Comparison of Cathedralized Attics to Conventional Attics: Where and When Do Cathedralized Attics Save Energy and Operating Costs?

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ABSTRACT

Significant energy losses associated with HVAC ductwork located in a house attic have resulted in a proposed attic design called the "cathedralized attic." In this design, the attic floor insulation is replaced by insulation located against the bottom of the roof deck, and no outside ventilation to the attic space is permitted. This approach offers both advantages and disadvantages. Previous researchers have reported on how these attics perform in hot, dry climates using a whole building simulation tool. The analysis reported here uses a computer model of heat transfer within the attic space to examine the net effect of this approach compared to a traditional attic in six different climates. Parametric analysis was used to explore the effect of climate, varying levels of attic insulation, and different duct details. These duct details included length, leakage rate, insulation level, and HVAC run time. The computer model includes radiative heat exchange, as well as conductive and convective heat transfer modes and has been previously benchmarked against experimental data.

INTRODUCTION

Location of duct systems in attics is a common practice in cooling climates. Supply outlets in the attic floor are a convenient and effective way to distribute cool conditioned air to the living space. In a conventional attic with insulation on top of its floor, the attic space is exposed to outside conditions through attic vents, if present, and through the uninsulated roof deck. The attic can get very hot in summer. Cool air inside the ducts in a conventional attic, therefore, gains energy by convection and radiation with the attic environment. Any air that leaks into the return ducts exacerbates the energy gain. Any air that leaks from the supply ducts is lost and the energy that is used to condition it is wasted. The fan and air-conditioning equipment must be oversized to compensate for such losses. These two types of energy losses—heat transfer through duct walls and air leaks through duct connections—are major concerns for ducts located within conventional attics. If the same ducts are used for heating, the two types of energy losses are of more concern because of potentially more severe differences between attic and duct air conditions during the heating season. Because of these significant energy losses, a "cathedralized attic" design has been proposed (Rudd et al. 1996, 1998, 2000).

The cathedralized attic configuration offers a means to avoid these duct-related energy losses. A cathedralized attic is a structure that provides the same flat attic floor that is characteristic of a conventional attic. However, the underside of the roof deck and the inside of the gables are insulated and the attic space is never vented. There is no insulation on top of the attic floor. The ducts in a cathedralized attic are effectively within the living space. A cathedralized attic requires extra insulation and effort to insulate the roof deck and the other exterior-facing surfaces of the attic to the same level as the attic floor in a conventional attic. It also requires sealing of all the exterior-facing surfaces instead of sealing the attic floor. A benefit of the extra expense and attention to sealing for a cathedralized attic is that duct losses are no longer a concern. The relatively leaky and uninsulated attic floor allows the ducts to communicate with the living space as if the ducts were inside the living space.

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A project was undertaken to determine where and when cathedralized attics save energy and operating costs for the range of U.S. climates, and this paper summarizes some of the results obtained. Cooling and heating energy requirements for each type of attic are translated into operating costs by using appropriate efficiencies and energy costs for the respective cooling and heating equipment. The annual cooling or heating per unit ceiling area is generated for cathedralized attics and conventional attics with a thermal model of attic systems that was developed at the Oak Ridge National Laboratory (Wilkes 1989, 1991). It is called ATICSIM in this paper. The model has been validated and augmented since its initial development (Wilkes et al. 1991a, 1991b; Wilkes and Childs 1992, 1993). Of particular interest for this project is the addition by Wilkes of duct modeling capability to the model and experiments (Petrie et al. 1998) to validate this feature. Previous researchers (Hendron et al. 2002, 2003) have reported on how these attics perform using a whole building simulation tool.

PROCEDURES AND PARAMETERS

ATICSIM is a transient model of the thermal performance of an attic. The model is sensitive to the thermal mass in the attic. Figure 1 shows a sketch of the geometry of a conventional attic with arrows to indicate the various heat transfer mechanisms that can occur for the attic. Although the sketch shows ventilation occurring at soffit-and-ridge vents, the location of the vents may be elsewhere, such as at the gables. Geometric detail is specified in terms of lengths, widths, angles, and orientations of the various surfaces. This is important for energy exchange by radiation within the attic and for solar radiation incident upon the outside roof surfaces. The solar absorptance of the outside surfaces and the infrared emittance of both the inside and outside surfaces must be known to do the radiation calculations.

At each time step during the period of interest, the heat transfer phenomena are treated through a system of heat balance equations. Balances are done on the air mass within the attic and at the interior and exterior surfaces of the attic floor, roof sections, and gables. Single average temperatures are assigned to the air and to each surface as a result of the heat exchange. If ducts are included in the modeling, they are specified as a series of connected segments, exchanging air and energy with other pieces and with the attic.

The short vertical walls around the perimeter of the attic sketched in Figure 1 allow raised trusses to be included. The attics in this study consisted of an attic floor, two roof sections, two gables, two very short (default) vertical eave sections, and the air space. Fifteen heat balance equations were satisfied at each time step for which the simulation was done. The thermal bridging effects of the nominal 2×4 wooden joists and rafters were included in the energy balances. When ducts were included, additional terms were added for the effect of each supply duct segment and a single return duct.

The effect on heat transfer of thermally massive and insulative materials between the interior and exterior surfaces of thermal structures in an attic is specified in terms of conduction transfer functions. A thermal structure may include significantly different heat flow paths, such as ones through the center of cavity and through the joists above the attic floor. Conduction transfer functions were generated for each path and combined by the method of parallel paths.

Conduction transfer functions follow from use of the thermal response factor method to account for transient heat transfer and thermal energy storage phenomena. The method is based on an exact analytical solution of the heat conduction equation for one-dimensional heat flow through a multilayer slab having temperature-independent thermal properties. Surface temperatures are taken to vary linearly with time between time steps. ATICSIM uses time steps that are one hour long. The results of the exact analytical solution are reduced to algebraic equations. These equations use the transfer functions to relate heat fluxes at the two surfaces of the slab to the current and previous temperatures of the surfaces.

For this project, a standard-sized building along with standardized operating conditions were selected. Obviously, not all combinations of physical structures, operating conditions, duct flow rates, and airflow temperature and relative humidity conditions could be analyzed. Since this was a parametric study, a constant set of conditions was selected for all of the simulations. In doing so, some compromises needed to be made. There was no intent to bias the study in any particular manner. We simply attempted to select conditions that were practical for a broad region within the continental U.S.

The attic had a length of 40 ft (12.2 m) and width of 30 ft (9.1 m). The ridge was oriented from east to west, and the roof pitch was 4 in 12 (18.4°). For these specifications, a cathedralized attic would require about 18% more insulation to achieve the same level of attic insulation as a conventional attic. A duct system, if present in the conventional attic, consisted of 12-in. (305-mm)-inside-diameter round duct running down the

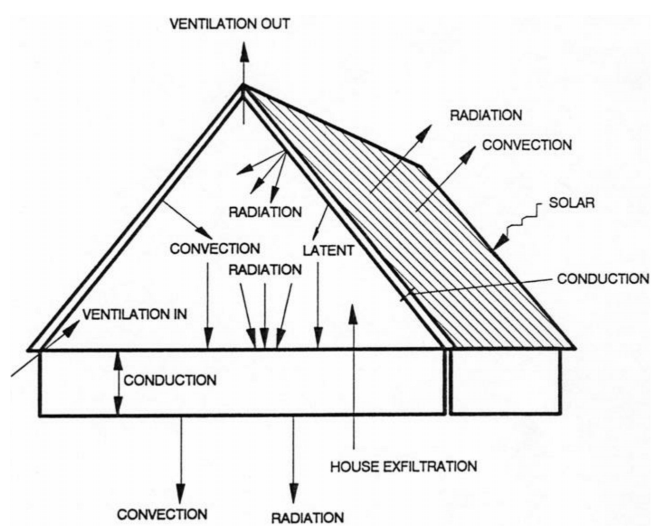

Figure 1 *Schematic of a typical attic showing the various heat transfer mechanisms that occur within it.*

center of the attic for the return duct and supply trunks. Supply branch ducts consisted of 6-in. (152-mm)-inside-diameter round ducts running toward the eaves. The duct system shown in Figure 2 was termed the duct system with long length because it goes down the entire center of the attic and completely out to the eaves. A medium-length duct system was specified wherein all lengths were 75% of the lengths shown in Figure 2. A short-length duct system had all duct lengths 50% of the lengths in Figure 2. The medium-length duct system is considered typical.

A flow rate of 900 cfm (0.425 m^3/s) was specified in all duct systems, if present, during both summer and winter. Separate annual runs were made that had temperatures and humidities for the return and supply air in the ducts that were termed cooling and heating conditions, respectively. For cooling, return air was at 75°F (24°C) and 50% relative humidity (W = 0.009237, h = 28.12 Btu/lb_a or 47.64 kJ/kg_a using psychrometric conventions) and supply air was at 60°F (16°C) and the same humidity ratio (h = 24.46 Btu/lb_a or 39.46 kJ/kg_a). The air has an effective heat capacity of 0.244 Btu/(lb_a·°F) [1.022 kJ/(kg-°C)] at cooling conditions. For heating, return air was at 70°F (21°C) and 35% relative humidity (W = 0.005429, h = 22.74 Btu/lb_a or 34.91 kJ/kg_a) and supply air was at 85°F (29°C) and the same humidity ratio (h = 26.38 Btu/lb_a or 43.04 kJ/kg). The air has an effective heat capacity of 0.243 Btu/(lb_a·°F) [1.017 kJ/(kg-°C)] at heating conditions. In this paper, results were obtained with a heat capacity of 0.24 Btu/(lb_a·°F) [1.005 kJ/(kg-°C)] for both heating and cooling.

There are several parameters required by ATICSIM for which a range of values was appropriate, including location, attic insulation level, and duct insulation level. Location is varied by climatic data for typical meteorological years (TMY2) in six locations in the "lower 48" United States (NREL 1995). The six locations have climates that require predominant heating (Minneapolis and Boulder), significant heating and cooling (Atlanta and Dallas), and predominant cooling (Miami and Phoenix). Levels of attic insulation include R-19, R-30, and R-38 h·ft²·°F/Btu (R-3.3, R-5.3, and R-6.7 m²·K/W), with R_{US}-38 (R_{SI}-6.7) considered most typical of new construction. Commercially available levels of duct insulation are R-4 and R-6 h·ft²·°F/Btu (R-0.7 and R-1.1 m²·K/W) and include a foil covering with an infrared emittance that was assumed to be 0.1 in this study. R_{US}-6 (R_{SI}-1.1) is used for the results presented in this paper. The complete study showed only 5% to 10% more annual cooling or heating for R_{US}-4 (R_{SI}-0.7) compared to R_{US}-6 (R_{SI}-1.1) insulated ducts. The decrease to R_{US}-4 (R_{SI}-0.7) from R_{US}-6 (R_{SI}-1.1) does not result in proportionally more heat gain or loss. The surface area of circular ducts decreases as insulation thickness decreases, which decreases convection and radiation exchange between the duct and its surroundings. No radiant barrier was specified in the attic. Asphalt shingles with solar reflectance of 0.1 were specified as the outside covering of the sloped roof for most runs. Shingles were selected because they are the most widely used roofing product, representing over 80% of the U.S. market. Comparisons were made to a highly solar reflecting, white-painted, metal roof.

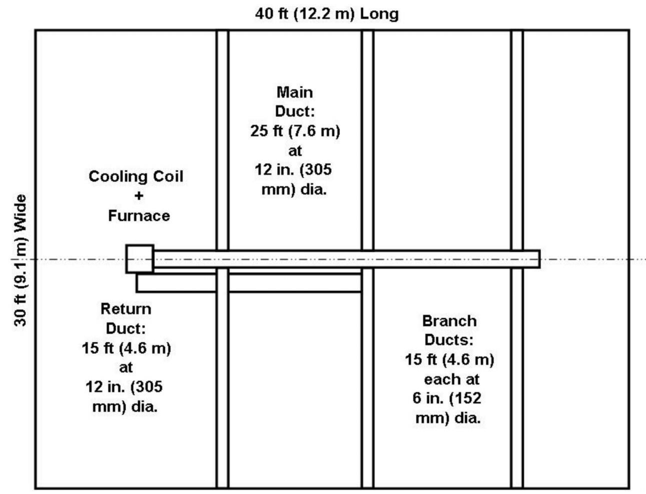

Figure 2 *Schematic of long duct system in the conventional attic for this project.*

It is assumed that the cathedralized attic is sealed against any ventilation with outside air. Some runs with ducts in the conventional attic assume that the ducts are free of leaks. Successfully sealing a cathedralized attic and successfully sealing ducts in a conventional attic are daunting tasks. They involve areas that are difficult to reach in order to do the proper sealing and are difficult to inspect afterward in order to ensure that proper sealing was done.

Duct leakage was varied from 0% to 25% (15% from the supply ducts and 10% to the return duct). Leakage is expressed as a percentage of supply airflow rate. For ducts in residences, leakage is not only dependent upon the attention that is paid initially to sealing but on the longevity of the materials that are used. Many federal, state, and utility construction programs promote no more than about 5% duct system and air handler leakage (Lstiburek 2002).

ATICSIM allows the user to input the percentage of time between 0% and 100% that a duct system operates during each hour of the simulation. To estimate typical run times for a duct system, the annual whole building energy-estimating program DOE-2 was run for a small residence in each climate. The modeled building was a 1200 ft^2 (111 m²) single-story residence with R_{US}-11 (R_{SI}-2.0) walls, R_{US}-19 (R_{SI}-3.3) floors over a crawlspace, and an R_{US}-30 (R_{SI}-5.3) insulated conventional attic. Setpoints for heating and cooling were 68°F (20°C) with setback and 78°F (26°C) with setup, respectively. The conditioning system consisted of an electric air conditioner and a natural gas furnace. An algorithm in DOE-2 sized each in order to meet the peak loads during cooling and heating for each climate. Sizes were rounded up to approximate commercially available sizes. Run times for cooling and heating for the six climates chosen for this study were obtained from hourly reports generated by the DOE-2 system simulation.

Table 1. Seasonal HVAC System Run Times (the Average of the Hourly Ratios of Demand on the System and Its Capacity) and Annual Hours of Operation in the Six Climates Chosen for This Study

	Minneapolis	Boulder	Atlanta	Dallas	Miami	Phoenix
Demand/cooling capacity	20.5%	27.8%	24.0%	26.4%	18.8%	30.2%
Cooling operating hours	728	904	1465	2065	3788	3518
Demand/heating capacity	16.7%	11.4%	11.1%	9.6%	6.4%	6.7%
Heating operating hours	4099	3166	1629	1188	18	448

Table 1 summarizes the separate hourly cooling and heating HVAC run times that were extracted for use in ATICSIM. The seasonal averages vary randomly with location and are higher for cooling than heating. This is consistent with the technique used to size the systems in each climate. Annual hours when the HVAC system was active are also included. They vary significantly in a manner that is consistent with the climate at each location.

Ventilation in a conventional attic results from the combination of natural and forced convection. Parker et al. (1991) present the following semi-empirical equations for the flow rate of attic ventilation air due to buoyancy and wind forces, which were adapted to the geometry and conditions of the simple attic of this study. For buoyancy,

$$\dot{m}_{buoyancy} = L_o\left[\frac{gH_s|T_d - T_a|}{T}\right]^{1/2}, \quad (1)$$

where

$\dot{m}_{buoyancy}$ = flow rate of air through the attic caused by buoyancy forces, ft^3/s (m^3/s);

L_o = free inlet area, here the inlet area of the soffit vents, ft^2 (m²);

g = acceleration due to gravity, ft/s^2 (m/s²);

H_s = height to the neutral pressure plane, ft (m);

T_a = absolute ambient temperature, R (K);

T_d = absolute deck surface temperature, R (K); and

T = minimum of T_a and T_d, R (K).

Parker et al. determined the height to the neutral pressure plane with an equation that they deduced from the *1989 ASHRAE Handbook—Fundamentals* (ASHRAE 1989).

$$H_s = \frac{H}{1 + \left(\frac{A_i}{A_o}\right)^2\left(\frac{T_o}{T_i}\right)} \quad (1a)$$

where

H_s = height to the neutral pressure plane, ft (m);

H = attic inlet to outlet height, ft (m);

A_i = lower (soffit) vent inlet opening area, ft^2 (m²);

A_o = upper (ridge) vent outlet opening area, ft^2 (m²);

T_i = absolute inlet air temperature, R (K); and

T_o = absolute outlet air temperature, R (K).

Equal soffit and ridge ventilation areas are assumed in our study.

For wind,

$$\dot{m}_{wind} = L_o C V_i, \quad (2)$$

where

$\dot{m}_{wind}$ = flow rate of air through the attic caused by wind forces, ft^3/s (m^3/s);

L_o = free inlet area, here the area of the soffit vents, ft^2 (m²);

C = soffit vent opening discharge coefficient with a maximum value of 0.38 (Burch and Treado 1979); and

V_i = speed of the wind incident upon the vent openings, ft/s (m/s).

The wind speed at the vent openings is assumed to be the expression from the tests of Peavy (1979) that accounts for orientation and geometry.

$$V_i = V[0.087 + 0.13|\sin(D + 90)|] \quad (2a)$$

where

V_i = speed of the wind incident upon the vent openings, ft/s (m/s)

V = actual wind speed, ft/s (m/s), and

D = wind direction measured in degrees from north. Because the ridge of the attic in this study runs east-west, 90° is added to D in order that a north or south wind has maximum effect.

The total ventilation is found by combining the results from Equations 1 and 2 according to the square root of the sum of the squares of each term (Parker et al. 1991).

$$\dot{m}_{ventilation} = (\dot{m}^2_{buoyancy} + \dot{m}^2_{wind})^{1/2} \quad (3)$$

The buoyancy effect depends upon the deck temperature, which is a function of the ventilation flow rate. This could lead to an iterative situation. To generate nominal hourly ventilation rates, ATICSIM was exercised in each climate for a moderately insulated (R_{US}-30 or R_{SI}-5.3), duct-free attic with a fixed ventilation rate of 2.4 air changes per hour and roof solar reflectance of 0.1. The resulting deck temperatures were used to generate hourly values of ventilation rate by Equation 3. Iterations were done to determine the variations from these

Table 2. Annual Average Extremes in Deck Temperature, °F (°C), and Attic Air Changes Per Hour, ACH, for Roof Solar Reflectance of 0. 1 in Six Climates Chosen for This Study

	Minneapolis	Boulder	Atlanta	Dallas	Miami	Phoenix
Highest average T_{deck}, °F (°C)	60 (16)	69 (21)	79 (26)	83 (28)	92 (34)	96 (36)
Lowest average T_{deck}, °F (°C)	58 (14)	66 (19)	75 (24)	79 (26)	88 (31)	90 (32)
Highest average ACH	4.0	4.1	3.9	4.3	3.6	4.0
Lowest average ACH	4.0	4.0	3.8	4.1	3.4	3.6

nominal values. The lowest annual average deck temperatures and ventilation rates resulted by starting with a poorly insulated (R_{US}-19 or R_{SI}-3.3), highly ventilated attic that was ventilated by one air change per hour on average more than resulted by Equation 3. The highest deck temperatures and attic ventilation rates resulted by starting with a well-insulated (R_{US}-38 or R_{SI}-6.7), nonventilated attic. Results for these extremes are given in Table 2. The range from lowest to highest deck temperatures is not very great at each location. The ventilation rates do not show enough variation to require an iterative technique. The nominal ventilation rates from the deck temperatures for the R_{US}-30 (R_{SI}-5.3), 2.4 ACH ventilated, duct-free attic are used for all runs except those with highly solar-reflecting, painted metal roofs. For these cases, iterations similar to those for Table 2 were done.

Parker et al. (1991) present a survey of measured attic ventilation rates from short-term sulfur hexafluoride tracer gas tests. Three houses with soffit vents showed 1.7 to 2.3 ACH during the month of August 1976 in Houston, Texas. A house in Princeton, New Jersey, displayed 3 to 4 ACH under moderate wind conditions. A long-term test on an Illinois house yielded 2.9 ACH. Two attics in Ocala, Florida, had average air change rates of 0.9 to 1.8 ACH during 2- to 27-day test periods. Their own attic test cells under normal summer wind and thermal conditions in Cape Canaveral, Florida, yielded an average of 2.7 ACH over a three-day period with variation from 0.5 to 4.5 ACH. The annual averages in Table 2 are at the high end of the rates in the survey.

With the deck temperatures from R_{US}-30 (R_{SI}-5.3), 2.4 ACH ventilated attics, the resulting minimum ventilation rates were 0 ACH at the six locations in Table 2 while the maximum ventilation rates varied from 8.6 to 11.6 ACH. The variation of ventilation rate with hourly changes in buoyancy and wind driving forces is the valuable feature of Equation 3. Since the ventilation rates it yields are at the high end of rates that were observed, results with it can be said to be characteristic of well-ventilated attics. In the complete study we found that, compared to no ventilation, these ventilation rates caused 19% to 25% less annual cooling energy and 7% to 10% more annual heating energy in a conventional attic without ducts.

ENERGY USAGE DURING HEATING AND COOLING

Climatic data for typical meteorological years in Minneapolis, Boulder, Atlanta, Dallas, Miami, and Phoenix were used. For each hour of the year, the outside dry-bulb temperature and humidity ratio, the cloud amount and type, the direction and speed of the wind, and the total horizontal and direct incident solar heat fluxes were extracted from the TMY2 set for the location. In order to initiate the transient calculations, the January 1 weather data were repeated three times before the start of the study period.

The hourly output from ATICSIM consists of temperatures for the air in the attic and for the inside and outside surfaces of the attic components. The heat fluxes through the attic floor are reported. For a duct system in the conventional attic, the air temperature out of each duct segment is also produced and the effects of air leakage—if any are specified for the ducts—are taken into account by the energy balances. The net duct heat transfer was calculated as the product of the mass flow rate of air through the duct, its heat capacity, and the relevant temperature difference. Note that this value includes both heat flow through the duct walls and the heat loss or gain associated with all duct leakage flows. This net duct energy loss or gain was then converted to flux by dividing it by the attic floor area.

The 8760 hourly duct and attic floor heat fluxes for both cooling and heating conditions were combined in a spreadsheet with local climatic conditions for each case. Cooling conditions were defined as the coincidence of an outside air temperature greater than 75°F (24°C) and a downward attic floor heat flux. The "annual cooling" was defined as the sum of the attic floor heat flux and the duct flux over all hours that met the cooling conditions. Heating conditions were defined as the coincidence of an outside air temperature below 60°F (16°C) and an upward attic floor heat flux. The "annual heating" was defined as the sum of the attic floor heat flux and the duct flux over all hours that met the heating conditions. The annual sums are reported in units of Btu per ft² of attic floor area.

In the text and figures that follow, the words "small," "medium," and "large" refer to the three duct lengths considered. All cases except those labeled "cathedralized" refer to a conventional attic. The words "no leak" indicate that there were no air leaks from the supply ducts or to the return duct. The words "no duct" indicate that there were no ducts located within the attic.

Figure 3 is a summary of results for annual cooling across the attic floor for R_{US}-38 (R_{SI}-6.7) attic insulation in both cathedralized attics (the first set of bars) and conventional attics (the other six sets of bars). Note that this comparison assumes that it is possible to reach an insulation level up to R_{US}-38 (R_{SI}-6.7) in the cathedralized configuration. In the conventional attics, attic ventilation rates with the soffit-and-ridge vents are the nominal hourly values from Equation 3 using deck temperatures determined as described above. The ducts, if present, are wrapped with foil-covered R_{US}-6 (R_{SI}-1.1) insulation. HVAC run times are the hourly values that yielded Table 1.

The variation in cooling load with location appears to be a function of both traditional 65°F (18°C) cooling degree-days (CDD_{65}) and the amount of solar radiation. This result was discovered for low-slope roofs in development of the DOE Cool Roof Calculator (Petrie et al. 2001). CDD_{65} alone do not account for the direct effect of solar radiation on the exposed attic surfaces. Table 3 lists CDD_{65}, hourly average solar flux and a cooling index formed by multiplying them together and dividing by 500,000. The divisor was arbitrarily chosen to produce cooling indices roughly in the range from 0 to 1. The cooling for two attics from Figure 3 is also shown. Thus, Table 3 provides an example of how the variation in annual cooling follows the cooling index better than it does solar flux or cooling degree-days alone.

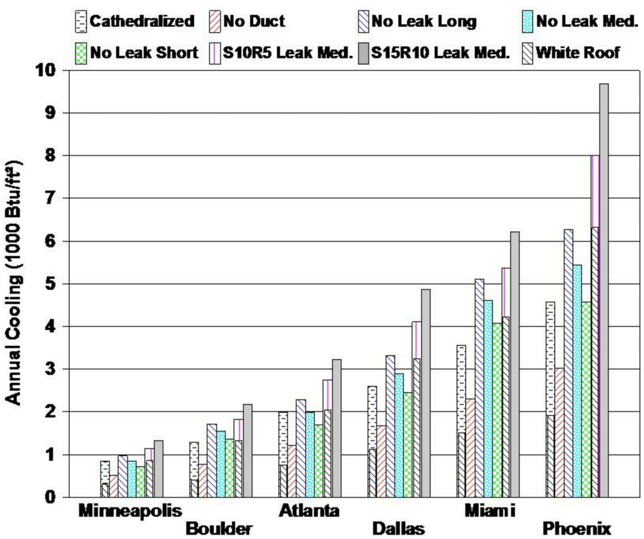

Figure 3 *Comparison of annual cooling loads per unit area of ceiling for cathedralized attics and various configurations of conventional attics. All attics have R-38 h·ft²·°F/Btu (R-6.7 m²·K/W) insulation. To convert 1000 Btu/ft² to MJ/m², multiply by 11.36.*

The results in Table 3 are arranged in order of increasing annual cooling. Note that the cooling index is also in increasing order, but CDD_{65} is not. Solar flux is about equal for Boulder and Atlanta and for Dallas and Miami. There is relatively high solar load in Phoenix compared to Miami and in Boulder compared to Minneapolis. Solar flux affects the annual cooling and is included in the cooling index. The cooling index is a useful parameter for the generalization of attic data as it was for the generalization of low-slope roof data.

Of direct interest in this study is the difference between cathedralized attics and conventional attics. Again, remember that this comparison assumes it is possible to reach an insulation level of R_{US}-38 (R_{SI}-6.7) in the cathedralized configuration. Comparing results in Figure 3 in the first and second sets of bars shows that well-ventilated conventional attics without ducts outperform the corresponding cathedralized attics. The vented attic space over the insulated ceiling provides significant thermal benefit for cooling. These attics have, on average, 37% less annual cooling than the cathedralized attics. Trials with approximately one more air change per hour in the conventional attics in all locations showed about 40% less cooling than the cathedralized attics. The conclusion is that additional ventilation beyond the level of that given by Equation 3 is not significantly more beneficial, even if it could be naturally induced.

The third, fourth, and fifth sets of bars in Figure 3 show results for long-, medium-, and short-length, leak-free ducts, respectively, in well-ventilated conventional attics. The well-ventilated conventional attics with leak-free, long ducts have slightly larger annual cooling than the corresponding cathedralized attics. The well-ventilated conventional attics with

Table 3. Cooling Factors for the Locations in Figure 3 with the Corresponding Annual Cooling for R_{US}-38 (R_{SI}-6.7) Cathedralized Attics and for Well-Ventilated R_{US}-38 (R_{SI}-6.7) Conventional Attics with Medium-Length, R_{US}-6 (R_{SI}-1.1) Duct Systems That Leak 10% of the Supply Air and 5% of the Return Air

	Minneapolis	Boulder	Atlanta	Dallas	Miami	Phoenix
CDD_{65} (°F-day)	634	622	1611	2414	4126	3814
Solar flux, Btu/(h·ft²) (W/m²)	52 (165)	61 (193)	62 (194)	65 (205)	65 (205)	77 (242)
Cooling index	0.066	0.076	0.198	0.314	0.535	0.584
Conventional, Btu/ft² (MJ/m²)	1146 (13.0)	1829 (20.7)	2751 (31.2)	4110 (46.7)	5372 (61.0)	7995 (90.8)
Cathedralized, Btu/ft² (MJ/m²)	847 (9.6)	1284 (14.6)	1989 (22.6)	2599 (29.5)	3551 (40.3)	4577 (52.0)

leak-free, medium- and short-length ducts perform about the same as the cathedralized attics in all locations except Phoenix and Miami. There only the well-ventilated conventional attics with leak-free, short ducts have about the same performance as the cathedralized attics. If the medium-length ducts leak, as illustrated by the sixth and seventh sets of bars for leakages of 10% supply, 5% return and 15% supply, 10% return, respectively, these additional energy effects increase the annual cooling above that of the corresponding cathedralized attics in all climates. Results for white roofs over cathedralized attics and over conventional attics with S10R5 leaky medium-length ducts are superimposed on the respective results for black roofs. Significantly less cooling energy is needed with the white roofs, especially over the cathedralized attics.

Figure 4 presents information over the heating season for the same R_{US}-38 (R_{SI}-6.7) insulated attics as in Figure 3. Behavior of well-ventilated conventional attics during heating is significantly different from that during cooling. Comparing the first and second sets of bars, energy performance of well-ventilated conventional attics without ducts is only slightly better than that of the corresponding cathedralized attics in all locations, including Minneapolis and Boulder with their significant heating requirements. Conventional wisdom and many building codes call for ventilated attic spaces in heating climates to avoid moisture problems. Energy performance does not appear to rule this out but does not give much of an additional energy-related incentive for ventilation.

As ducts are added and their configurations are changed, the heating season results in Figure 4 for ducts in well-ventilated conventional attics show a clear lesson. A significant energy penalty is associated with using heating ducts in well-ventilated conventional attics. Miami and Phoenix have so little heating needs that there are no meaningful differences among the cases. As heating needs increase, the cathedralized attics use significantly less energy than any of the conventional attics with ducts. For cooling, only leaky ducts cause a significant energy penalty. See the attics in Figure 3 for Miami and Phoenix. The results for white roofs in Figure 4 are placed behind those for the corresponding black roofs to show the heating penalty associated with white roofs. This penalty is significant in the heating climates of Minneapolis and Boulder. See Appendix A for detailed comparisons of annual cooling and heating energy for R_{US}-38 (R_{SI}-6.7) insulated attics. The same details are also given there for R_{US}-30 (R_{SI}-5.3) and R_{US}-19 (R_{SI}-3.3) attic insulation levels.

ECONOMIC IMPLICATIONS OF ENERGY USAGE FOR HEATING AND COOLING

The differences in annual heating and cooling for the cathedralized and well-ventilated conventional attics have economic consequences. Heat flow up through the attic floor during heating must be replaced by the heating system to maintain acceptably comfortable conditions in the living space. Heat flow down through the attic floor during cooling must be removed by the air-conditioning system to do the same. The energy to accomplish the comfortable conditions costs money. Since heating equipment generally operates with a different efficiency and often with a different energy source than cooling equipment, it is most convenient to translate energy usage for heating and cooling into operating costs. Heating and cooling costs can be added for each comparable cathedralized and well-ventilated conventional attic to produce an annual estimate of differences between the attics.

Assume that equipment can be assigned an average efficiency over the heating or cooling season that gives the ratio between output heating or cooling effect and input energy. Further assume that the energy source to run the equipment has a known annual average cost per unit of input energy to the equipment. Then, annual heating or cooling energy can be translated to annual cost by the formula:

$$\text{Annual Cost} = (\text{Annual Energy}) \cdot (\text{Cost per Unit Energy}) / (\text{Average Efficiency}) \qquad (4)$$

Prices for energy sources in the U.S. are available in many categories at the Energy Information Administration Web site, http://www.eia.doe.gov/. For example, annual average U.S. residential electricity cost for 2001 was \$0.0836 per kWh (3412 Btu). Annual average residential natural gas cost for 2001 was \$9.63 per 1000 ft^3 (approximately 1.055×10^6 kJ or 10^6 Btu or 10 therm). For the analysis herein, electricity cost of \$0.10 per kWh and natural gas cost of \$10.00 per 1000 ft^3 is assumed. A typical annual average efficiency for cooling with an electric air conditioner is 8.5 Btu/(watt-h) (9.0 kJ/[W-h]) or, as a dimensionless coefficient of performance, COP = 2.5. A typical annual average efficiency for heating with a natural gas furnace is 0.80 (Petrie et al. 2001).

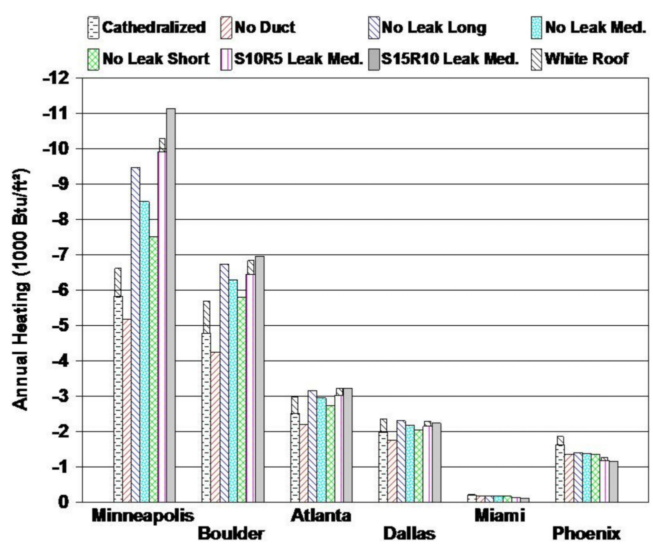

Figure 4 *Comparison of annual heating loads per unit area of ceiling for cathedralized attics and various configurations of conventional attics. All attics have R-38 h·ft²·°F/Btu (R-6.7 m²·K/W) insulation. To convert 1000 Btu/ft² to MJ/m², multiply by 11.36.*

Using appropriate costs and efficiencies in Equation 4 translates cooling and heating energies into costs so that they can be compared directly. Figures 5 to 8 show annual costs for cathedralized attics and three configurations of conventional attics, respectively. The conventional attics have, in turn, no ducts; medium-length, leak-free ducts with foil-covered R_{US}-6 (R_{SI}-1.1) insulation; and the same ducts that leak 10% of the supply air and 5% of the return air. Heating costs are graphically added to cooling costs in these figures. The total height of the bar for each attic insulation level and location represents the annual sum of operating costs per square foot of the attic floor. To convert to costs per square meter, multiply by 10.76.

The total costs at each location and for each attic insulation level in Figure 5 for the cathedralized attic are consistently higher than those in Figure 6 for the well-ventilated conventional attic with no ducts. In both figures, costs for attics with R_{US}-38 (R_{SI}-6.7) attic insulation are slightly more than half of those with R_{US}-19 (R_{SI}-3.3) at each location. Despite the dominance of cooling costs in Phoenix and Miami and the dominance of heating costs in Minneapolis and Boulder, total costs are highest and about equal for Phoenix and Minneapolis for these cases. Atlanta and Dallas show lower but equal costs. Boulder shows costs that are slightly higher than for Atlanta and Dallas. Miami shows the lowest costs of the six locations.

Figure 7 for the conventional attic with leak-free ducts clearly shows the effect of the heating penalty for ducts in an attic, even if the ducts are leak-free. Minneapolis has the highest total costs when ducts are in the conventional attic. Boulder and Phoenix have about the same costs despite Phoenix's severe cooling climate. Miami, Atlanta, and Dallas have about the same costs despite Miami's severe cooling climate. All costs in Figure 7 are significantly higher than the corresponding costs for the conventional attic without ducts in Figure 6. Figure 8 shows that 10% supply duct leakage and 5% return duct leakage increases operating costs slightly relative to Figure 7 for all insulation levels and all locations.

Table 4 quantifies the economic lessons that Figures 5 through 8 teach about the cathedralized attics and the three configurations of conventional attics. It shows the differences between total annual operating costs for each of the three conventional attics versus the cathedralized attic for each level of attic insulation and climate location. The first set of three rows for the well-ventilated conventional attics without ducts has, in effect, ducts in the conditioned space for both types of attics. If ducts are not in the attic, they may be in other nonconditioned spaces, such as crawlspaces or basements. Effects of losses for such ducts are ignored. With no ducts in the attic, the differences of –\$0.01 to –\$0.04/ft² (–\$0.11 to –\$0.43/m²) (here, negative means in favor of the conventional attics) show the benefit of having insulation on the attic floor with a vented air space above it. The benefit decreases as attic insulation level increases. It disappears in general with ducts in the conventional attic, except for R_{US}-19 (R_{SI}-3.3) insulated attics in non-heating-dominated climates. S10R5 leaky ducts in the conventional attics in Minneapolis show the highest cost differential, reaching \$0.055/ft² (\$0.59/m²) per year for the R_{US}-38 (R_{SI}-6.7) attics.

A different comparison between cathedralized and conventional attic constructions is presented in Figure 9. Cathedralized attics are often insulated by applying blown-in loose fill or open cell foam insulation between the rafters and against the gables. This procedure limits the R-value of the cathedralized attic to about R_{US}-22 (R_{SI}-3.9) if the insulation thickness is limited to about 5.5 in. (140 mm). The annual operating cost of this single configuration of cathedralized attic is shown in the first bar for each location. The other three bars at each location repeat from Figure 8 the annual operating cost for well-ventilated conventional attics with ceiling insulation levels of R_{US}-19 (R_{SI}-3.3), R_{US}-30 (R_{SI}-5.3), and R_{US}-38 (R_{SI}-6.7), respectively. These attics contain medium-length ducts that are insulated with foil-covered R_{US}-6 (R_{SI}-1.1) duct insulation and leak 10% of the supply air and 5% of the return air. The ducts carry air at hourly fractions for HVAC systems sized for each climate.

Table 5 summarizes the differences in operating costs for cooling only and for both heating and cooling between the conventional attics with varying R-value and the cathedralized attics with fixed R-value of R_{US}-22 (R_{SI}-3.9). The cathedralized attics cost less to operate than any of their R_{US}-19 (R_{SI}-3.3) conventional counterparts for cooling only and for heating and cooling. Despite the effects of leaky ducts, the conventional attic insulated to R_{US}-30 (R_{SI}-5.3) has equal operating cost compared to an R_{US}-22 (R_{SI}-3.9) cathedralized attic in the same location. The conventional R_{US}-38 (R_{SI}-6.7) attics show a slight operating cost advantage compared to cathedralized attics. If a cathedralized attic cannot be insulated to more than R_{US}-22 (R_{SI}-3.9), its operating cost advantage over the R_{US}-30 (R_{SI}-5.3) and R_{US}-38 (R_{SI}-6.7) conventional attics with leaky ducts that was evident in Table 4 disappears.

CONCLUSIONS

For six locations that cover the range of heating and cooling loads in the "lower 48" United States and attic insulation levels from R-19 to R-38 h·ft²·°F/Btu (R-3.3 to R-6.7 m²·K/W), the following conclusions are made regarding the question: Where and when do cathedralized attics save energy?

- Climate, roof color, duct leakage rate, and attic insulation level consistently affect the amount of energy for cooling or heating that can be attributed to cathedralized and conventional attics. The relative effects of other parameters, such as duct length and duct insulation level, are minor.
- Well-ventilated conventional attics without ducts require about 40% less annual cooling than cathedralized attics with the same insulation level for the six locations. This is attributed to the favorable effects of ventilation with outside air of the air space above the ceiling insulation.
- Well-ventilated conventional attics without ducts are marginally better regarding energy for heating than

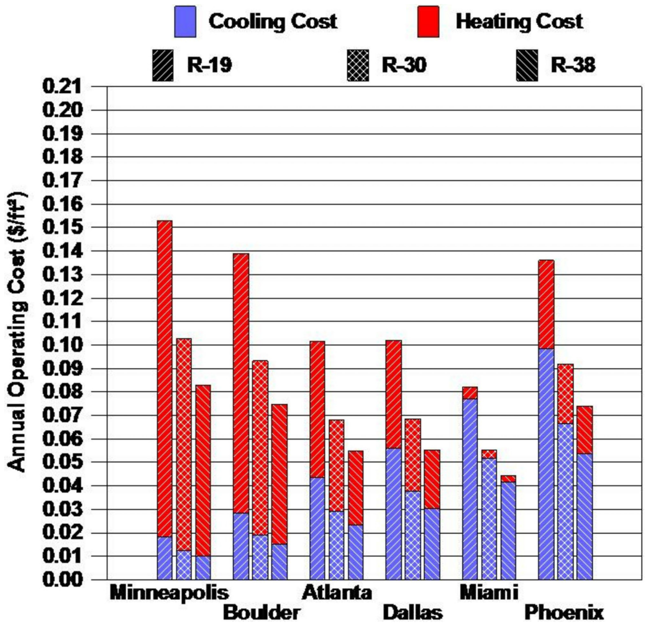

Figure 5 *Annual cooling and heating costs for a cathedralized attic. To convert $/ft^2$ to $/m^2$, multiply by 10.76.*

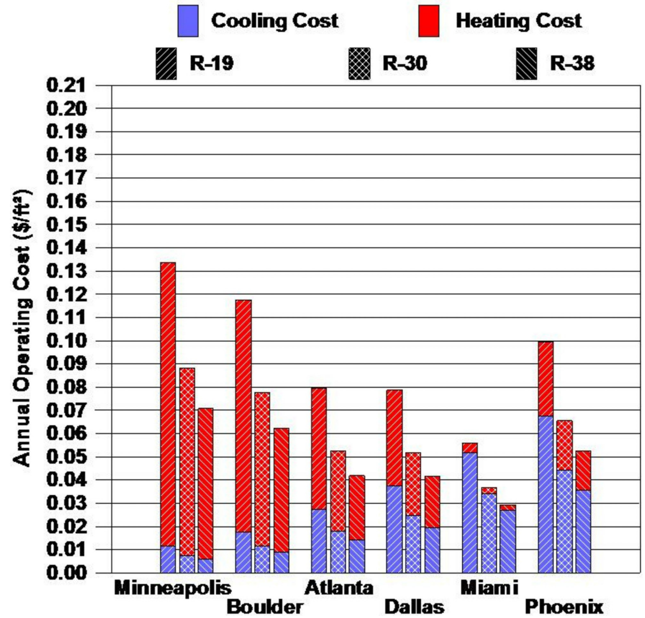

Figure 6 *Annual cooling and heating costs for a well-ventilated conventional attic without ducts. To convert $/ft^2$ to $/m^2$, multiply by 10.76.*

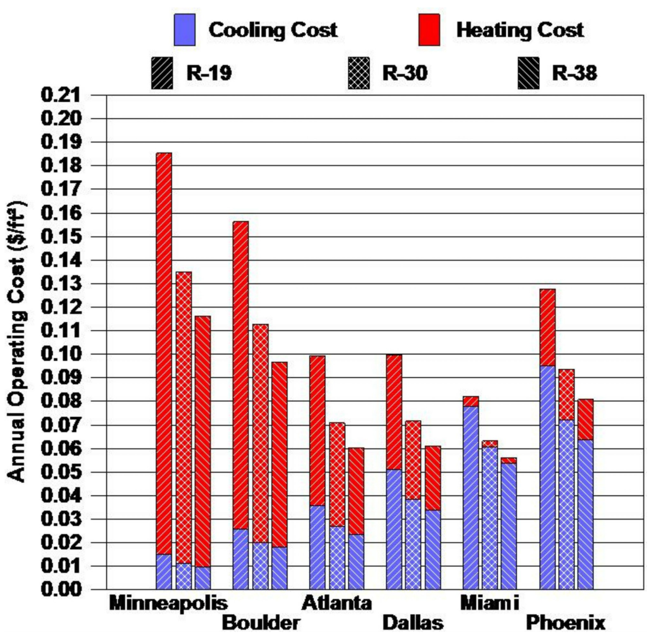

Figure 7 *Annual cooling and heating costs for a well-ventilated conventional attic with medium-length ducts that are leak-free. To convert $/ft^2$ to $/m^2$, multiply by 10.76.*

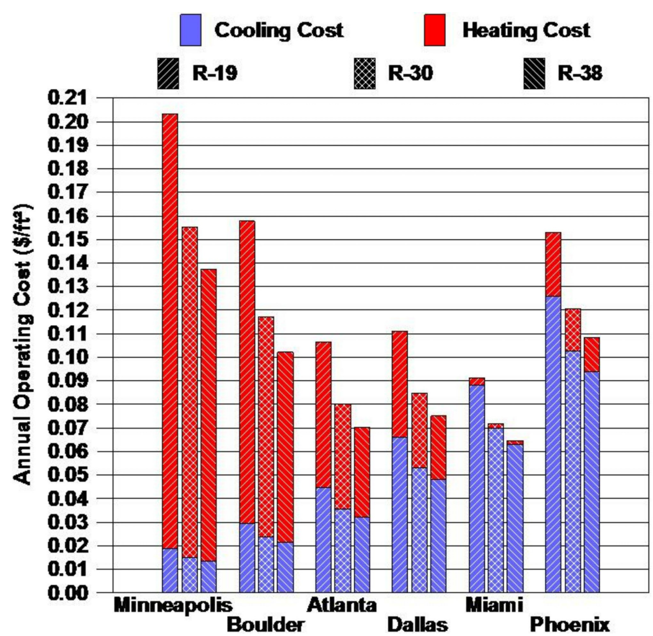

Figure 8 *Annual cooling and heating costs for a well-ventilated conventional attic with medium-length ducts that have S10R5% leakage. To convert $/ft^2$ to $/m^2$, multiply by 10.76.*

Table 4. Annual Difference between Conventional Attics and Cathedralized Attics in Operating Cost for Heating and Cooling ($/ft² of Attic Floor Area) When Both Have R-19, R-30, or R-38 h·ft²·°F/Btu (R-3.3, R-5.3, or R-6.7 m²·K/W) Attic Insulation; for $/m², Multiply by 10.76

Conv. – Cath. ($/ft²)	Minneapolis	Boulder	Atlanta	Dallas	Miami	Phoenix
No ducts in a conventional well-ventilated attic						
R-19 attic insulation	–0.019	–0.021	–0.022	–0.023	–0.026	–0.037
R-30 attic insulation	–0.014	–0.016	–0.016	–0.017	–0.018	–0.026
R-38 attic insulation	–0.012	–0.013	–0.013	–0.014	–0.015	–0.021
Medium-length R-6(+foil) leak-free ducts in a conventional well-ventilated attic						
R-19 attic insulation	+0.032	+0.017	–0.002	–0.002	+0.000	–0.008
R-30 attic insulation	+0.032	+0.020	+0.003	+0.003	+0.008	+0.002
R-38 attic insulation	+0.033	+0.022	+0.006	+0.006	+0.012	+0.007
Medium-length R-6(+foil) ducts with S10R5 leaks in a conventional well-ventilated attic						
R-19 attic insulation	+0.050	+0.019	+0.005	+0.009	+0.009	+0.017
R-30 attic insulation	+0.052	+0.024	+0.012	+0.016	+0.017	+0.029
R-38 attic insulation	+0.055	+0.027	+0.016	+0.020	+0.020	+0.035

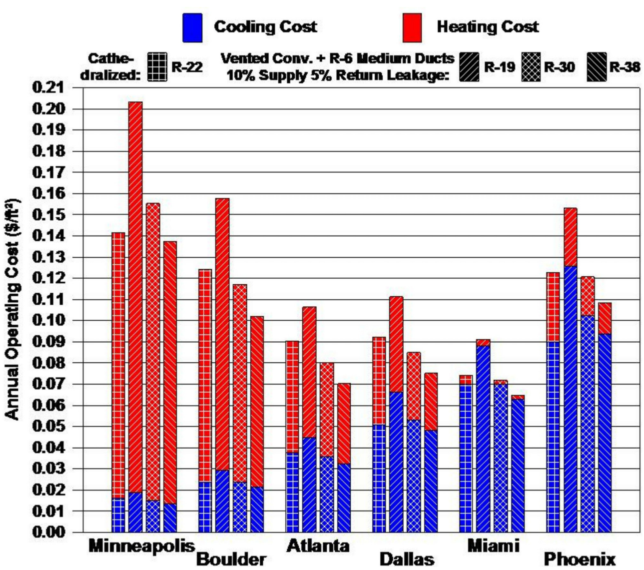

Figure 9 *Annual cooling and heating costs for a cathedralized attic insulated to R-22 h·ft²·°F/Btu compared to well-ventilated conventional attics with various insulation levels and medium-length ducts with R-6 foil-covered insulation and S10R5 leaks. To convert $/ft² to $m/², multiply by 10.76.*

cathedralized attics with the same insulation level. This conclusion ignores the fact that heating ducts in other locations, such as in an unheated basement or in a crawl-space, will have energy losses that they would not have if they were placed inside a conditioned space, such as a cathedralized attic. Ducts in a ventilated conventional attic cause a significant heating penalty, even if they are leak-free. Placing heating ducts in conventional attics is not a good idea.

- If cathedralized attics are limited to insulation levels of about R_{US}-22 (R_{SI}-3.9), conventional attics with insulation level of R_{US}-38 (R_{SI}-6.7) and S10R5 leaky ducts perform about the same as these cathedralized attics. This is due to the limited R-value of the cathedralized attics, not to smaller losses from the heating ducts in the conventional attics.

  Regarding saving of operating costs, $0.10/kWh electricity for cooling, $10/MCF ($0.35/m³) natural gas for heating, and typical operating efficiencies yielded the following conclusions. They resulted from a comparison in the six locations of well-ventilated conventional attics and cathedralized attics, each with insulation levels of R_{US}-19 (R_{SI}-3.3), R_{US}-30 (R_{SI}-5.3), and R_{US}-38 (R_{SI}-6.7). Alternately, the cathedralized attic was limited to R_{US}-22 (R_{SI}-3.9) insulation level.
- Without ducts in the conventional attic, annual savings of $0.01 to $0.04/ft² ($0.11 to $0.44/m²) of attic floor area can be attributed to insulation on the attic floor with a well-ventilated air space above it in the conventional attic compared to an equal level of insulation under the roof and inside the gables of the cathedralized attic.
- If ducts are put in well-ventilated conventional attics, even leak-free ducts cause $0.00 to $0.03/ft² ($0.00 to $0.32/m²) more annual operating costs compared to equally insulated cathedralized attics. The penalty is small in cooling and mixed climates and high in heating climates regardless of attic insulation level. The high penalty in heating climates is further reason not to consider this very unsatisfactory location for heating ducts.
- Leakage of 10% of the supply airflow and 5% of the return airflow for ducts in well-ventilated conventional attics exacerbates the penalty in operating costs compared to cathedralized attics with the same R-value, but less than

Table 5. Annual Difference in Operating Cost for Cooling Only and for Heating and Cooling ($/ft^2 of Attic Floor Area) between Conventional Attics with S10R5 Leaky Ducts and an R_{US}-22 (R_{SI}-3.9) Cathedralized Attic; for $/m^2, Multiply by 10.76

Conv. – Cath. ($/ft²)	Minneapolis	Boulder	Atlanta	Dallas	Miami	Phoenix
R_{US}-19 (R_{SI}-3.3) insulation in the conv. attic vs. R_{US}-22 (R_{SI}-3.9) in the cathedralized attic						
Cooling only	+0.003	+0.006	+0.007	+0.015	+0.018	+0.036
Heating and cooling	+0.062	+0.034	+0.016	+0.019	+0.017	+0.030
R_{US}-30 (R_{SI}-5.3) insulation in the conv. attic vs. R_{US}-22 (R_{SI}-3.9) in the cathedralized attic						
Cooling only	-0.001	+0.000	-0.002	+0.002	+0.000	+0.013
Heating and cooling	+0.014	-0.007	-0.010	-0.007	-0.002	-0.002
R_{US}-38 (R_{SI}-6.7) insulation in the conv. attic vs. R_{US}-22 (R_{SI}-3.9) in the cathedralized attic						
Cooling only	-0.003	-0.002	-0.006	-0.003	-0.007	+0.004
Heating and cooling	-0.004	-0.022	-0.020	-0.017	-0.010	-0.014

$0.03/ft² ($0.32/m²) over the costs with leak-free ducts. If the cathedralized attics are limited to insulation levels of about R_{US}-22 (R_{SI}-3.9), conventional attics with insulation levels of R_{US}-30 (R_{SI}-5.3) and R_{US}-38 (R_{SI}-6.7) cause the same (±$0.02/ft² or ±$0.22/m²) heating and cooling costs despite the leaky ducts.

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APPENDIX A
ANNUAL COOLING AND HEATING PREDICTED BY ATICSIM

Cooling and heating values are in Btu/ft². For kJ/m², multiply by 11.36. (Percentages in parentheses are relative to the cathedralized attic under a black roof in the same location.)

Cooling: All attics have R-38 h·ft²·°F/Btu (6.7 m²·K/W) insulation. Ducts, if present in the conventional attics, have R-6 h·ft²·°F/Btu (1.1 m²·K/W) foil-covered insulation.

	Cathedralized		Conventional Attics and Various Duct Configurations						
	Black Roof	**White Roof**	**No Ducts**	**Long, No Leak**	**Med., No Leak**	**Short, No Leak**	**Med. S10R5 Black Roof**	**Med. S10R5 White Roof**	**Med. S15R10**
Minneapolis	847 (n.a.)	302 (–64.3)	516 (–39.1)	967 (14.1)	845 (–0.3)	719 (–15.1)	1146 (35.4)	854 (0.9)	1331 (57.2)
Boulder	1284 (n.a.)	410 (–68.1)	770 (–40.0)	1718 (33.7)	1539 (19.9)	1357 (5.6)	1829 (42.4)	1325 (3.1)	2179 (69.6)
Atlanta	1989 (n.a.)	749 (–62.3)	1211 (–39.1)	2290 (15.1)	1995 (0.3)	1692 (–14.9)	2751 (38.3)	2050 (3.1)	3230 (62.4)
Dallas	2599 (n.a.)	1123 (–56.8)	1676 (–35.5)	3315 (27.6)	2887 (11.1)	2447 (–5.8)	4110 (58.2)	3246 (24.9)	4875 (87.6)
Miami	3551 (n.a.)	1517 (–57.3)	2309 (–35.0)	5112 (44.0)	4602 (29.6)	4078 (14.8)	5372 (51.3)	4227 (19.0)	6210 (74.9)
Phoenix	4577 (n.a.)	1922 (–58.0)	3030 (–33.8)	6265 (36.9)	5432 (18.7)	4578 (0.0)	7995 (74.7)	6317 (38.0)	9686 (111.6)
Avg.% (all locations)		–61.1	–37.1	28.6	13.2	–2.6	50.0	14.8	77.2
Avg.% (no Mia, Pnx)		–62.9	–38.4	22.6	7.7	–7.5	43.6	8.0	69.2

Heating: All attics have R-38 h·ft²·°F/Btu (6.7 m²·K/W) insulation. Ducts, if present in the conventional attics, have R-6 h·ft²·°F/Btu (1.1 m²·K/W) foil-covered insulation.

	Cathedralized		Conventional Attics and Various Duct Configurations						
	Black Roof	**White Roof**	**No Ducts**	**Long, No Leak**	**Med., No Leak**	**Short, No Leak**	**Med. S10R5 Black Roof**	**Med. S10R5 White Roof**	**Med. S15R10**
Minneapolis	–5834 (n.a.)	–6617 (13.4)	–5182 (–11.2)	–9478 (62.4)	–8514 (45.9)	–7507 (28.7)	–9927 (70.1)	–10302 (76.6)	–1114 (91.0)
Boulder	–4781 (n.a.)	–5700 (19.2)	–4246 (–11.2)	–6747 (41.1)	–6286 (31.5)	–5802 (21.4)	–6455 (35.0)	–6841 (43.1)	–6956 (45.5)
Atlanta	–2510 (n.a.)	–2991 (19.2)	–2214 (–11.8)	–3162 (26.0)	–2952 (17.6)	–2733 (8.9)	–3037 (21.0)	–3234 (28.9)	–3222 (28.4)
Dallas	–1978 (n.a.)	–2368 (19.7)	–1748 (–11.6)	–2304 (16.5)	–2182 (10.3)	–2053 (3.8)	–2150 (8.7)	–2302 (16.4)	–2238 (13.2)
Miami	–211 (n.a.)	–234 (10.6)	–177 (–15.9)	–169 (–19.8)	–170 (–19.5)	–171 (–19.2)	–129 (–39.0)	–136 (–35.5)	–120 (–43.2)
Phoenix	–1621 (n.a.)	–1863 (14.9)	–1354 (–16.5)	–1400 (–13.7)	–1375 (–15.2)	–1349 (–16.8	–1180 (–27.2)	–1266 (–21.9)	–1154 (–28.8)
Avg.% (all locations)		16.2	–13.0	18.8	11.8	4.5	11.4	17.9	17.7
Avg.% (no Mia, Pnx)		17.9	–11.4	36.5	26.3	15.7	33.7	41.2	44.5

Cooling and heating values are in Btu/·ft^2. For kJ/m^2, multiply by 11.36. (Percentages in parentheses are relative to the cathedralized attic under a black roof in the same location.)

Cooling: All attics have R-30 h·ft^2·°F/Btu (5.3 m^2·K/W) insulation. Ducts, if present in the conventional attics, have R-6 h·ft^2·°F/Btu (1.1 m^2·K/W) foil-covered insulation.

	Cathedralized		Conventional Attics and Various Duct Configurations						
	Black Roof	**White Roof**	**No Ducts**	**Long, No Leak**	**Med., No Leak**	**Short, No Leak**	**Med. S10R5 Black Roof**	**Med. S10R5 White Roof**	**Med. S15R10**
Minneapolis	1059 (n.a.)	382 (–63.9)	651 (–38.6)	1091 (3.0)	969 (–8.5)	844 (–20.3)	1273 (20.2)	936 (–11.6)	1457 (37.6)
Boulder	1615 (n.a.)	522 (–67.7)	978 (–39.4)	1903 (17.8)	1725 (6.8)	1542 (–4.5)	2019 (25.0)	1442 (–10.7)	2367 (46.6)
Atlanta	2490 (n.a.)	943 (–62.1)	1529 (–38.6)	2580 (3.6)	2285 (–8.3)	1982 (–20.4)	3046 (22.3)	2244 (–9.9)	3524 (41.5)
Dallas	3228 (n.a.)	1399 (–56.6)	2101 (–34.9)	3720 (15.2)	3291 (2.0)	2853 (–11.6)	4527 (40.2)	3544 (9.8)	5289 (63.9)
Miami	4421 (n.a.)	1890 (–57.2)	2900 (–34.4)	5671 (28.3)	5163 (16.8)	4641 (5.0)	5954 (34.7)	4638 (4.9)	6787 (53.5)
Phoenix	5673 (n.a.)	2385 (–58.0)	3791 (–33.2)	6995 (23.3)	6162 (8.6)	5310 (–6.4)	8742 (54.1)	6848 (20.7)	10428 (83.8)
Avg.% (all locations)		–60.9	–36.5	15.2	2.9	–9.7	32.8	0.5	54.5
Avg.% (no Mia, Pnx)		–62.6	–37.9	9.9	–2.0	–14.2	27.0	–5.6	47.4

Heating: All attics have R-30 h·ft^2·°F/Btu (5.3 m^2·K/W) insulation. Ducts, if present in the conventional attics, have R-6 h·ft^2·°F/Btu (1.1 m^2·K/W) foil-covered insulation.

	Cathedralized		Conventional Attics and Various Duct Configurations						
	Black Roof	**White Roof**	**No Ducts**	**Long, No Leak**	**Med., No Leak**	**Short, No Leak**	**Med. S10R5 Black Roof**	**Med. S10R5 White Roof**	**Med. S15R10**
Minneapolis	–7231 (n.a.)	–8197 (13.4)	–6455 (–10.7)	–10839 (49.9)	–9884 (36.7)	–8888 (22.9)	–11225 (55.2)	–11670 (61.4)	–12418 (71.7)
Boulder	–5942 (n.a.)	–7075 (19.1)	–5298 (–10.8)	–7856 (32.2)	–7403 (24.6)	–6929 (16.6)	–7482 (25.9)	–7952 (33.8)	–7955 (33.9)
Atlanta	–3118 (n.a.)	–3711 (19.0)	–2760 (–11.5)	–3735 (19.8)	–3531 (13.2)	–3316 (6.4)	–3548 (13.8)	–3790 (21.6)	–3714 (19.1)
Dallas	–2462 (n.a.)	–2943 (19.5)	–2182 (–11.4)	–2756 (12.0)	–2638 (7.1)	–2513 (2.1)	–2544 (3.4)	–2733 (11.0)	–2616 (6.3)
Miami	–264 (n.a.)	–292 (10.6)	–223 (–15.8)	–213 (–19.4)	–214 (–18.9)	–215 (–18.5)	–162 (–38.6)	–172 (–35.0)	–151 (–43.0)
Phoenix	–2021 (n.a.)	–2319 (14.7)	–1692 (–16.3)	–1729 (–14.4)	–1708 (–15.5)	–1685 (–16.6)	–1451 (–28.2)	–1560 (–22.8)	–1408 (–30.4)
Avg.% (all locations)		16.1	–12.7	13.3	7.9	2.1	5.2	11.7	9.6
Avg.% (no Mia, Pnx)		17.8	–11.1	28.5	20.4	12.0	24.6	32.0	32.8

Cooling and heating values are in Btu/·ft². For kJ/m², multiply by 11.36. (Percentages in parentheses are relative to the cathedralized attic under a black roof in the same location.)

Cooling: All attics have R-19 h·ft²·°F/Btu (3.3 m²·K/W) insulation. Ducts, if present in the conventional attics, have R-6 h·ft²·°F/Btu (1.1 m²·K/W) foil-covered insulation.

	Cathedralized		Conventional Attics and Various Duct Configurations						
	Black Roof	**White Roof**	**No Ducts**	**Long, No Leak**	**Med., No Leak**	**Short, No Leak**	**Med. S10R5 Black Roof**	**Med. S10R5 White Roof**	**Med. S15R10**
Minneapolis	1574 (n.a.)	572 (–63.7)	993 (–36.9)	1417 (–9.9)	1296 (–17.7)	1171 (–25.6)	1607 (2.1)	1151 (–26.8)	1789 (13.6)
Boulder	2411 (n.a.)	785 (–67.4)	1501 (–37.7)	2389 (–0.9)	2211 (–8.3)	2029 (–15.9)	2513 (4.2)	1743 (–27.7)	2858 (18.5)
Atlanta	3712 (n.a.)	1411 (–62.0)	2340 (–37.0)	3344 (–9.9)	3050 (–17.8)	2748 (–26.0)	3825 (3.0)	2749 (–25.9)	4297 (15.7)
Dallas	4790 (n.a.)	2080 (–56.6)	3201 (–33.2)	4797 (0.1)	4371 (–8.7)	3935 (–17.8)	5638 (17.7)	4332 (–9.6)	6389 (33.4)
Miami	6584 (n.a.)	2815 (–57.3)	4424 (–32.8)	7160 (8.7)	6656 (1.1)	6138 (–6.8)	7510 (14.1)	5732 (–12.9)	8327 (26.5)
Phoenix	8401 (n.a.)	3533 (–58.0)	5761 (–31.4)	8550 (1.8)	8119 (–3.4)	7272 (–13.4)	10733 (27.8)	8260 (–1.7)	12402 (47.6)
Avg.% (all locations)		–60.8	–34.8	–1.7	–9.1	–17.6	11.5	–17.5	25.9
Avg.% (no Mia, Pnx)		–62.4	–36.2	–5.2	–13.1	–21.3	6.8	–22.5	20.3

Heating: All attics have R-19 h·ft²·°F/Btu (3.3 m²·K/W) insulation. Ducts, if present in the conventional attics, have R-6 h·ft²·°F/Btu (1.1 m²·K/W) foil-covered insulation.

	Cathedralized		Conventional Attics and Various Duct Configurations						
	Black Roof	**White Roof**	**No Ducts**	**Long, No Leak**	**Med., No Leak**	**Short, No Leak**	**Med. S10R5 Black Roof**	**Med. S10R5 White Roof**	**Med. S15R10**
Minneapolis	–10759 (n.a.)	–12200 (13.4)	–9754 (–9.3)	–14539 (35.1)	–13610 (26.5)	–12640 (17.5)	–14752 (37.1)	–15390 (43.0)	–15879 (47.6)
Boulder	–8846 (n.a.)	–10535 (19.1)	–8005 (–9.5)	–10859 (22.8)	–10429 (17.9)	–9979 (12.8)	–10263 (16.0)	–10962 (23.9)	–10662 (20.5)
Atlanta	–4638 (n.a.)	–5526 (19.2)	–4166 (–10.2)	–5287 (14.0)	–5096 (9.9)	–4896 (5.6)	–4930 (6.3)	–5295 (14.2)	–5046 (8.8)
Dallas	–3665 (n.a.)	–4386 (19.7)	–3297 (–10.0)	–3977 (8.5)	–3870 (5.6)	–3757 (2.5)	–3610 (–1.5)	–3898 (6.3)	–3636 (–0.8)
Miami	–394 (n.a.)	–438 (11.0)	–337 (–14.6)	–331 (–16.2)	–333 (–15.5)	–336 (–14.9)	–251 (–36.3)	–267 (–32.3)	–233 (–41.0)
Phoenix	–3005 (n.a.)	–3451 (14.8)	–2547 (–15.2)	–2614 (–13.0)	–2602 (–13.4)	–2589 (–13.8)	–2176 (–27.6)	–2346 (–21.9)	–2088 (–30.5)
Avg.% (all locations)		16.2	–11.5	8.5	5.2	1.6	–1.0	5.5	0.8
Avg.% (no Mia, Pnx)		17.8	–9.8	20.1	15.0	9.6	14.5	21.9	19.0