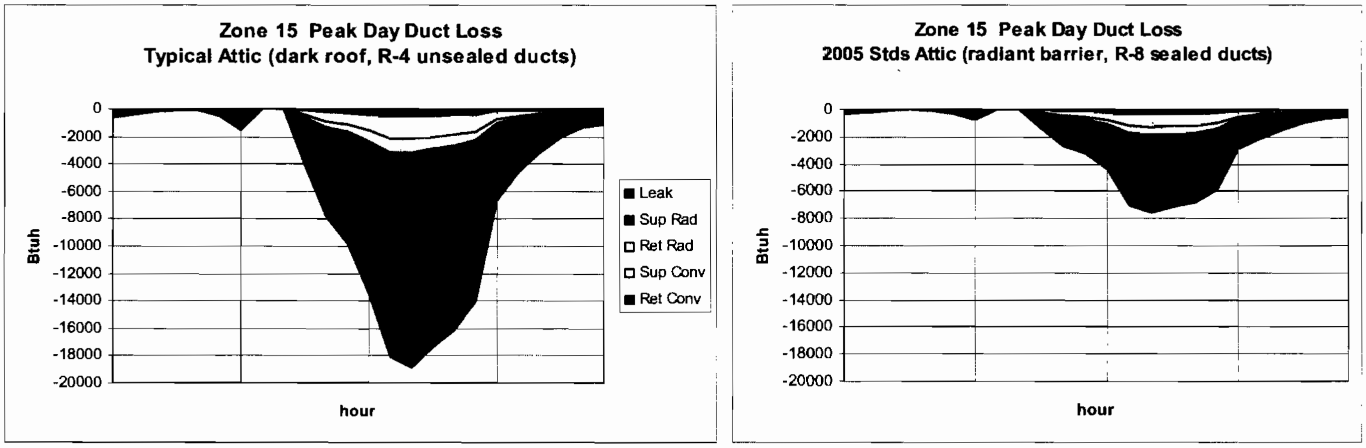

Figure 2. Peak HVAC Duct and Attic Efficiency Measure Impact

California uses computer simulation models to both develop and comply with its performance based building standards. State law requires that efficiency measures must be shown to be cost effective in order to be included in the code requirements. Most builders use computer simulation programs to optimize the cost effectiveness of their own custom package of energy efficiency measures to meet the performance standard. Both of these uses demand an accurate roof/attic/duct model that evaluates all of the relevant efficiency measures in combination. The Residential Alternative Compliance Methods Manual (ACM Manual) adopted by the California Energy Commission (CEC) contains requirements for computer simulation programs to be used in complying with the standards. The UZM model is intended to published in the 2008 ACM manual.

There are severe constraints on the design of the UZM model such as the need to include all of the currently available efficiency measures allowed credit in the standards. Significant variations in building type such as crawl spaces with ducts, flat roofs, multiple air conditioning zones and/or systems also need to be handled on an equitable basis. It is very important the inputs are limited to the items that can be checked by a building inspector in a field inspection of a new home. The UZM model is designed to handle the following efficiency variables:

- Duct sealing
- Duct insulation (including buried ducts)
- Duct location (including conditioned space)
- Roof solar absorptivity and emmissivity
- Tile roofs
- Radiant barriers mounted on the roof deck
- Attic ventilation
- Attic insulation
- Sealed attics
- Insulation construction quality

Approach

The first step in developing the UZM attic model was to review the existing attic/duct models (see Appendix A) to see what approaches have been made to work and to assemble a kit of algorithms that potentially fit our specification. We then developed a proposed UZM in a beta version that allowed us to test and compare results with measured data. The details of the data comparison are discussed in the next section. The next step was to integrate UZM into a special version of the Micropas ACM model in order to allow it to be used by stakeholders in the 2008 Standards development process. We used this Micropas development version to compare the UZM model distribution efficiency results to the seasonal duct efficiency calculation used in the 2005 ACM Manual and translated this comparison into typical compliance tradeoff results. We intend the UZM model to be published in the 2008 ACM manual.

Comparison with Measured Field Data

Comparison with measured data is useful to ensure that a model responds to all the significant environmental driving forces and that the algorithms have been integrated correctly. Hourly attic air temperature measured in detailed monitored experiments offers a useful comparison for testing the UZM model. We have selected data sets from an experimental facility at the Florida Solar Energy Center (FSEC) and from a test home in Roseville California for detailed comparisons.

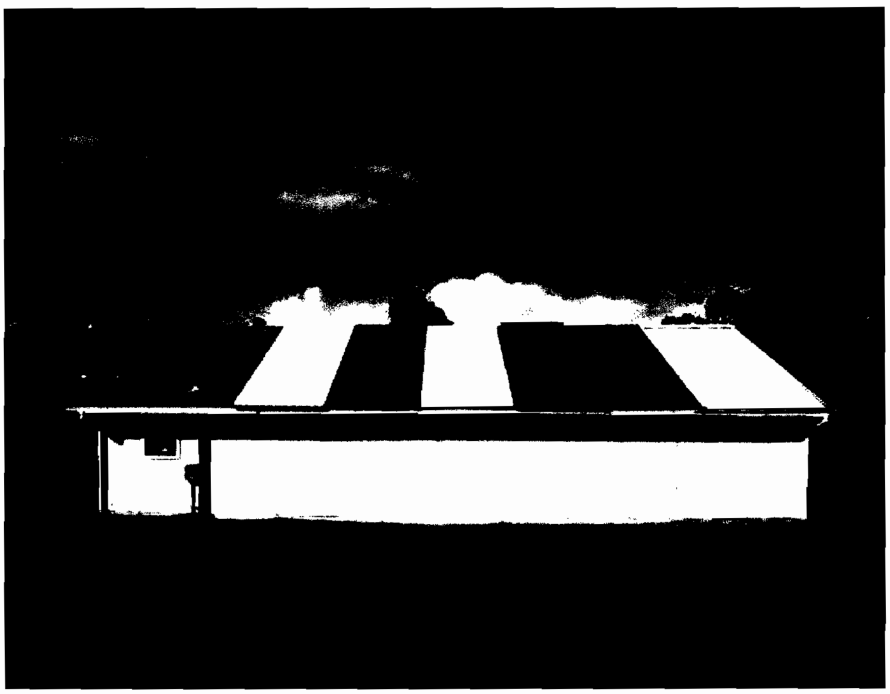

Figure 3. The Flexible Roof Facility

Florida Solar Energy Center Flexible Roof Facility

FSEC's Flexible Roof Facility (FRF) is located in Cocoa, Florida, ten miles (17 km) west of the Atlantic Ocean on mainland Florida. The FRF is a 24 ft by 48 ft (7.3 x 14.6 m) frame building constructed in 1987 with its long axis oriented east-west (Figure 3). The roof and attic are partitioned to allow simultaneous testing of multiple roof configurations. The orientation provides a northern and southern exposure for the roofing materials under evaluation. The attic is sectioned into six individual 6 foot (1.8 m) wide test cells spanning three 2 ft (0.6 m) trusses thermally separated by partition walls insulated to R-20 ft2-hr-oF/Btu

(RSI-3.5 m2-K/W) using 3 inches (7.6 cm) of isocyanurate insulation. The partitions between the individual cells are also well sealed to prevent air flow crosscontamination. The gable roof has a 5/12 pitch (22.6o) and 3/4 inch (1.9 cm) plywood decking. On the attic floor, R-19 (RSI-3.3) unsurfaced batt insulation is installed between the trusses in all of the test bays in a consistent fashion. The attic is separated from the conditioned interior by 0.5 inch (1.3 cm) gypsum board. The interior of the FRF is a single open air conditioned space.

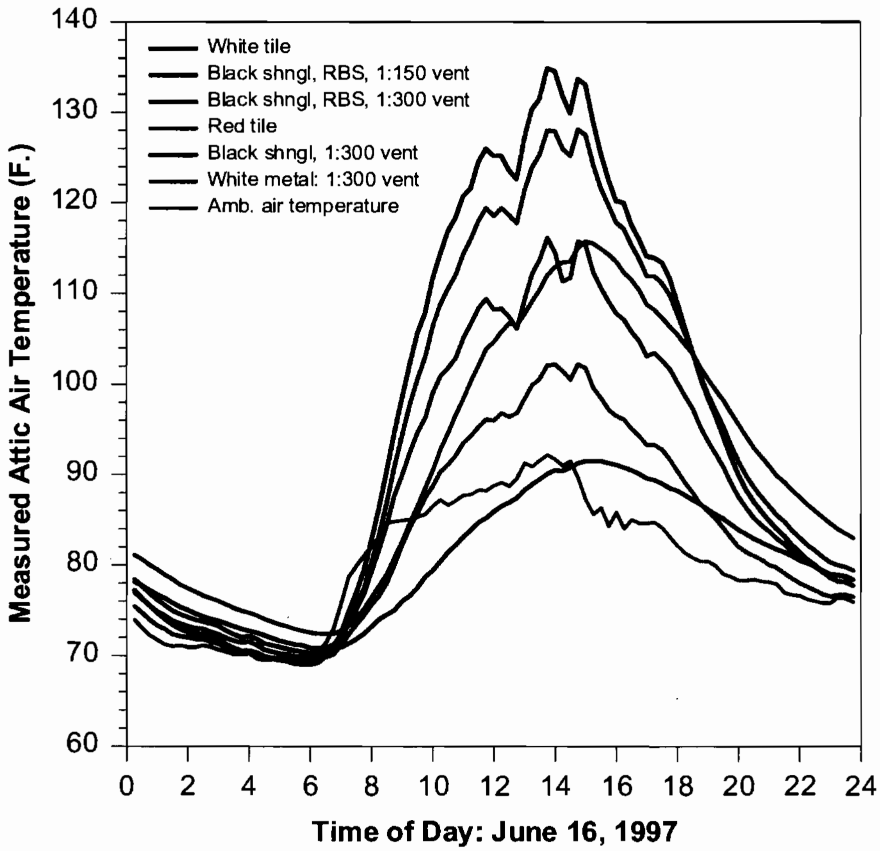

Figure 4. Example Attic Temperatures for the 1997 Tests

Figure 4 shows the impact of roof type on attic temperatures recorded on one day during 1997. That summer FSEC configured the test cells in the following fashion:

Cell 1: Direct nailed white concrete barrel tile
Cell 2: Black asphalt shingles; radiant barrier ; increased vent area
Cell 3: Black asphalt shingles; radiant barrier
Cell 4: Direct nailed red concrete barrel tile;
Cell 5: Black asphalt shingles; (reference cell)
Cell 6: White standing seam metal;

All roofing materials were installed in a conventional manner, and according to manufacturer's specifications and current practice in the Central Florida area. Although raised counter-batten type tile installations which promote ventilation have been shown thermally beneficial (see Beal and Chandra, 1994), current practice, with its focus on lower first costs, dictated a direct nailed application method for the tile roofs. Perforated vinyl soffit vents were used; ridge vents were the "shingle vent" type with foam mesh over the ridge outlet covered by shingles. Standard tile ridge vents were utilized for the two tile roof sections and a manufacturer supplied ridge vent was used with the standing seam metal roof. In each test cell the free ventilation area was first estimated based on dimensional measurements and then verified by a fan pressurization test of the attic to estimate the equivalent leakage area. Soffit or ridge vent area was then closed off to match the target free vent area to within 10%. The 1:300 attic vent to floor area was observed for all of the test cells, except for a cell 2 which had twice the vent area (1:150) to examine its relative influence on RBS performance.

Table 1. Tested Roofing Material Solar Reflectances and Emittances*

Sample	Solar Reflectance	Long-wave emittance
Black asphalt shingle	2.7%	0.9
White tile	75.4%	0.88
Red tile	19.5%	0.91
White metal	67.6%	0.83

Samples of the roofing materials were sent to a laboratory to establish their integrated solar reflectance using ASTM Test Method E-903 (1996). :Long wave emittance was measured also using the ASTM E-408 test procedure. Table 1 shows the tested values.

In order to compare model predicted to measured attic temperatures we formatted the measured FRF weather data for the summer into appropriate formats and prepared input files for UZM for each roof case. We also carried out simulations for selected cases using EnergyGuage USA (EGUSA) and ASTM C 1340 (ASTM) models (see Appendix A for description). A key problem was estimating cloud cover inputs for the sky radiant model in UZM since cloud cover observations were not made at the FRF. We used cloud cover data for the experimental period from the airport at Orlando to estimate cloud cover at the FRF. Since Orlando is approximately 45 miles away, the cloud data is approximately correct at best.

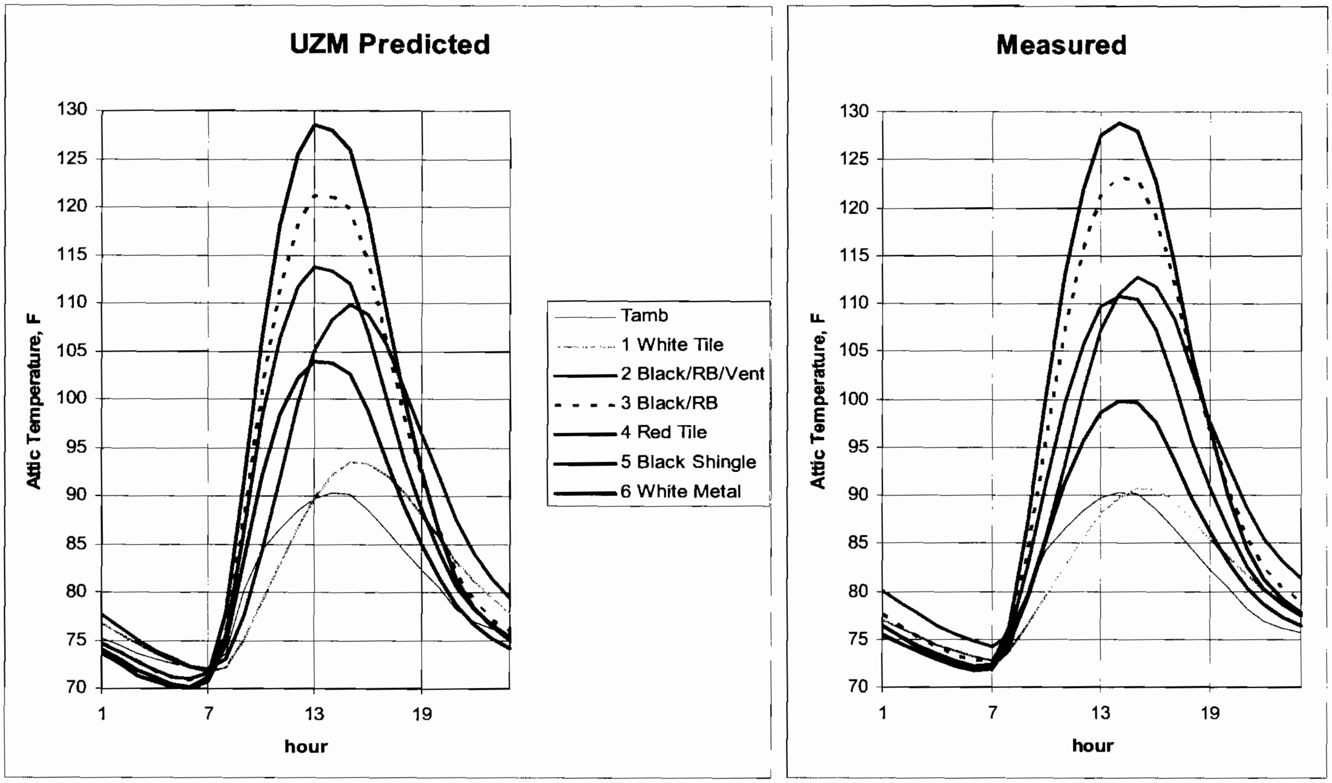

Figure 5. FRF July Average Attic Air Temperatures

The left plot of Figure 5 shows the hourly average attic temperature for the month of July calculated by UZM for each of the 6 roof systems compared to the measured hourly averages on the right. UZM gets the overall picture right, with the temperatures very close to measured values for most systems and the hot attic cases clearly differentiated from the cool attic cases.

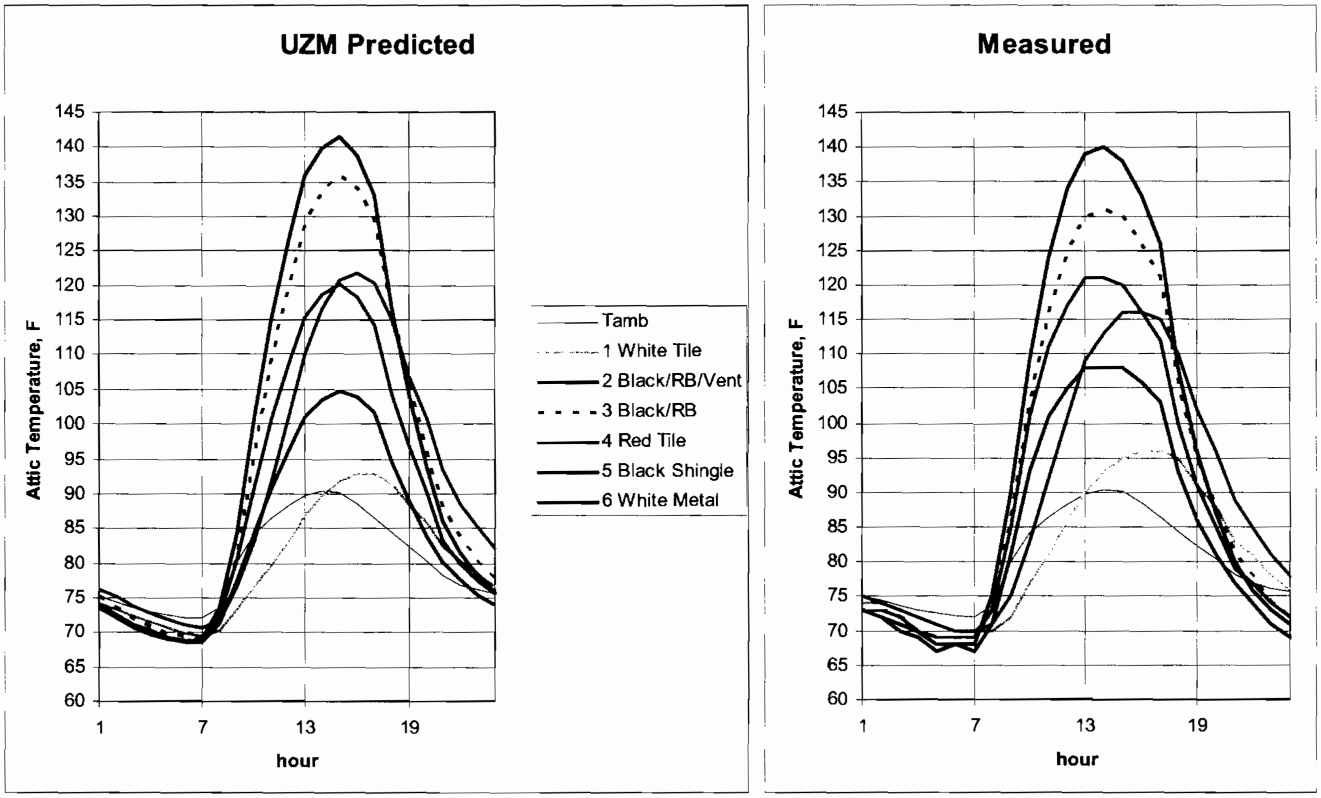

Figure 6. FRF July Peak Day Attic Air Temperatures

Figure 6 shows the same comparison for the peak attic temperature day in July 1997. Again, UZM matches the overall picture pretty well, including the difference between the hottest attic with black shingles and the coolest attic with white roof tiles.

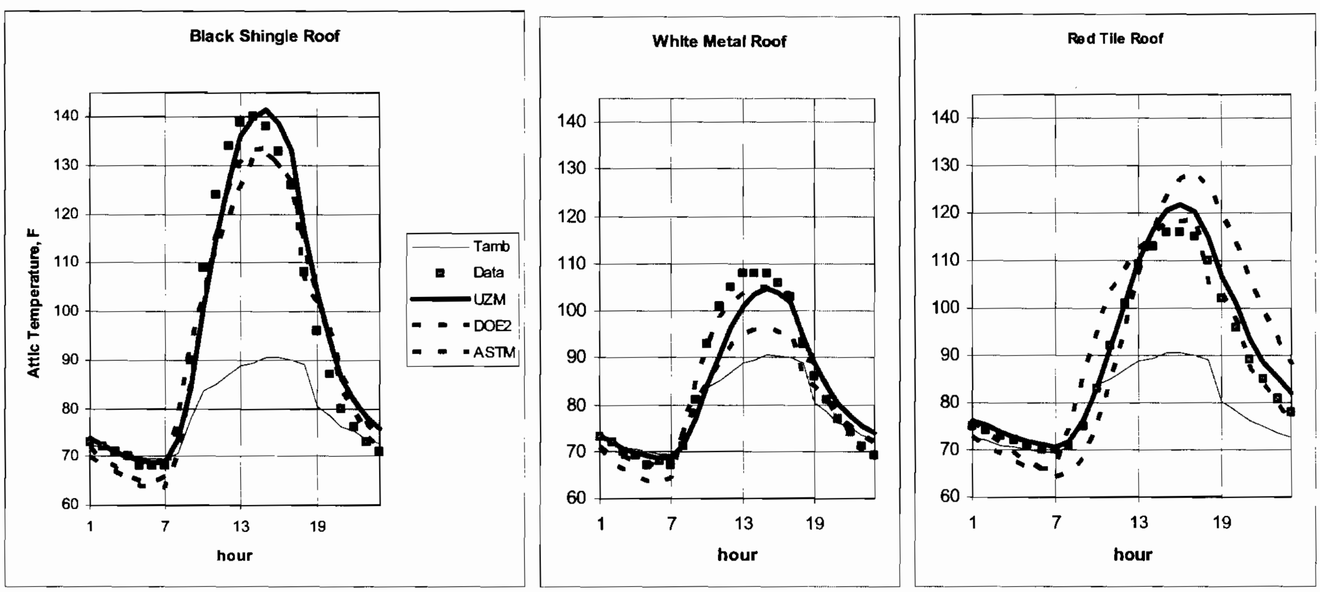

Figure 7. FRF July Peak Model Comparison

Figure 7 compares UZM predictions for 3 of the FRF peak day cases with predictions for the EGUSA and ASTM models. The UZM predictions compare very well with the other 2 models.

Cardinal Roseville Data

We used a year of data from the Cardinal Roseville project[2] [3] to test UZM predictions against measured attic temperatures for a typical production home in a California valley climate. Roseville is a bedroom community in California's central valley east of Sacramento (lattitude 38.7, longitude 121.2, elevation 160 ft (49 m)). The central valley has hot dry summers with clear sunny skies almost every day. The house is a single story 1854 ft2 (172 m2), 2 bedroom production home. Figure 8 shows the front of the house which faces East. Concrete tile roofs were installed over ventilated attics with R-38 (R-6.7) loose fill insulation. The roofs had high and low vents for enhanced attic ventilation. The air conditioning systems featured a split system air conditioning system with sealed and tested R4.2 flex ducts located in the attic.

Figure 8. Cardinal Test House in Roseville

The unoccupied, unfurnished houses were operated to simulate normal residential occupancy. Thermostats were set to maintain 68 F (20 C) for heating and 75 F (24 C) for cooling. There was a data logger in each house which recorded hourly temperatures and electricity and gas use for cooling and heating. The system also included a complete weather station with outdoor temperature, relative humidity, wind and solar measurements. Electric heaters controlled by the data loggers simulated sensible heat generated by occupants using the California Energy Commission standard internal gain profile which varies by hour and month.

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[2] Wilcox, B.; Larsen, J. "Measured Cooling Load, Energy and Peak Demand Savings from High Performance Glass in a California Production House", Proceedings of Thermal Performance of the Exterior Envelopes of Buildings IX, ASHRAE, Atlanta, GA, 2004.

[3] Wilcox, B.; Larsen, J. "Comparison of Calculated and Measured Air conditioning Design Loads for Alternative Glazing Options in Production Homes in California, Proceeding of the ACEEE 2004 Summer Study, American Council for an Energy Efficient Economy, Washington, DC, 2004.

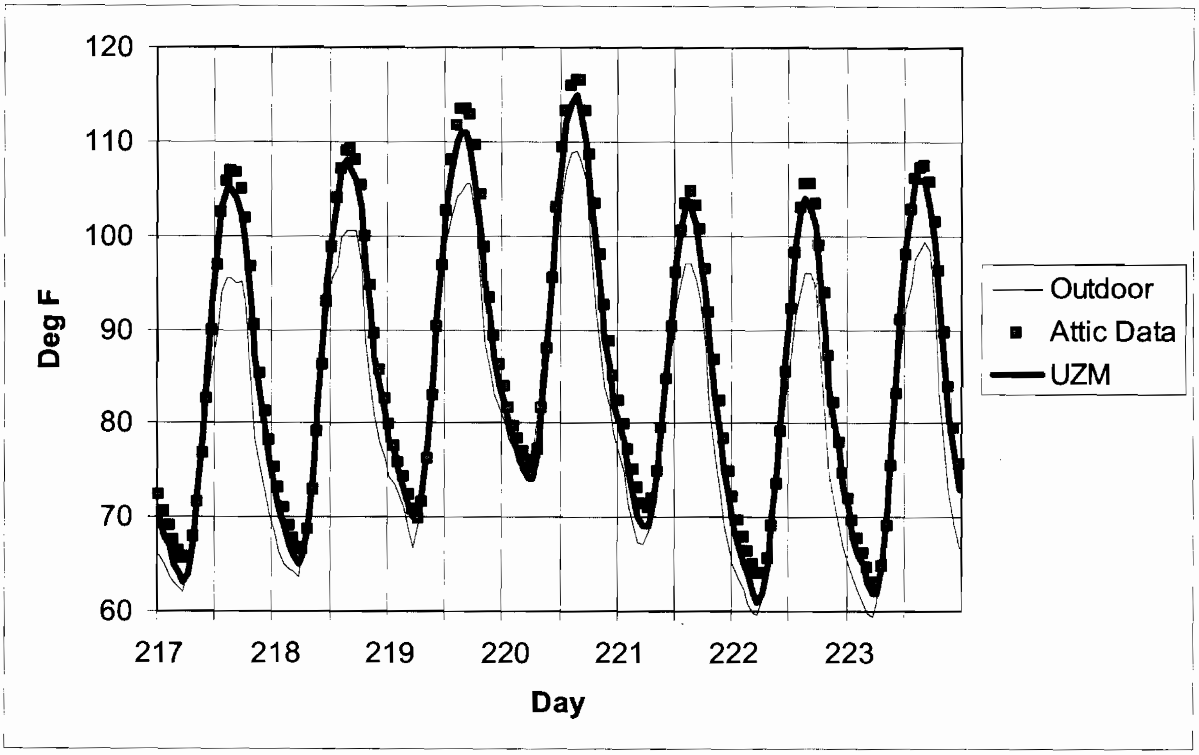

Figure 9 Hourly Roseville Attic Temperatures During the Hottest Week

Figure 9 shows the UZM predicted attic temperatures compared to measured data for the hottest week of the Roseville data set including the highest attic temperature of the year. The UZM predictions follow the overall pattern and match the peak temperature in the attic within 2 degrees F.

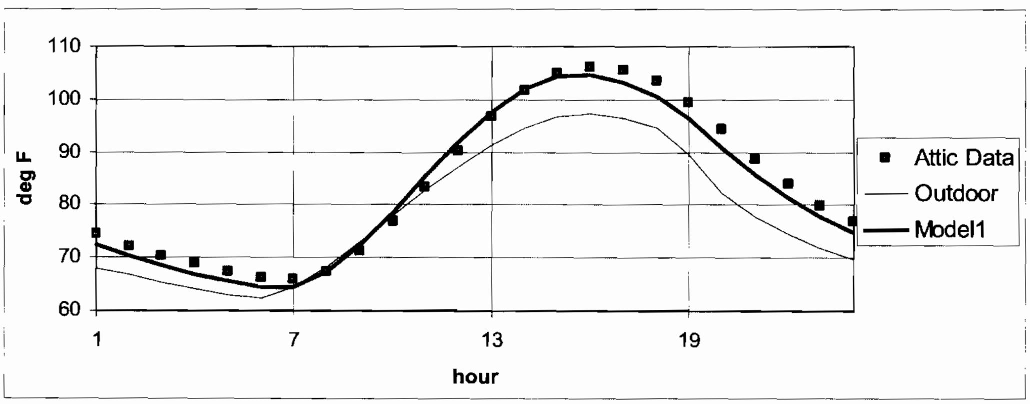

Figure 10. August Average Attic emperatures

Figure 10 compares average UZM predicted attic temperatures with average measured data for August. The excellent agreement indicates that the model is correctly representing the overall summer attic conditions.

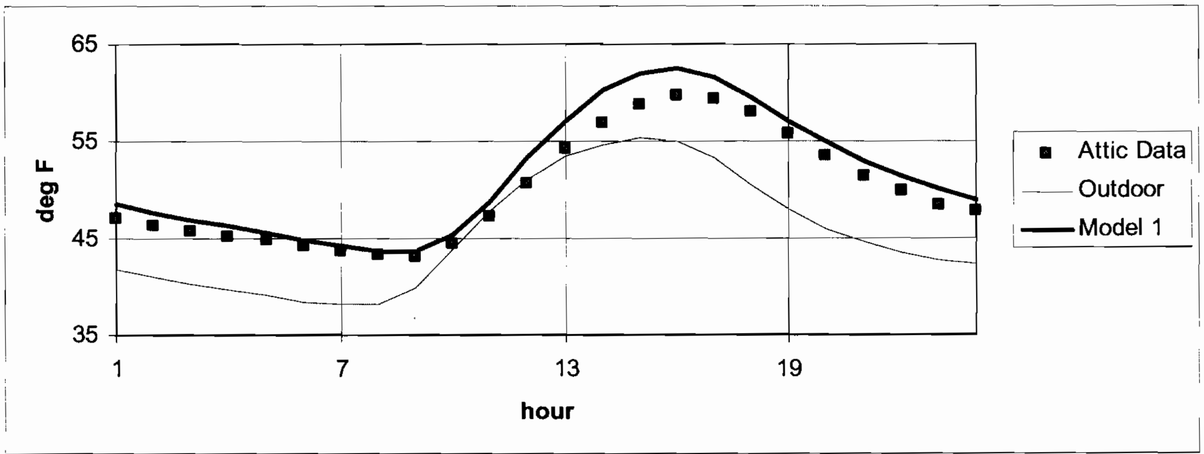

Figure 11. January Average Attic Temperatures

Figure 11 shows that the UZM predicted average January attic temperatures also agree well with the measured data. This shows that UZM also gives usable winter attic temperature predictions.

Comparison with 2005 ACM Calculations

ACM Modeling of Attics and Ducts

The 2005 Standards ACM Manual[4] specifies the calculation to be used by certified computer programs for attics and ducts in calculations for residential buildings. In the 2005 ACM (and all previous editions) attics are treated as part of the ceiling construction and not as a thermal zone with an air temperature and ventilation. Seasonal distribution efficiencies are calculated using an adaptation of the ASHRAE Standard 152[5] equations and combined with an hourly multiplier that accounts for the average impact of solar radiation and outdoor temperature variations.

Attic Temperatures

The 2005 ACM Manual specifies the attic temperature to be used in the modified ASHRAE 152 equation to calculate seasonal duct efficiencies. Table 2 compares these specified temperatures to load weighted seasonal temperatures calculated for the 1761 square foot prototype using UZM for attics with black shingles (Base Case) and the same attics with radiant barriers and enhanced ventilation (RB). Load weighted temperatures are calculated by weighting the temperature each hour by the fraction of the seasonal heating or cooling loads which occur during that hour. The 2005 required temperatures are in the column labeled ACM. Since duct losses affect the attic temperature, the UZM calculated temperatures depend on whether there are ducts in the attic and whether they are sealed or not. The 3 cases shown are no ducts in the attic (Perfect) sealed ducts with balanced supply and return leakage of 4% each and unsealed ducts with supply and return leakage of 11% of fan flow each. Averages for all the climate zones and a housing starts weighted average for the state are shown in the bottom 2 rows. The row labeled CIRB is the average value weighted by housing starts in each climate zone using data from the Construction Industry Research Board[6].

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[4] CEC, 2003. 2005 Building Energy Efficiency Standards, Residential ACM Manual, California Energy Commission, Sacramento, CA. http://energy.ca.gov/2005_standards/documents

[5] ASHRAE Standard 152-2004 – Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ANSI Approved)

[6] www.cirbdata.com

Table 2. Comparison of Seasonal Attic Temperatures

	Heating								Cooling							
	Attic				RB				Attic				RB			
Climate	ACM	UZM	UZM	UZM	ACM	UZM	UZM	UZM	ACM	UZM	UZM	UZM	ACM	UZM	UZM	UZM
Zone		Perfect	4%	11%		Perfect	4%	11%		Perfect	4%	11%		Perfect	4%	11%
1	52.0	47.1	49.4	51.4	52.0	47.5	49.6	51.3	60.0	111.9	109.5	107.3	65.4	95.8	93.3	93.6
2	48.0	44.2	47.5	50.5	48.0	44.2	47.0	49.3	87.0	118.7	114.2	110.0	84.3	104.0	101.6	99.2
3	55.0	46.9	49.2	51.1	55.0	47.7	49.7	51.4	80.0	104.2	101.8	99.5	79.4	93.2	92.0	90.7
4	53.0	44.7	47.7	50.2	53.0	45.5	48.0	50.1	79.0	104.7	102.2	100.1	78.7	94.1	92.6	91.4
5	49.0	44.9	47.3	49.6	49.0	45.8	48.0	49.9	74.0	106.0	103.6	101.3	75.2	93.9	92.6	91.3
6	57.0	48.3	50.5	52.1	57.0	49.2	51.3	52.7	81.0	103.0	100.3	98.3	80.1	91.9	90.4	89.2
7	62.0	47.8	50.5	52.4	62.0	49.0	51.4	53.0	74.0	106.0	102.7	100.4	75.2	93.7	92.1	90.8
8	58.0	45.3	48.2	50.2	58.0	46.5	49.1	50.8	80.0	114.2	109.3	106.1	79.4	100.6	97.9	96.0
9	53.0	46.5	48.8	50.9	53.0	47.5	49.6	51.4	87.0	114.4	110.4	106.8	84.3	101.8	99.5	97.4
10	53.0	42.8	45.7	48.2	53.0	43.9	46.4	48.4	91.0	118.6	113.8	109.4	87.1	105.5	102.7	100.1
11	48.0	43.6	46.2	48.5	48.0	43.8	46.2	48.1	95.0	119.1	114.1	109.5	89.9	106.8	103.7	100.8
12	50.0	43.8	46.4	48.8	50.0	44.2	46.6	48.6	91.0	117.3	112.9	109.0	87.1	104.9	102.2	99.8
13	48.0	43.4	46.2	48.6	48.0	43.9	46.4	48.5	92.0	125.1	118.8	113.5	87.8	110.2	106.6	103.4
14	39.0	36.2	39.9	43.6	39.0	37.3	40.4	43.2	99.0	119.7	115.0	110.0	92.7	107.2	104.5	101.5
15	50.0	40.8	43.0	45.1	50.0	42.4	44.3	46.2	102.0	120.2	115.1	109.8	94.8	109.5	106.3	102.9
16	32.0	35.4	38.8	42.4	32.0	35.7	38.6	41.5	80.0	118.5	114.1	109.6	79.4	101.7	99.5	97.2
Ave	50.4	43.9	46.6	49.0	50.4	44.6	47.0	49.0	84.5	113.8	109.9	106.3	82.6	100.9	98.6	96.6
CIRB	51.5	44.0	46.7	49.1	51.5	44.7	47.2	49.1	87.3	114.9	110.7	106.9	84.5	102.3	99.8	97.6

The UZM model generally predicts lower attic temperatures in the heating season and significantly higher temperatures in the cooling season, even after accounting for duct losses. The variation in attic temperature between climate zones is also much smaller in the UZM model, particularly in cooling. There is limited documentation on how the ACM attic temperatures were originally derived.

Seasonal Distribution Efficiency

The seasonal distribution efficiency as used here is defined to include all of the effects of a duct system on the loads and energy use of the home. In addition to energy lost through conduction and air leakage from the ducts this may include:

1. Changes to the air tightness of the house caused by duct leakage including leakage around registers which acts as envelope leakage when the system fan is off. The ACM rules specify a different SLA for houses with no ducts, sealed ducts and unsealed ducts and this is effect is included in the calculated distribution efficiency.
2. Changes in loads due to regain of duct losses changing the attic temperature which changes heat flow through ceiling. A version of this effect is included in both the 2005 ACM and UZM calculations.
3. Changes in infiltration due to unbalanced duct leakage induced pressurization of the house. This effect is not included in this analysis even though UZM can handle it because the 2005 ACM approach specifies balanced leakage.

The distribution efficiency is calculated as the seasonal energy use of a house with perfect ducts (ducts located completely in the conditioned space or a system with no ducts) divided by the energy use of the same house with ducts in the attic. Because we are including the items in the list above, the distribution efficiency for the 2005 ACM will not be the values produced by the distribution efficiency equation in the ACM.

Table 3 compares the seasonal heating distribution efficiency calculated according to the 2005 ACM and UZM with the seasonal efficiency calculated using the UZM hourly calculation. Efficiencies are presented for base case dark roof and the same with radiant barrier and enhanced ventilation. The table shows distribution efficiency for sealed (4%) and unsealed (11%) ducts for each attic type.

Table 3. Comparison of Seasonal Heating Distribution Efficiency

	Heating											
Climate	Attic						RB					
Zone	4%			11%			4%			11%		
	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff
1	81%	81%	1%	69%	70%	1%	81%	82%	1%	70%	70%	0%
2	81%	84%	3%	71%	74%	3%	82%	84%	3%	72%	74%	2%
3	81%	82%	1%	70%	71%	0%	81%	82%	1%	71%	71%	0%
4	82%	83%	2%	71%	73%	2%	82%	84%	2%	72%	73%	1%
5	80%	82%	2%	69%	71%	2%	80%	83%	2%	70%	71%	1%
6	79%	78%	-1%	68%	66%	-2%	79%	78%	-1%	69%	67%	-2%
7	81%	78%	-3%	70%	67%	-3%	81%	79%	-2%	71%	68%	-3%
8	80%	79%	-1%	70%	69%	-1%	81%	80%	-1%	71%	69%	-1%
9	81%	82%	1%	70%	71%	0%	81%	82%	1%	71%	71%	0%
10	81%	81%	0%	70%	70%	0%	81%	82%	0%	71%	70%	-1%
11	81%	82%	1%	70%	71%	1%	81%	82%	1%	70%	71%	0%
12	81%	82%	1%	70%	71%	1%	81%	82%	1%	71%	71%	0%
13	80%	82%	2%	69%	71%	2%	81%	82%	2%	70%	71%	1%
14	80%	82%	3%	67%	70%	3%	80%	83%	3%	68%	70%	2%
15	79%	78%	-1%	66%	64%	-2%	79%	78%	0%	67%	65%	-2%
16	79%	83%	4%	66%	70%	4%	79%	83%	4%	67%	70%	3%
Ave	80%	81%	1%	69%	70%	1%	81%	82%	1%	70%	70%	0%
CIRB	81%	81%	1%	70%	70%	0%	81%	82%	1%	70%	70%	0%

Heating distribution efficiency for the UZM model is very similar to the values calculated according to the 2005 ACM. The average and construction weighted average change in efficiencies is 1% or less for each case. Individual climate zones have larger variations, particularly in mild zones such as 7 (San Diego) and in zone 16 which is the coldest in the state (Mount Shasta). The UZM model includes the effects of radiant barriers in heating where the 2005 ACM assumes that they have no heating impact. The UZM calculated heating impact of radiant barriers appears very small.

Table 4. Comparison of Seasonal Cooling Distribution Efficiency

	Cooling											
Climate	Attic						RB					
Zone	4%			11%			4%			11%		
	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff
1	93%	81%	-12%	90%	67%	-23%	93%	71%	-22%	90%	77%	-14%
2	87%	77%	-10%	79%	64%	-15%	89%	82%	-6%	83%	71%	-11%
3	91%	83%	-8%	86%	72%	-14%	92%	88%	-4%	88%	80%	-9%
4	92%	79%	-13%	88%	68%	-20%	93%	84%	-9%	90%	74%	-16%
5	93%	83%	-10%	89%	72%	-18%	93%	87%	-6%	90%	79%	-11%
6	91%	83%	-8%	86%	75%	-11%	92%	88%	-4%	89%	82%	-8%
7	94%	76%	-18%	90%	65%	-25%	95%	82%	-13%	93%	73%	-20%
8	91%	74%	-18%	86%	63%	-23%	93%	80%	-13%	90%	71%	-19%
9	89%	79%	-10%	81%	67%	-14%	91%	84%	-7%	85%	73%	-12%
10	87%	79%	-8%	78%	67%	-11%	89%	83%	-5%	82%	72%	-9%
11	84%	78%	-6%	74%	66%	-8%	86%	83%	-4%	78%	71%	-6%
12	87%	78%	-9%	77%	65%	-12%	88%	82%	-6%	81%	71%	-10%
13	86%	77%	-8%	76%	65%	-11%	87%	82%	-6%	79%	71%	-8%
14	84%	80%	-4%	73%	67%	-5%	86%	84%	-2%	76%	72%	-4%
15	82%	81%	-1%	69%	69%	-1%	84%	84%	0%	73%	73%	0%
16	92%	81%	-11%	87%	68%	-19%	93%	86%	-7%	89%	76%	-14%
Ave	89%	79%	-10%	82%	67%	-14%	90%	83%	-7%	85%	74%	-11%
CIRB	88%	79%	-10%	80%	67%	-14%	90%	83%	-6%	84%	73%	-11%

The change due to the UZM model is much larger in the corresponding values for cooling distribution efficiency in Table 4. Most UZM calculated distribution efficiencies in the table are lower than the 2005 ACM values. One notable exception is zone 15 (Palm Springs) the hottest California climate. These differences are consistent with the large change in attic temperatures calculated by UZM from the assumed attic temperatures in the 2005 ACM.

Impact on Measure Life Cycle Cost and Compliance

The change in distribution efficiency impacts the calculated energy savings for other conservation measures that might be considered for inclusion in the 2008 Standards or used for compliance. To illustrate the magnitude of the effects, Tables 5 and 6 shows the standard TDV compliance budget and compliance margin for perfect ducts (ducts totally in conditioned space or no ducts), unsealed ducts, a high efficiency furnace and a high efficiency air conditioner.

Table 5. Impact on Compliance Margin (kTDV/ft2)

Total 2008 TDV Compliance Margin (kBtu/ft2)															
	Base Case Energy			Compliance Margin											
Climate	Standard Design			Perfect Ducts			Unsealed Ducts			92% AFUE			14 SEER / 12 EER		
Zone	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff	ACM	UZM	diff
1	51.62	49.51	-2.11	5.95	5.45	-0.50	-5.00	-4.67	0.33	4.55	4.27	-0.28	0.03	0.02	-0.01
2	71.65	67.90	-3.75	8.68	8.02	-0.66	-6.51	-7.22	-0.71	5.45	5.19	-0.26	1.91	1.66	-0.25
3	46.71	44.22	-2.49	4.65	4.39	-0.26	-3.69	-3.85	-0.16	3.31	3.09	-0.22	0.36	0.27	-0.09
4	53.90	51.58	-2.32	5.58	5.30	-0.28	-4.12	-4.62	-0.50	4.11	3.99	-0.12	0.63	0.49	-0.14
5	46.59	42.42	-4.17	4.70	4.05	-0.65	-3.82	-3.75	0.07	3.21	2.78	-0.43	0.41	0.30	-0.11
6	32.02	30.42	-1.60	2.24	2.39	0.15	-1.62	-1.75	-0.13	1.27	1.11	-0.16	0.32	0.28	-0.04
7	33.85	32.97	-0.88	2.25	3.33	1.08	-1.65	-2.32	-0.67	1.36	1.31	-0.05	0.44	0.39	-0.05
8	43.47	42.77	-0.70	3.36	4.98	1.62	-2.33	-3.45	-1.12	1.68	1.64	-0.04	1.40	1.35	-0.05
9	51.63	48.97	-2.66	4.55	5.39	0.84	-3.55	-4.81	-1.26	1.74	1.60	-0.14	2.71	2.50	-0.21
10	66.03	64.08	-1.95	6.91	8.25	1.34	-5.64	-7.40	-1.76	2.21	2.08	-0.13	4.59	4.46	-0.13
11	92.91	91.60	-1.31	12.45	13.55	1.10	-10.45	-11.93	-1.48	4.87	4.78	-0.09	6.24	6.16	-0.08
12	74.68	72.68	-2.00	9.04	9.98	0.94	-7.31	-8.65	-1.34	4.42	4.34	-0.08	3.68	3.50	-0.18
13	86.42	87.60	1.18	10.58	13.03	2.45	-8.81	-11.14	-2.33	3.37	3.26	-0.11	6.88	7.23	0.35
14	96.24	94.46	-1.78	13.21	13.01	-0.20	-12.08	-13.28	-1.20	4.68	4.49	-0.19	7.19	7.16	-0.03
15	112.85	112.18	-0.67	16.33	16.66	0.33	-16.75	-16.77	-0.02	0.72	0.65	-0.07	15.70	15.72	0.02
16	102.91	98.23	-4.68	14.98	14.00	-0.98	-13.22	-14.22	-1.00	9.46	8.77	-0.69	1.74	1.73	-0.01
Ave	66.47	64.47	-1.99	7.84	8.24	0.40	-6.66	-7.49	-0.83	3.53	3.33	-0.19	3.39	3.33	-0.06
CIRB	66.67	64.98	-1.70	7.65	8.44	0.79	-6.36	-7.50	-1.14	3.26	3.13	-0.13	3.69	3.61	-0.08

Table 6. Impact on Compliance Margin (Percent)

Total 2008 TDV Compliance Margin (%)															
	Base Case Energy			Compliance Margin											
Climate	Standard Design			Perfect Ducts			Unsealed Ducts			92% AFUE			14 SEER / 12 EER		
Zone	ACM	Attic	diff	ACM	Attic	diff	ACM	Attic	diff	ACM	Attic	diff	ACM	Attic	diff
1	51.62	49.51	-4%	12%	11%	-1%	-10%	-9%	0%	9%	9%	0%	0%	0%	0%
2	71.65	67.90	-6%	12%	12%	0%	-9%	-11%	-2%	8%	8%	0%	3%	2%	0%
3	46.71	44.22	-6%	10%	10%	0%	-8%	-9%	-1%	7%	7%	0%	1%	1%	0%
4	53.90	51.58	-4%	10%	10%	0%	-8%	-9%	-1%	8%	8%	0%	1%	1%	0%
5	46.59	42.42	-10%	10%	10%	-1%	-8%	-9%	-1%	7%	7%	0%	1%	1%	0%
6	32.02	30.42	-5%	7%	8%	1%	-5%	-6%	-1%	4%	4%	0%	1%	1%	0%
7	33.85	32.97	-3%	7%	10%	3%	-5%	-7%	-2%	4%	4%	0%	1%	1%	0%
8	43.47	42.77	-2%	8%	12%	4%	-5%	-8%	-3%	4%	4%	0%	3%	3%	0%
9	51.63	48.97	-5%	9%	11%	2%	-7%	-10%	-3%	3%	3%	0%	5%	5%	0%
10	66.03	64.08	-3%	10%	13%	2%	-9%	-12%	-3%	3%	3%	0%	7%	7%	0%
11	92.91	91.60	-1%	13%	15%	1%	-11%	-13%	-2%	5%	5%	0%	7%	7%	0%
12	74.68	72.68	-3%	12%	14%	2%	-10%	-12%	-2%	6%	6%	0%	5%	5%	0%
13	86.42	87.60	1%	12%	15%	3%	-10%	-13%	-3%	4%	4%	0%	8%	8%	0%
14	96.24	94.46	-2%	14%	14%	0%	-13%	-14%	-2%	5%	5%	0%	7%	8%	0%
15	112.85	112.18	-1%	14%	15%	0%	-15%	-15%	0%	1%	1%	0%	14%	14%	0%
16	102.91	98.23	-5%	15%	14%	0%	-13%	-14%	-2%	9%	9%	0%	2%	2%	0%
Ave	66.47	64.47	-3%	12%	13%	1%	-10%	-12%	-2%	5%	5%	0%	5%	5%	0%
CIRB	66.67	64.98	-3%	11%	13%	2%	-10%	-12%	-2%	5%	5%	0%	6%	6%	0%

Perfect ducts savings according to the UZM model are higher in every climate zone. The statewide savings on both an average and construction weighted basis is 11% of total budget versus 7% for the 2005 ACM values. On the other hand, the penalty for unsealed ducts is almost identical under both calculations. A high efficiency furnace is slightly better under the UZM calculation, particularly in the cold climates zones such as 16 where it gets 1/3 more compliance credit than under the 2005 ACM. A high efficiency air conditioner also gets slightly more compliance credit on average, but the effect varies and the credit is actually slightly lower in zone 13 (Fresno).

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Appendix A: Review of Other Models

ASTM C 1340-99.

The ASTM attic model was developed by Ken Wilkes at Oak Ridge National Laboratory over a number of years. First developed as part of an ASHRAE project to investigate attic thermal performance it was adopted as an ASTM Method in 1999. A duct model was later added to this program. This model was reviewed and particular note was made of the following features. The thermal response factor method is used to analyze envelope transient conduction on an hourly basis. A detailed hourly radiant heat exchange analysis is made using the Sparrow and Case enclosure method.

Internal air to surface convection assumes an unmixed ventilation attic air model and a heat exchanger effectiveness approach. Moisture transfer and storage is considered.

Given supply duct inlet temperatures and flows as input, the supply and return duct heat transfer to the attic is analyzed by a heat exchanger effectiveness approach, assuming suspended ducts. No air handler analysis is included. Duct leakage enthalpy heat transfer to the attic is accounted for. The program does not account for any interaction between infiltration/ventilation air and unbalanced duct leakage.

EnergyGuage USA

Reference: Parker, D., P. Broman, J. Grant, L. Gu, M. Anello, R. Vieira and H. Henderson, 1999

This program is a user interface shell for the DOE2 program produced by the Florida Solar Center for use in Florida building code compliance and now marketed nationally. To overcome DOE-2.1E's inability to appropriately simulate the interaction between duct systems located in attics and building cooling energy use, the authors developed a simulation of the heat transfer to the thermal distribution system which was used to development a function within DOE-2.1 which can simulate this interaction (Parker, Fairey, and Gu 1993).

Since a DOE2 attic model is used, convective and radiative exchange between the roof decking and the attic insulation is calculated by setting the interior film coefficient according to the values in the ASHRAE Handbook of Fundamentals depending on their slope and surface emittance.

The duct model does not use an effectiveness approach for duct losses/gains, but uses supply temperature minus attic temperature for supply losses and conditoned zone minus attic for return duct losses.

FSEC 3.0

The FSEC 3.0 program is a general building simulation tool for analysis of whole-building systems, including simultaneous evaluation of energy, moisture, multizone airflows, and air distribution systems.

The program consists of three main sections. The first section calculates heat and moisture transfer in the building envelope. The second section calculates overall energy and moisture balances for the building zones. The third section focuses on HVAC systems, including calculations of system airflows and pressures for multiple zones. Air distribution system performance is calculated in the third section.

The attic model used for this analysis was developed by Gu, et al. (1996), under ASHRAE Research Project 852, Comparison of Duct System Computer Models That Could Provide Input to the Thermal

Distribution Standard Method of Test (SPC152P). Four features of the model make it particularly appropriate for our analysis.

The attic model accounts for the interactions between the attic thermal environment and the air distribution system. Specifically, both duct leakage and surface heat transfer can be modeled.

1. The attic can be modeled as two interacting thermal zones. Specifically, the upper portion of the attic can be at a different temperature than the lower portion.
2. The model accounts for radiative exchange among surfaces in the attic. Specifically, the model includes radiation among the roof, the upper ceiling surface, and the duct system in the attic.
3. The model accounts for natural ventilation of the attic, reflecting the interacting effects of roof and attic temperature on attic ventilation.

REGCAP

Reference: Iain Walker, 2005.

RegCap is a research model maintained by Iain Walker at Lawrence Berkeley National Laboratory which has a single story house with attic and a duct system either in the house or attic. Both zones have a detailed ventilation model, a heat transfer model and a simple moisture model. The ventilation/infiltration model accounts for detailed envelope leakage, duct leakage with and without fan operation, and ceiling leakage between the zones. Based on wind, stack effect induced pressure differences, the hourly balanced mass flows through all parts are determined through an iterative solution that alternately does the heat transfer analysis and the ventilation analysis until convergence.

The attic heat transfer analysis is by lumped capacitance, lumped resistance network, with radiation treated separately from convection. Sixteen mass and massless nodes are used in the analysis. The radiation model assumes the interacting surfaces are the ceiling, the two pitched roof surfaces, and the supply and return duct surfaces. The house model is apparently simpler, using building UA appraoch, with solar loads, and a coupling to the thermal mass of the zone.

An equipment model is used to determine heating and cooling system capacities, efficiencies and energy consumption.