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Thermal Performance of Unvented Attics in Hot-Dry Climates: Results from Building America

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THERMAL PERFORMANCE OF UNVENTED ATTICS IN HOT-DRY CLIMATES: RESULTS FROM BUILDING AMERICA

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ABSTRACT

As unvented attics have become a more common design feature implemented by Building America partners in hot-dry climates of the United States, more attention has been focused on how this approach affects heating and cooling energy consumption. By eliminating the ridge and eave vents that circulate outside air through the attic in most new houses and by moving the insulation from the attic floor to the underside of the roof, an unvented attic becomes a semiconditioned space, creating a more benign environment for space conditioning ducts. An energy trade-off is made, however, because the additional surface area (and perhaps reduced insulation thickness) increases the building loss coefficient. Other advantages and disadvantages, unrelated to energy, must also be considered. This paper addresses the energy-related effects of unvented attics in hot-dry climates based on field testing and analysis conducted by the National Renewable Energy Laboratory.

INTRODUCTION

Unvented attics have gained a significant amount of attention in the building science community over the past 5 years as several builders have eliminated attic vents and moved the insulation layer from the ceiling plane to the roof plane. This creates a semiconditioned space where air ducts can reside in a much milder environment, particularly in hot climates. This report evaluates the energy impacts of unvented attics from the body of evidence that has accumulated through the research of Building America in hot-dry climates, where the most extensive adoption of this technique has occurred. Beyond the energy impacts of unvented attics, many other performance and quality-assurance issues must be considered when evaluating this technology. Some of the most important advantages and disadvantages of unvented attics are summarized below.

Potential Advantages

- Milder environment for air ducts
- Eliminates cost of installing vents
- Semiconditioned storage area
- Smaller latent load on air conditioner (humid climates only).

Potential Disadvantages

- Larger area for air leakage and heat gain/loss
- More difficult to install insulation at roof level compared to ceiling plane
- Higher roof sheathing temperature
- Higher shingle/tile temperature
- Gas appliances (e.g., furnace, water heater) located in attic must be closed-combustion or be moved to garage.

The basic approach to creating an unvented attic, or cathedralized roof, is illustrated in Figure 1. The fiberglass batts, blown-in cellulose, or blown-in fiberglass insulation that typically fills the joist space in a vented attic is replaced with either netted and blown cellulose or fiberglass batts placed between roof trusses or rafters. Eave, ridge, and other roof vents are eliminated. The continuous air barrier is moved to the roof plane instead of the ceiling, requiring careful attention to detail when installing the air barrier around complex roof geometries. Supply and return air ducts remain in the semiconditioned space of the attic, avoiding the severe temperature swings experienced by a traditional vented attic.

The remainder of this paper describes field-testing and analysis conducted by the National Renewable Energy Laboratory (NREL) and the Building America teams. The Building Science Consortium (BSC) has done the most extensive research in this area, and the two builder projects described in detail in the following sections were led by this partnership: Watt Homes in Las Vegas and Pulte Homes in Tucson.

KEYWORDS
attic ventilation, unvented attic, residential, duct leakage, energy efficiency, Building America

NOMENCLATURE

ACH	Air changes per hour
BSC	Building Science Consortium
BSP	Builder Standard Practice
DOE-2.2	An hourly building energy-simulation software tool
HVAC	Heating, ventilation, and air-conditioning
NREL	National Renewable Energy Laboratory
SEER	Seasonal Energy Efficiency Ratio
UA_o	Building loss coefficient: the rate of heat loss or gain as a function of temperature difference between the inside and outside under steady-state conditions

APPROACH

Direct measurements of the performance characteristics of attics under realistic field conditions, in combination with a calibrated model, provide vitally important information when estimating annual energy savings for unvented attics. It is extremely helpful if a side-by-side test can be conducted, where the only difference between two houses is the type of attic. This allows for the isolation of specific performance differences resulting from the unvented attic.

The most useful specific field measurements include the air temperatures of the attic and house interior, building loss coefficient (UA_o) and air infiltration determined during co-heating, change in UA_o and air infiltration resulting from air-handler operation, effective leakage area as measured with a blower door, and duct leakage as measured with a duct blaster It is also important to have access to local temperature, wind, and solar conditions. A thorough site audit should also be conducted to verify that all features of the house are as expected.

An accurate and detailed whole-house model is essential to capture the difference between a vented and unvented attic. The following discussion provides the approach used by the authors to simulate the energy usage of houses with vented and unvented attics using DOE-2.2. However, it is important to make specific judgments regarding the most reasonable modeling assumptions, and even the most appropriate modeling tool, in the context of the project at hand. Important considerations include the attic design, air leakage characteristics, and the local climate. It is also very important to use field test results to the largest extent possible as inputs to the model and to validate the results. More comprehensive descriptions of the engineering analyses and model calibration process that support the modeling assumptions are described in an NREL Technical Report on unvented attics (Hendron et al. 2002).

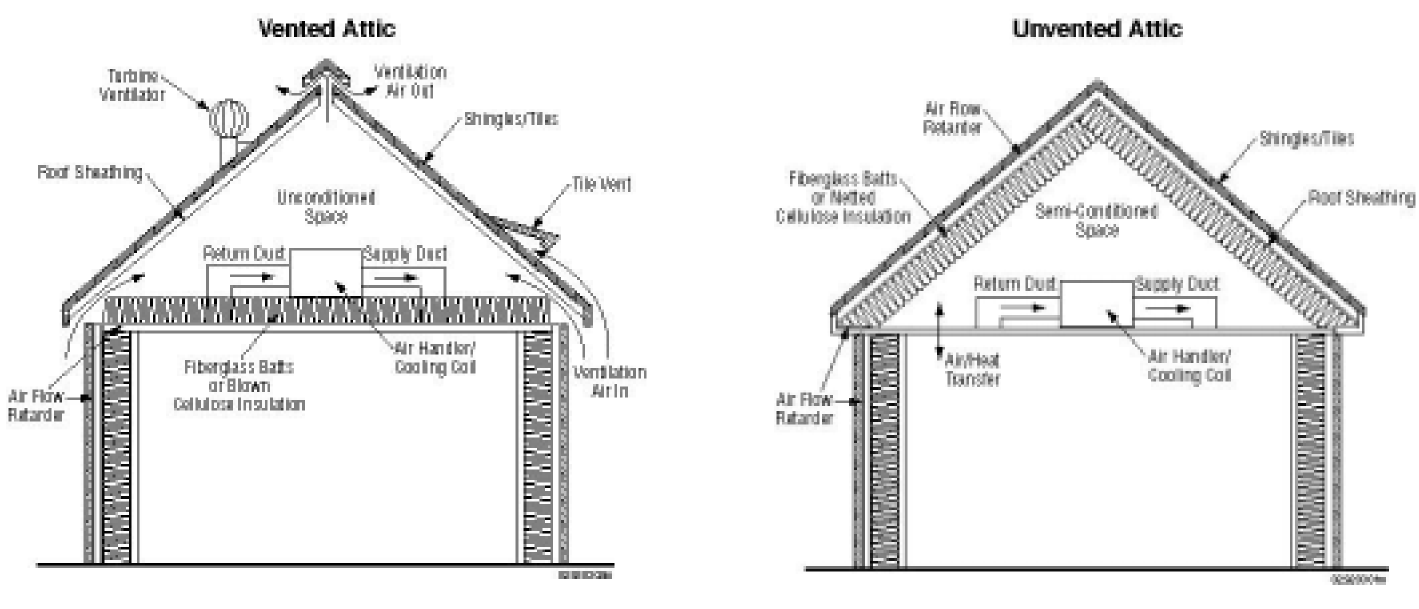

Figure 1. Vented and unvented attic concepts

For the vented scenario, the attic was modeled as an unconditioned space. The attic air-exchange rate was specified as 1.5 air changes per hour (ACH), or approximately 0.5 l/s (1 cfm) per square meter of attic area (ASHRAE 2001). Conductive losses from the supply ducts to the vented attic were based on the measured value of 12.7 W/°C (24 Btu/hr·°F) for the Las Vegas model and the observed insulation value of R-5 of the Tucson model. The Las Vegas model assumed that all of the supply duct leakage was replaced by infiltration of outside or attic air into the conditioned space. The cooling energy of the supply air was not completely lost in the model because the leaks provide some cooling of the attic space. In the Tucson model, 80% of the supply duct leakage was assumed to be lost to the outside.

Assumptions for both models were derived from a combination of engineering judgment and a process of reconciling simulated results with field measurements. Because the vented attic and outdoor air were approximately the same temperature in the Las Vegas field test, a simple DOE-2.2 specification of "outdoor air" infiltration was used for air induced into the house from either the outside or the attic. This assumption would not have been appropriate in the winter months when the vented attic temperature was likely to be noticeably higher than the outdoor temperature or for houses with asphalt shingles instead of tile roofs.

At the time the analysis described in this paper was performed, DOE-2.2 could not directly model the affect of return duct leakage in the vented attic. For the Tucson model, an equivalent heat transfer was approximated using an "air wall" between the attic and the main house space in addition to the normal ceiling, with a total thermal conductance equivalent to the heat capacity of the return air leak. The result was an additional load on the heating or cooling system equal to the amount of energy necessary to raise or lower the temperature of the return air leak from the attic temperature to that of the conditioned space.

The unvented attic was modeled with the insulation in the roof portion of the attic, creating a much tighter space and reducing the natural ventilation in the attic. The attic was unintentionally conditioned by the supply air leaks and was modeled as a conditioned space in DOE-2.2. Duct leakage into the attic, which was measured during field-testing, was modeled using an equivalent flow rate of conditioned supply air. The Las Vegas model assumed that 100% of the supply air mixed with the attic air. However, the Tucson model assumed that 25% of the supply air leakage was lost immediately to the outside and replaced with outside air added directly to the return airstream. The other 75% was assumed to mix with the attic air. This assumption was based on both engineering judgment and calibration of the simulated results with field measurements.

The outdoor airflow into the house was a combination of the natural infiltration and the outdoor airflow induced by the heating, ventilation, and air-conditioning (HVAC) system. A DOE-2.2 residential infiltration model was used along with the measured outdoor airflow rate induced when the HVAC and ventilation systems were activated to simulate the total air infiltration of the house. The residential infiltration model is a multiple linear-regression model that estimates the hourly infiltration rate based on a constant, a wind-driven component, and a component driven by temperature difference.

Simulations were first run using actual test conditions to verify the accuracy of the models and then using more realistic typical operating conditions to predict cooling energy savings after the houses were occupied. The typical conditions were intended to represent average occupant behavior and lead to better predictions of annual energy use (Hendron et al. 2001).

RESULTS

Las Vegas, Nevada

In partnership with BSC, NREL tested a prototype and a base-case house built by Watt Homes in August 1998 to examine the performance of an unvented attic in hot summer conditions. The two test houses were nearly identical except for the unvented attic and the smaller attic R-value in the prototype (R-22 at the roof, compared to R-30 at the ceiling). Summaries of the specifications for both houses are presented in Table 1.

Table 1. Las Vegas Test House Descriptions

		Vented Attic	Unvented Attic
Model		Spring, Plan #4113, 125 m^2 (1,350 ft^2) one-story, slab-on-grade, three bedrooms	Same
Insulation	- Walls	R-13 cellulose	Same
	- Attic	R-30 cellulose at ceiling, vented, tile roof	R-22 cellulose at roof plane, unvented, tile roof
	- Slab	None (carpet pad installed)	Same
Windows		Double-pane, vinyl frame Low-emissivity spectrally selective	Same
Ventilation		Outside air duct to return plenum, manual damper, FanRecycler control (disabled for testing)	Same
Air handler / ducts		Located in attic	Same
Cooling		8.8 kW (2.5 tons), 10 SEER	Same
Air distribution fan		~520 l/s (1,100 cfm) measured	Same

The four test conditions described in Table 2 were established to evaluate the effects of duct leakage on the performance of the two attics. These conditions were in effect at the same time in both houses. Holes were cut in the supply and return air plenums to create the desired amount of duct leakage. Pressure drop across a calibrated orifice plate was used to verify the leakage rate for Cases 2 and 3.

Weather conditions during the test period were hot and sunny with mild winds less than 1.5 m/s (3.4 mph). Outside temperatures peaked over 38°C (100°F) every day, except Tuesday, and dropped down to 21°–27°C (70°–80°F) at night. Inside temperatures were well controlled at about 24˚C (75°F) throughout the test.

The total air infiltration was measured using a tracer gas for each test house while applying the four duct-leakage conditions. The ventilation system was made inactive during the test period by disabling the FanRecycler. The hourly results are shown in Figure 2 and summarized in Table 3. Air infiltration for each house was very small during normal cooling system operation before additional duct leaks were introduced (Case 1). As one would expect, the unvented attic was significantly less sensitive to increases in duct leakage because the ducts were within the conditioned space of the house.

The hourly power consumption for the air conditioner in each test house is also summarized in Table 3. The electric power consumption was very similar for the two test houses when the ducts were tight. The house with the unvented attic used significantly less energy when the ducts were very leaky.

Attic temperatures for the two test houses are shown in Figure 3. The unvented attic very closely tracked the interior temperature of the house. This demonstrated that the unvented attic was thermally well connected to the interior conditioned space and well isolated from the outside environment. Meanwhile the vented attic temperature was approximately the same as the outside temperature. In many attics the temperature would have been much higher during the summer, but not in this case because the tile roof on the vented attic reflected much of the solar radiation, thereby reducing solar heat gain.

When interpreting these results, it is important to note that the unvented attic is only insulated to R-22, compared to R-30 for the vented attic. A smaller R-value is not an inherent characteristic of unvented attics. However, a larger thermal envelope surface area can be expected with an unvented attic as defined in this paper, leading to larger heat loss for the same insulation R-value.

Two DOE-2.2 models were created based on the alternative attic constructions observed in the field. The modeling approach described earlier in this paper was used for the analysis. More comprehensive descriptions of the models are provided in the full NREL report about this project (Hendron 2002).

An important goal of the simulation was to match the actual performance of the houses under a range of conditions. Table 4 shows the measured cooling energy use and the predicted cooling energy use for the two test houses during the test period. Measured energy use in this table is accurate within 0.5%.

The measured average and peak cooling energy use were closely matched by the simulation results throughout the test period. The model responded accurately to changes in the cooling load and changes in the amount of duct leakage. Both the simulation and the field test indicated that there was very little difference in cooling energy use between the vented and unvented attics when the ducts were very tight. However, both peak and average cooling energy for the unvented attic was about 20% less than it was for the vented attic on the final day of testing, when the ducts were extremely leaky and the outside temperature was the hottest.

The simulation models were used with typical summer weather conditions to predict the annual cooling energy requirements using a variety of duct leakage characteristics. In addition to the differences in attic ventilation, these simulations assumed R-22 insulation at the roof plane for the unvented attic and R-30 at the ceiling plane for the vented attic. These measures were treated as a package for the purpose of this analysis, but clearly the unvented attic would perform better if R-30 insulation were used at the roof plane.

Figure 4 shows the estimated annual cooling requirement over a range of duct losses under normal operating conditions. Below 24 l/s (50 cfm) of supply leakage, the annual cooling energy was very similar for both attic types. With 47 l/s (100 cfm) of supply duct leakage, annual energy use for the house with the vented attic was predicted to be approximately 8% more than for the house with the unvented attic. At 94 l/s (200 cfm) of supply duct leakage, the difference increased to about 20%.

Table 2. Leakage Conditions for Las Vegas Field Test

Case 1.	Tight Ducts	Estimated 14 l/s (30 cfm) total duct leakage as measured using a duct blaster.
Case 2.	47±5 l/s (100±10 cfm) Supply Leak	Same as Case 1 with a hole in the supply air plenum that leaked 47 l/s (100 cfm) out of the system at normal operating pressure.
Case 3.	47±5 l/s (100±10 cfm) Supply and Return Leaks	Same as Case 2 with a hole in the return air plenum that leaked 47 l/s (100 cfm) into the system at normal operating pressure.
Case 4.	Additional Supply Leakage	Same as Case 3 with an enlarged hole in the supply air plenum. Although this case is not representative of observed levels of duct leakage, it was included in the test plan to provide an upper extreme.

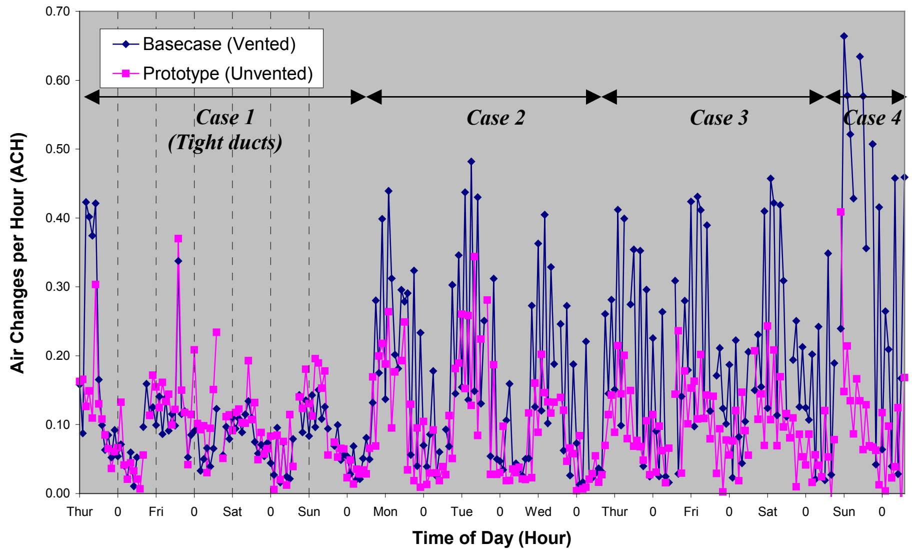

Figure 2. Air infiltration during the summer test period as measured by a tracer gas

Tucson, Arizona

Another prototype house tested by NREL was in a Building America community built by Pulte Homes in Tucson, Arizona. The test was conducted in late August 1999. The prototype featured an unvented attic with R-22 netted cellulose insulation under a sloped roof deck. Because an appropriate base case was unavailable to isolate the effects of the unvented attic based on testing, modeling was used to evaluate the energy use of the prototype house with an unvented attic compared to a similar base case with a vented attic.

The prototype was operated for 3 consecutive days with a constant thermostat set point from the morning of August 23 until the morning of August 26, representing normal operation under typical summer conditions. Outside temperatures peaked over 38°C (100°F) in the afternoon, and wind speeds were mild except during two early evening thunderstorms. The ventilation fan in the prototype house was not operated during this test period. The temperature of the unvented attic was usually about midway between the outside air temperature and the conditioned interior of the house, as shown in Figure 5. Clearly, the air ducts were exposed to milder summer temperatures in the unvented attic than they would have been in a typical vented attic.

Figure 6 shows the air-exchange rate for the prototype house, measured using a tracer gas during the normal operation test period. It is important to note that tracer gas was injected in the living space and not in the attic, although mixing with the attic was expected. The air change rate for the house was relatively low, rarely exceeding 0.20 ACH. The ACH did not appear to increase significantly during periods of nearly continuous air-handler operation in the late afternoon, even though the driving forces of wind and temperature difference were also higher during this period. These results indicate that the amount of additional air exchange induced by air handler operation was relatively small for the prototype house, approximately 4.7-7.1 l/s (10–15 cfm), supporting the notion that the unvented attic in the prototype was well sealed. However, blower door tests conducted by BSC indicated that the total ACH of the house increased about 50% when the attic

Table 3. Summary of Tracer Gas Test Results During Daytime Test Periods (10:00 a.m. to 4:00 p.m.)

	Operating Conditions	Case 1: Tight Ducts		Case 2: 47±5 l/s (100-cfm) Supply Leak		Case 3: 47±5 l/s (100-cfm) Supply and Return Leaks		Case 4: Additional Supply Leakage	
		Base	Proto	Base	Proto	Base	Proto	Base	Proto
Daytime	Average ACH	0.11±.01	0.14±.01	0.26±.03	0.18±.02	0.28±.03	0.14±.01	0.49±.05	0.19±.02
	Average Wind Speed (m/s)	0.63±0.32		1.12±0.56		0.80±0.40		0.91±0.46	
	Average ΔT (°C)	13.3±0.1		11.8±0.1		14.9±0.1		17.9±0.1	
	Avg A/C Power (kW)	1.79±.01	1.74±.01	1.62±.01	1.54±.01	1.98±.01	1.73±.01	2.90±.01	2.09±.01

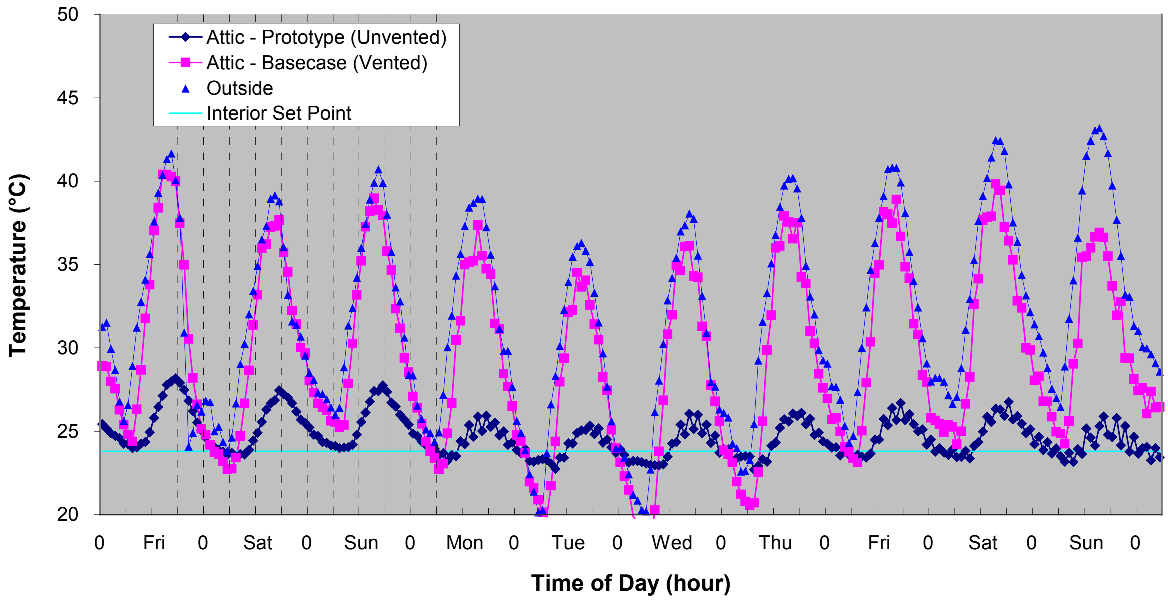

Figure 3. Attic temperatures during the summer test period

hatch was open. This result demonstrated that a significant amount of air leakage occurred at the roof plane, and there was some restriction of air exchange between the attic and the rest of the house. It is, therefore, apparent that the ducts themselves must have been very tight.

A DOE-2.2 model was developed to simulate annual energy usage for the prototype house with and without various design attributes, including the unvented attic. To the extent possible, field measurements were used as inputs to the model to ensure realism, including infiltration rates, air-handler flow rate and power, and duct leakage. The assumptions described earlier were used for the model and normal operating conditions were applied.

Simulations were run starting with the builder standard practice building description, and then measures were added one at a time until the building matched the prototype specifications. In one case where the unvented attic was the seventh increment, there was a small increase in total energy cost ($15/ year), primarily because of a 30% increase in heating energy. However, the order in which the energy efficiency features are added can have a profound effect on the calculated energy savings or loss. When the model was run a second time with the unvented attic added earlier in the sequence, there was a small reduction in energy cost ($15/year) as the increase in heating energy was more than matched by the decrease in cooling energy.

Table 4. Comparison of Average Cooling Energy and Standard Deviation Based on Simulations and Field Measurements (Monitored Energy Accurate to ±0.5%)

Operating Conditions	Case 1: Tight Ducts		Case 2: 100-cfm Supply Leak		Case 3: 100-cfm Supply and Return Leaks		Case 4: Additional Supply Leakage	
	Base	Proto	Base	Proto	Base	Proto	Base	Proto
Monitored Average Cooling Energy (kW)	1.17	1.18	0.93	0.89	1.26	1.14	2.20	1.71
Simulated Average Cooling Energy (kW)	1.09	1.10	0.92	0.85	1.21	1.11	2.23	1.70
Monitored Standard Deviation (kW)	0.57	0.57	0.63	0.57	0.68	0.60	0.92	0.66
Simulated Standard Deviation (kW)	0.52	0.55	0.65	0.63	0.61	0.59	0.79	0.64

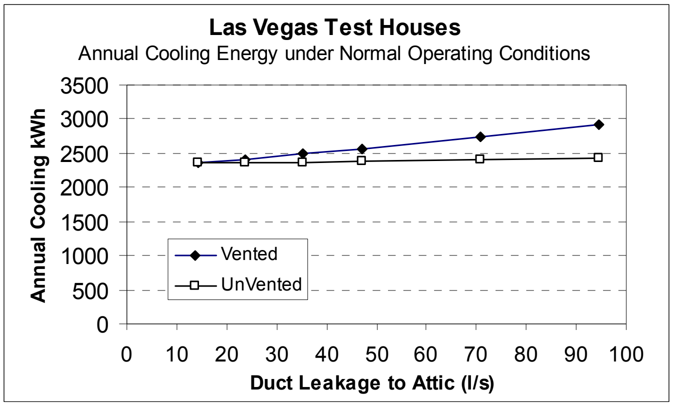

Figure 4. Annual cooling requirement versus duct leakage for Las Vegas test houses

A series of sensitivity runs were made with the Tucson model to ensure that building components were being modeled correctly and to gauge the importance of certain assumptions. Duct leakage, insulating-value, air infiltration at the roof plane, and solar heat absorption by the roof were found to be important factors when calculating the potential energy savings or penalty of an unvented attic compared to a vented attic. A more complete discussion of the sensitivity runs is provided in the full NREL Technical Report (Hendron et al. 2002).

Analysis of Unvented Attics in Other Hot-Dry/Mixed-Dry Climates

The base-case and prototype models for Watt Homes in Las Vegas were run with a range of duct leakage levels for two other climate zones: Phoenix (hot-dry) and Sacramento (mixed-dry). The simulations assumed that most of the duct leakage was on the supply side of the air distribution system, and the cooling capacity was set to a constant 13 m^2/kW (500 ft^2/ton) in each case. These assumptions were based on field-testing of similar Building America projects. For each location, a graph illustrating the sensitivity of cooling energy to duct leakage is presented. These results are shown in Figures 7 and 8.

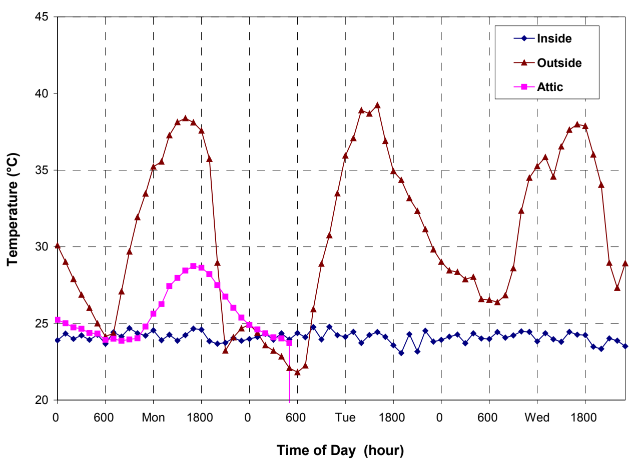

Figure 5. Inside and outside temperatures for Tucson prototype during a 3-day period of normal air conditioner operation.

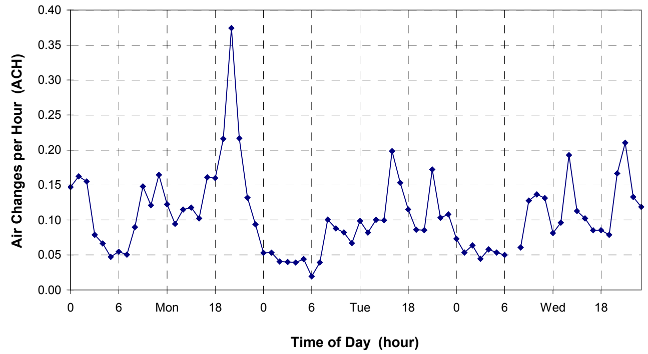

Figure 6. Air-exchange rate for Tucson prototype during 3-day period of normal operation

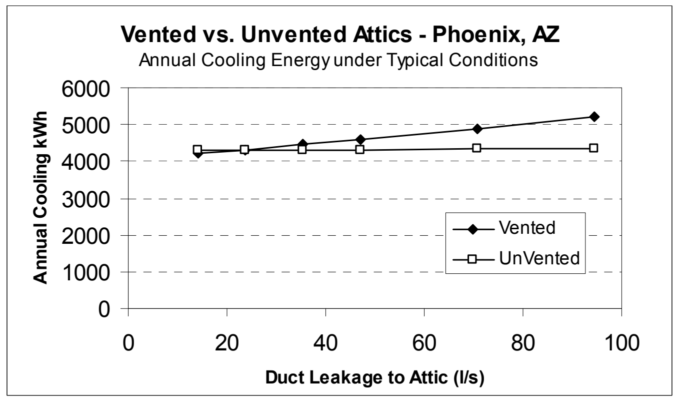

Figure 7. Comparison of cooling energy for vented and unvented attics in Phoenix, Arizona

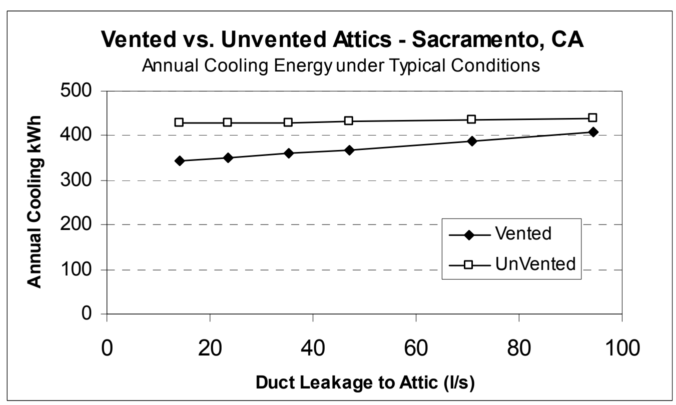

Figure 8. Comparison of cooling energy for vented and unvented attics in Sacramento, California

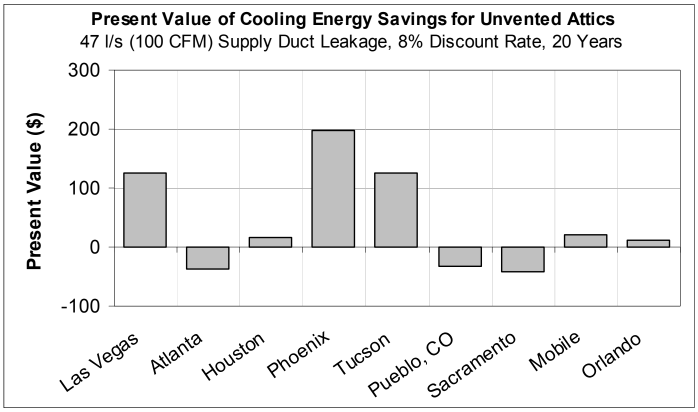

Figure 9. Present value of cooling energy savings for unvented attics in several hot and mixed climates

Climate is a very important factor when calculating how an unvented attic affects cooling energy usage. When the ducts are leaky, there seems to be a clear benefit associated with the unvented attic in the case of Phoenix, which has a very large number of cooling degree days during the summer. However, the same house in Sacramento seems to have a cooling energy penalty compared to a house with a vented attic. Heating energy also becomes an important consideration in milder climates like Sacramento, but the model used for this study was not designed to accurately predict heating loads.

Furthermore, it is clear that the trade-off between vented and unvented attics is strongly influenced by the amount of duct leakage regardless of climate. As one would expect, the performance of a vented attic is more sensitive to the amount of duct leakage because the attic temperature is more variable and a greater fraction of the leakage is lost to the outside.

Additional simulations of cooling energy in a variety of hot-dry, hot-humid, and mixed climates were performed to examine the cost impacts of unvented attics when cooling loads, outside temperatures, and attic solar gains are changed. As shown in Figure 9, the benefits of unvented attics are clear in very hot and sunny climates such as Las Vegas, Tucson, and Phoenix. In cooler climates, the benefits are not as pronounced, and there may even be energy penalties during the cooling season. Any potential changes in construction costs associated with unvented attics are not included in this analysis.

CONCLUSIONS

The field tests and DOE-2.2 simulations conducted by NREL on unvented attics in hot-dry climates lead to several important conclusions:

- Properly constructed unvented attics can save energy in cooling-dominated climates under the right circumstances.
- Unvented attics in hot-dry climates have a small effect on cooling energy use when duct leakage is small.
- When supply duct leakage is greater than 5% of total flow rate, unvented attics begin to produce meaningful energy savings for cooling. For example, cooling energy savings is predicted to be about 8% when duct leakage is 10%, which is fairly typical for Building America base-case houses.
- Weather conditions, duct leakage, roof R-value, attic air-exchange rate, and roof solar heat absorption all play important roles in determining whether or not energy savings are achieved with an unvented attic. Because of these sensitivities, it is difficult to recommend specific sets of conditions where unvented attics save energy.
- The cost-effectiveness of alternative measures, such as improving the airtightness of ducts, should be carefully considered when deciding whether or not to use an unvented attic.

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13. ABSTRACT *(Maximum 200 words)* Unvented attics have become a more common design feature implemented by Building America partners in hot-dry climates of the United States. More attention is being focused on how this approach affects heating and cooling energy consumption. By eliminating the ridge and eave vents that circulate outside air through the attic and by moving the insulation from the attic floor to the underside of the roof, an unvented attic becomes a semi-conditioned space, creating a more benign environment for space conditioning ducts.

14. SUBJECT TERMS
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