Roof and Attic Design Guidelines for New and Retrofit Construction of Homes in Hot and Cold Climates

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ABSTRACT

Guidelines for improving the energy efficiency of roofs and attics are documented from research conducted for the Department of Energy (DOE) Building Technologies Office. The results of combined analytical and experimental studies were used to benchmark computer tools, which in turn, were used to simulate homes in hot and cold climates. Simulations of adding floor and roof insulation, above-deck ventilation, radiant barriers, cool-color shingles, and metal or tile roofs; sealing the attic floor and the duct system; and making the attic a semi-conditioned space (sealed attic) were performed to compute the cost of energy savings. Results are prioritized to help building owners make an informed economic decision when contemplating roof and attic retrofits. Sealing the attic floor is a top retrofit option. The approach of making the attic a semi-conditioned space (sealed attic) and exploiting a new prototype roof assembly—an insulated and ventilated roof—are good options for retrofit work but have paybacks ranging from 15 to 25 years. A new sealed attic concept is proposed, and computations show its simple payback is about 10 to 12 years in hot and cold climates; its first cost is significantly reduced from that of a spray foam approach. For new construction the best option is to keep the ducts out of the attic, make sure the attic floor is sealed to limit whole-house air leakage, and add at least the code level of insulation to the ceiling.

INTRODUCTION

Several conservation measures are described for improving the energy efficiency of new and retrofit roofs and attics. We define the attic to broadly include the roof as well as the space between the roof and the finished ceiling. The attic often includes air-conditioning ducts and a heating, ventilating, and air-conditioning (HVAC) system. In the United States (mostly the south), single-family homes with slab foundations rose from 26% of homes built in 1971 up to 70% of homes completed in 2011 (CB 2011). These statistics imply a growing trend to place HVAC and air distribution systems in the attic. In the colder northern climates, basements dominate about 80% of the residential market, and a smaller percentage of HVAC systems are placed in attics (CB 2011). As land demand and prices have risen, however, the percentage of two-story homes built in the northeast has jumped from 44% in 1971 up to 81% of homes built in 2011.

Dodge (2002) reported that in about 85% of U.S. homes, existing worn-out roofs have been replaced with asphalt shingles, as shown in Table 1. The consensus shows that retrofit work predominates over new construction as homeowners upgrade their home. Therefore, the paper first focuses on retrofit options that reflect the present market; it then addresses options for roof and attic systems.

Demographics provided by the U.S. Census Bureau (2009A, 2009B) reveal that roughly half of the existing 112 million homes in the country were built from about 1960 to 1979. ASHRAE 90-1980 was the code of practice; however, few states measured or enforced code compliance because of the complexity and or expense of the task. Too often a state's adoption of the current IECC code lags the code of practice by several years (U.S. DOE 2010).

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Several roofing contractors with businesses in hot climates were surveyed, and almost all contractors commented that the homes they worked in had at best R_{US}-10 (R_{SI}-1.7)[1] on the attic floor because they could see the ceiling joists in the attics. The observation is very important because it controls the level of savings for retrofit applications.

Table 2 shows current ASHRAE 90.2 (ASHRAE 2007) practice and ASHRAE 90 (ASHRAE 1980) practice. The current ASHRAE 90.2 practice was used to estimate savings for new construction. ASHRAE 90-1980 was selected as the base for cold climates; however, R_{US}-10 (R_{SI}-1.7) was assumed for hot climates.

The best retrofit option for your attic depends on climate, attic geometry, duct arrangement, amount of ceiling insulation, air leakage, and thermostat setting used to comfort condition the home. If the ceiling currently has less than code insulation, savings will be greater and payback period will be shorter. If the ductwork has recently been repaired, sealed, and insulated, the savings for other measures will be less. Savings are also affected by the run time of the HVAC unit.

The breakdown of fuels used for cooling and heating is also very interesting, with electricity being the fuel of choice for comfort cooling. However, natural gas and bottled LP gas are used in about 56% of all American homes. Even in New York state about 3.8 million homes use natural gas, while some 2.2 million homeowners in New York utilize fuel oil to heat their homes (EIA 2005). A SEER 13 heat pump and a 0.85 energy efficient gas furnace are assumed when converting saved cooling and heating energy into costs using EIA 2012 state average fuel prices. Electricity rates are based on EIA (2012a) data, while comfort heat is based on the prices for natural gas in EIA (2012b), as shown in Table 2.

1. R_{US} represents the thermal resistance of ceiling insulation and has units: (h·ft^2·°F)/Btu; R_{SI} units: (m^2·°C)/W.

LEAKY DUCTS IN ATTICS

The convenience of the attic space is very appealing to builders, and all too often they install the HVAC unit and ducts in the attic. Parker et al. (1993) simulated the effects of ducts on space conditioning Florida homes and observed that air leakage and heat transfer to the duct were major contributors to the peak electrical burden on the utility. Energy costs are also increased if the attic floor leaks air to or from the conditioned space. Walker (1998), in his bibliography of duct leakage, provides average leakage rates of 10% to 20% of fan flow, as shown in Table 3.

The impacts of supply and return leaks can be different because the origin of the leak can affect airflow patterns in the attic. However, the computer simulations are based on overall energy balances for the attic and attic air; therefore, equal supply and return leakages were used in simulations.

The computer tool AtticSim (Version 11)[2] with input from Energy Plus was exercised to estimate potential savings.

Table 1. Number of Squares (100 ft^2) of New and Retrofit Roof Products Installed in the United States

	Asphalt Shingles	Metal	Concrete	Clay	Wood Shakes	Other
New	29,955,734	1,705,073	1,965,500	323,763	280,821	461,263
Reroof	115,054,533	9,550,899	1,657,307	892,926	6,445,277	4,400,195
Total	145,010.267	11,255,972	3,622,807	1,216,689	6,726,098	4,861,458

Table 2. Cities Representing the ASHRAE Standard 90.2 Climate Zones Selected for Simulating Retrofit and New Construction[a]

				ASHRAE Standard 90.2 New Construction		ASHRAE Standard 90-1980 Retrofit Construction		Fuel Costs	
				Ceiling	Duct[b]	Ceiling	Duct[c]	Electricity (EIA 2012a) ¢ per kWh	NG (EIA 2012b) \$/1000 CF
Zone	City, State	HDD_{65}	CDD_{65}	R-Value, (h·ft^2·°F)/Btu		R-Value, (h·ft^2·°F)/Btu			
1	Miami, FL	222	9368	30	8	20	5.5	12.52	21.69
2	Austin, TX	1481	7435	30	8	20	5.5	12.88	13.79
3	Atlanta, GA	2614	4814	30	8	20	5.5	9.55	18.5
4	Baltimore, MD	4731	3598	38	8	21	5.5	14.57	16.05
6	Minneapolis, MN	7787	2513	49	8	29	5.5	9.66	11.3

[a]Retrofit cases assumed the ceiling and duct levels of insulation listed under the column ASHRAE 90-1980 to compute the cost of energy savings.
[b]Inspected duct system assumes 4% air leakage.
[c]Existing duct system assumed 10% and 20% air leakage. ASHRAE 90-1980 does not address leakage.

The HERS BESTEST model home (NREL 1995a) was used to simulate a house having an attic footprint of 1550 ft^2 (144 m^2). The roof slope was set at 18° and a dark heat-absorbing shingle roof having solar reflectance of 0.10 was assumed for hot and cold climates using TMY2 (NREL 1995b) weather data. A supply and return duct placed in the attic was modeled by AtticSim. Energy Plus does not compute the radiation coefficients between the duct and seven attic surfaces. However, we used Energy Plus to estimate the hourly run times for a 2-ton heat pump certified with a seasonal energy efficiency ratio (SEER) of 13. The hourly indoor air temperature for the house, the run time for the HVAC, and the flow rate of air in the ducts were computed by Energy Plus and read by AtticSim to better estimate the roof and attic load as coupled to the building envelope. The procedures developed by Fairey et al. (2004) were used to de-rate the SEER and HSPF for climatic impacts. Savings are computed using as base a conventional stick-built roof and attic with 1:300 opening at the soffit and ridge.

Figure 1 illustrates why duct renovations should be a priority in a building program. The turquoise bars represent energy use for a roof and attic where the roof is dark and the attic is poorly insulated and has 20% leaky ducts and a leaky attic floor. The dark blue bars are for the same roof and attic but with a 10% leaky duct. The orange bars show energy use where the practitioner repaired the leaks in the attic and sealed and rewrapped the ducts in R_{US}-8 (R_{SI}-1.4) insulation. The green bars show the benefits of sealing the attic floor and moving ducts into the conditioned space. Often it is not feasible to remove ducts from the attic and totally eliminate duct losses, but the simulations vividly show the magnitude of the losses from the duct system. A new prototype roof studied by Miller et al. (2011) is also shown (black color bars) having the same dark shingle roof but with the attic floor sealed and the ducts in the conditioned space.

Figure 1 is of keen interest because it shows that adding ceiling insulation (view *x*-axis) reduces the energy bill for all roof and attic assemblies whether with or without a duct system. But the heat transfer tends to level off and there are diminishing returns for adding floor insulation above about R_{US}-19 (R_{SI}-3.3)[3] because losses from the ducts predominate. Therefore, if all one does is put more insulation down and ignore the HVAC system, then hundreds of dollars' worth of energy is still being lost from the HVAC in the attic. Frankly, adding only insulation still leaves a poorly performing home that has higher-than-necessary utility costs month after month.

The green bars (Figure 1) show energy savings if the ducts are in the conditioned space. Add to that a new roof design (Miller et al. 2011), and the annual roof and attic load drops from 45 MBtu/year down to 4.5 MBtu/year, about a 40 MBtu annual savings in energy in Austin, TX (Figure 1 viewed at R_{US}-30 [R_{SI}-5.3] level of ceiling insulation). The simple payback for this system is about 10 to 15 years, depending on the climate, the initial level of floor insulation, and the temperature settings on the thermostat. That 40 MBtu translates into about 4000 kWh, which in turn for electricity at 10¢/kWh, yields annual savings of $400. Therefore, implementing a single strategy is good, but more can be accomplished. Of course, renovations are more costly and most people want an affordable roof replacement. The initial cost and the simple payback are the major hurdles for market acceptance.

PRIORITIZING RETROFITS

The attics of the homes used to estimate the above savings, which represent those built between 1960 and 1979, have at best R_{US}-5.5 (R_{SI}-0.97) insulation wrapped around leaky ducts operating in the attic. Air leakage of the ductwork

Table 3. Survey of Homes Checked for Duct Leakage

Literature Cited in Walker (1998)	Supply Duct Leakage	Return Duct Leakage
Cummings et al. (ACEEE 1990) 91 homes surveyed	10%	10%
Jump et al. (ACEEE 1996) 24 homes surveyed	17%	16%
Modera et al. (CEC 1995 report) 100 homes (new construction)	8%	7%

Source: Data is courtesy of Walker (1998).

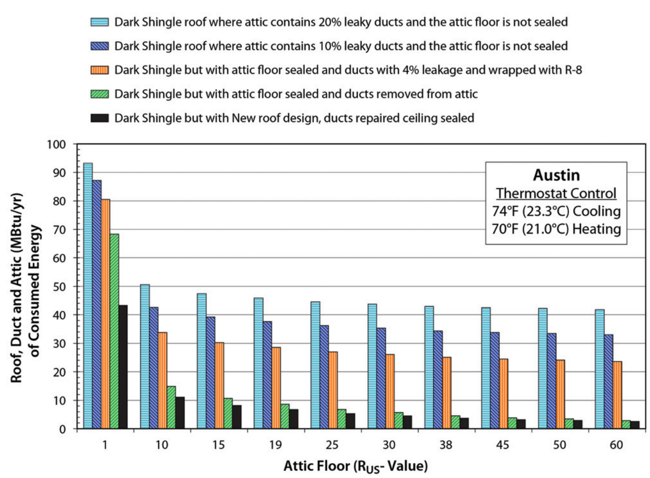


Figure 1 *Comparison of energy impacts of leaky ducts in attic space, sealing attic floors, insulating attic floors, and totally eliminating energy losses from HVAC ducts in unconditioned attics.*

2. AtticSim version 11 originated from the ASTM C1340 (2004) protocol. Version 11 contains revisions for above sheathing ventilation benchmarked by Miller et al. (2007).

3. Climate Zones 1 through 3 require by ASHRAE Standard 90.2-2007 code R_{US}-30 (R_{SI}-5.3).

is unknown; however, based on measurements made for a sampling of homes (Table 3), simulations for retrofit options assumed air losses of 4%, 10%, and 20% of supply airflow. Two different thermostat duty cycles for controlling the HVAC were implemented for the savings computations. The one described herein as "conservation mode" is for those interested in energy conservation (home at 68°F [20°C] in the winter and 78°F [25.6°C] in the summer). The other thermostat control is for comfort control (70°F [21°C] in the winter and 74°F [23.3°C] in the summer), herein referred to as comfort control. These conditions were used to compute a range for simple paybacks for implementing a given retrofit practice.

Seal the Attic Floor

The most important retrofit option, whether the duct system is in the attic or not, is to seal the attic floor. The ceiling is part of the home's perimeter, and air leakage is the major source of heat gains and losses to the home. d'Ambrosio et al. (2012) cites ceiling leakage as contributing to about 18% of the typical leakage in a home. Savings were estimated more conservatively based on 65 cfm (0.03 m^3/s) of air leakage crossing the ceiling, which contributes about 5% to the whole house leakage assumed at 5 ach by IECC 2012 code. Sealing yields annual savings ranging from just \$31–39 in Miami to \$126–132 in Atlanta. The cost of the renovation is about \$0.40 per square foot, and the savings payback for the renovation is about 16–22 years for a home in Miami, 8–9 years in Austin, 5 years in Atlanta, and 4 years in Baltimore, as shown in Table 4.

Sealing the attic floor saves money (Table 4); however, if the intent is to make the attic a semi-conditioned space, then sealing the attic floor will have only secondary effects on building load. Sealing the attic floor in conjunction with repair of a duct system operating in the attic is a viable option because both are part of the perimeter and the repairs reduce the overall house leak rate, which, in turn, reduces the building load.

Repair the Ducts in the Attic

Table 5 shows the savings for repairing only the ductwork. Again, these are based on a pre-1980 home built to the historical code (ASHRAE 1980) in cold climates. For hot climates, the ceiling of the control assumed R_{US}-10 (R_{SI}-1.8). As noted, a SEER 13 air conditioner was assumed for comfort conditioning. Repairing the ductwork saves \$46 for 10% leaky ducts with the air conditioner set for energy conservation in Miami but increases to \$138 if the duct leakage is as high as 20% and thermostat controls are for occupant comfort. Therefore, savings can vary significantly depending on duct leakage and thermostat setpoint. In Miami the base home has computed heat gains from the roof and attic that cost the homeowner about \$230 per year with the air conditioner set for energy conservation.

The EIA (2010) publishes typical residential electric and gas heating bills for various U.S. cities and for Miami the roof and attic contributes to about 13% of the simulated whole house electrical bill. For Austin a homeowner would pay \$457 per year for a poorly performing duct system in the attic, and the roof and attic is about 20% of the home's total use of gas and electricity. For Austin the electricity attributed to a conventionally designed roof and attic is about 25% of the total kilowatt-hour draw stated by the EIA (2010) for the Texas census region. Therefore, the consumption rate is within reason, considering the whole building load.

In Baltimore's colder climate, the pre-1980 home's roof and attic is roughly 30% of the total energy consumed by the home. Therefore, as the heating load increases, so does the cost for having a duct system in the unconditioned attic, and the payback for duct renovation becomes more and more enticing. The simple payback can be as low as 1 year for a home with 20% leaky ducts and thermostat set for comfort control. It is also seen that cold climate design of roof systems and attics is even more important than hot climate design because on a national basis, residential homes use 4.3 quads of total site energy for heating as compared to 0.64 quads for cooling (EIA 2013).

Radiant Barriers

Stovall et al. (2010) documented the performance of radiant barrier systems in limiting the radiation heat transfer occurring in the attic. Shrestha et al. (2013) showed it most effective when attached to the underside of the roof rafters so that the foil acts as a dual-acting radiation shield and as a channel for directing buoyancy-driven hot air in from the soffit and out the ridge vent, as in Figure 2. The radiant barrier foil costs about \$0.15 per square foot of material, and the labor to attach the foil directly to the underside of the roof rafters is estimated at \$0.65 per square foot[4] of coverage for a 4:12 pitch roof.

Table 4. Cost of Energy Attributed to the Base Roof, Attic, and Leaky Duct and the Subsequent Monetary Savings in Energy and Payback for Sealing the Attic Floor Having Footprint of 1550 ft^2 (144 m^2)[a]

	Miami	Austin	Atlanta	Baltimore
Base 1980 roof and attic	\$230–398	\$457–652	\$714–991	\$925–1287
Retrofit savings[b]	\$31–39	\$74–75	\$126–132	\$155–162
Payback[b] (years)	16–20	8–9	≈5	≈4

[a]All data ranges include values for attics containing leaky and poorly insulated ducts with 10% and 20% leakage.
[b]Sealing the attic floor eliminates 0.26 air changes per hour between the home and the attic.

Table 5. Cost of Energy Savings and Simple Payback for Repair of Ductwork Simulated with 10% and 20% Leakage in the Unconditioned Attic Having Footprint of 1550 ft^2 (144 m^2)[a]

	Miami	Austin	Atlanta	Baltimore
Base 1980 roof and attic	$230–398	$457–652	$714–991	$925–1287
Retrofit savings[b]	$46–138	$85–216	$120–348	$169–470
Payback (years)[b]	4.5–56	3–30	2–21	1–15

[a]All data ranges include values for repairing ducts of 10% and 20% initial leakage.
[b]Repair includes replacing R_{US}-5.5 with R_{US}-8 insulation and sealing duct to 4% of flow leakage. Indoor air handler is assumed to be in conditioned space.

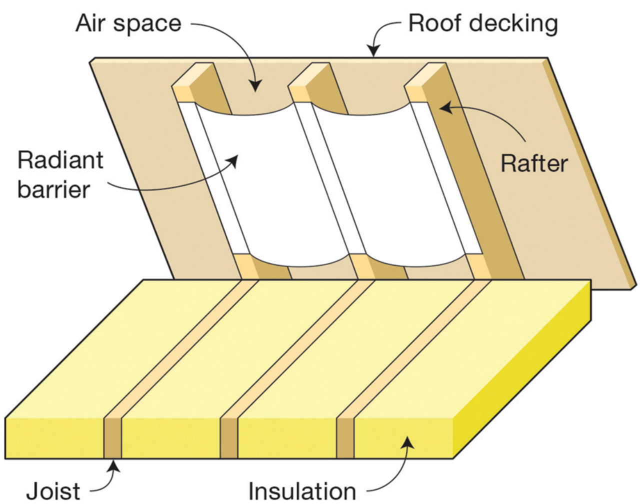


Figure 2 *Radiant barrier is installed to the underside of the roof rafters.*

Therefore, retrofitting the attic with a radiant barrier would cost about $0.80 per square foot of attic footprint.

Another alternative is to spray paint the attic interior with low emittance paints. The application qualifies as an internal radiation control coating (IRCC) if the paint has a thermal emittance less than or equal to 0.25. The cost of material and labor is comparable to the foil application.

Simulations for hot climates indicate that a radiant barrier can pay for itself in 20–25 years. Without leaky ducts in the attic, the payback increases to about 38–50 years. In cold climates the radiant barrier is not an effective measure.

Adding Insulation to the Attic

Adding insulation to meet IECC code (R_{US}-30 [R_{SI}-5.3]) has an incremental material and labor charge of $1.04 per square foot (RS Means 2011) for adding R_{US}-20 (R_{SI}-3.5) insulation in Miami, Austin, and Atlanta. Code for Baltimore is R_{US}-38 (R_{SI}-6.7), and the additional insulation needed to meet code costs $1.38 per square foot. The savings (Table 6) are estimated with no ductwork in the attic and also with 20% leaky ducts in the attic. In hot climates adding R_{US}-20 (R_{SI}-3.5) to a ceiling already covered with R_{US}-10 (R_{SI}-1.8) and with no ducts in the attic yields annual savings ranging from $64 in Miami to $238 in Baltimore (Table 6).

However, if the attic contains 20% leaky ducts, the savings are reduced as compared to having no ducts in the attic. This occurs because the leaky ducts actually condition the attic space, which reduces the heat transfer crossing the floor insulation. So, adding insulation to an attic that does not include ductwork has a larger savings than an attic that contains leaky ductwork. Savings also increase as the climate incurs more and more days of required comfort heating. Simple payback is 10–12 years in Atlanta and 9–11 years in Baltimore.

Cool-Color Shingles

Dark roofing can be formulated to reflect like a highly reflective white roof in the near infrared (NIR) portion of the solar spectrum. ORNL and LBNL collaborated on a cool roof study for the California Energy Commission and worked with pigment manufacturers to identify and characterize pigments with optical properties suitable for cool-color roof products (Levinson 2004a, 2004b).

Simulations for a home with cool-color shingles (solar reflectance of 0.25) on the roof in the hot climates of Miami and Austin show a reduction in the cooling load but also a slight increase in heating load, which results in a net annual savings of only $6–9 in Austin and an actual penalty in Atlanta (Table 7). The simulation was conducted with only R_{US}-10 (R_{SI}-1.8) on the attic floor to view the benefits of the cool roof shingle. Shingles with solar reflectance of 0.40 and 0.70 (white roof) were also simulated (Table 7).

In Austin and Atlanta the net savings for a 0.40 solar reflective shingle is respectively $13–18 and –$11–10, assuming R_{US}-10 (R_{SI}-1.8) on the attic floor. The cost premium for cool-color shingles according to local distributors installing the product is about $50 per 100 ft^2 (Mullenax 2010). Therefore, the simple payback for a commercially available 0.25 solar reflective shingle is on the order of 50 years.

However, in many existing homes, especially in the southwestern United States, the roof pitch is less than 4 in 12, making it difficult to renovate the attic. For example, retrofit-

[4] Estimates for labor based on costs provided by local distributors conducting attic renovations.

Table 6. Cost of Saved Energy and Payback for Adding Code-Level of Insulation to the Attic Floor Having Footprint of 1550 ft^2 (144 m^2)[a]

	Miami		Austin		Atlanta		Baltimore	
	No Duct	20% Leaky Duct	No Duct	20% Leaky Duct	No Duct	20% Leaky Duct	No Duct	20% Leaky Duct
Base Roof and Attic	$160	$400	$286	$652	$445	$990	$562	$1,288
Retrofit Savings[b]	$64	$52	$110	$88	$163	$135	$238	$196
Payback[b] (Years)	25	30	15	18	10	12	9	11

[a]Thermostat controlled for occupancy comfort. All data ranges include values for attics with no duct and attic with ducts of 20% leakage.
[b]R_{US}-20 (R_{SI}-3.5) insulation added to attic floor for hot climates.

Table 7. Cost of Saved Energy for Replacing Dark Shingles with 25% and 40% Solar Reflective Cool-Color Products[a]

	Miami	Austin	Atlanta	Baltimore
Base roof and attic	$230–398	$457–652	$714–991	$925–1287
Retrofit savings for SR25[b] shingle[c]	$9–12.5	$6.3–9	$(5)–(4.5)[d]	$(3.7)–(2.6)
Retrofit savings for SR40 shingle[c]	$18–25	$13–18	$(11)–(10)	$(8)–(6)
Retrofit savings for SR70 shingle[c]	$36–50	$24–34	$(23)–(22)	$(17)–(13)

[a]Attic footprint is 1550 ft^2 (144 m^2). All data ranges include values for attics containing ducts with 10% and 20% leakage.
[b]SR, solar reflectance.
[c]Homeowner replaces shingles and makes no other improvements.
[d]Values in parentheses imply a cost penalty.

ting a home in El Centro, CA with 0.25 reflective cool-color shingles drops roof and attic cooling energy by 6.4% of that used by a base roof with 0.05 dark shingles if the attic has only R_{US}-19 (R_{SI}-3.3) insulation on the attic floor. California Title 24 code calls for R_{US}-38 (R_{SI}-6.7). If an attic space cannot be modified, then the cool-color roof becomes a good option, with simple payback of about 10 years in El Centro (Miller and Kosny 2008).

SYSTEMS APPROACH TO HOME RETROFITS

Attic renovations show that incremental changes for some retrofits yield marginal savings and also that losses from ducts in attics predominate. A question one might ask is whether a combination of practices such as the insulated and ventilated roof deck reported by Miller et al. (2011) provides enough improvement to compensate for an attic with poorly performing, leaky ducts.

Ventilating the roof deck above the sheathing was proven to effectively reduce heat transfer crossing the roof deck, as shown in Figure 3. The ventilation also redirects solar-driven moisture out the ridge vent instead of it crossing the roof deck (Miller et al. 2006). Field data collected for an insulated and ventilated roof deck (R_{US}-8 [R_{SI}-1.4]) measured almost an 85% drop in the peak day heat transfer crossing the ceiling. Ventilation occurring above the sheathing reduced shingle temperature 16°F (9°C) and dropped the attic air temperature to about the outdoor air temperature. The design improved the durability of the shingles by keeping them cooler, and it reduced heat flows crossing into the conditioned space, thereby reducing energy consumed for comfort conditioning. The free ventilation flow occurring during the day helped dry the sheathing and limited moisture intrusion into the attic, as shown in Figure 3.

Annual performances of the insulated and ventilated roof deck and a sealed attic were cast into the scenario used in Figure 1 to show whether either system compensates for an attic with poorly performing, leaky ducts, as shown in Figure 4. The bars in the pale green color represent consumed energy for an insulated and ventilated roof deck (new design) installed on a poorly insulated attic that has a leaky attic floor and 10% leaky ducts. The black bars represent a sealed attic system that exploits the lost duct energy to make a semi-conditioned space in the attic. Insulation for the sealed attic is in the rafters, not the attic floor. Hence, the floor of the sealed attic was simulated without insulation.

The new design cannot compensate for the losses incurred by the leaky ductwork or for the air leakage crossing the attic floor. Repairing the leaky ducts (turquoise and navy blue bars) by sealing them to 4% leakage and wrapping them with R_{US}-8 (R_{SI}-1.4) insulation yields slightly more savings (orange bars) than simply installing a new roof design. The sealed attic (black bars) shows better performance (Figure 4); however, the initial cost for these retrofits is important because homeowners want the system at an affordable price. Repairing 140 ft of ductwork attached to a two-ton heat pump is estimated at $1.67 per square foot for an attic of 1550 ft^2 (144 m^2). Retrofitting a new roof design costs \$1.36 per square foot. Sealing the attic with code level of closed cell foam (R_{US}-30 [R_{SI}-5.3]) costs \$3.86 per square foot. Total first costs are as follows:

	Repair 10% Leaky Ducts on 2-Ton Heat Pump	Installation of New Roof and Attic Design	Seal Attic
Initial cost	\$2600	\$2200	\$6300
Simple payback	25 years	25 years	16 years

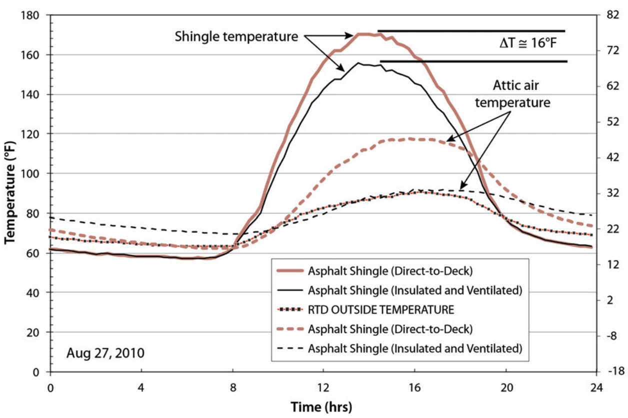


Figure 3 *Shingle and attic air temperatures for insulated and ventilated roof deck and direct-to-deck shingle roof.*

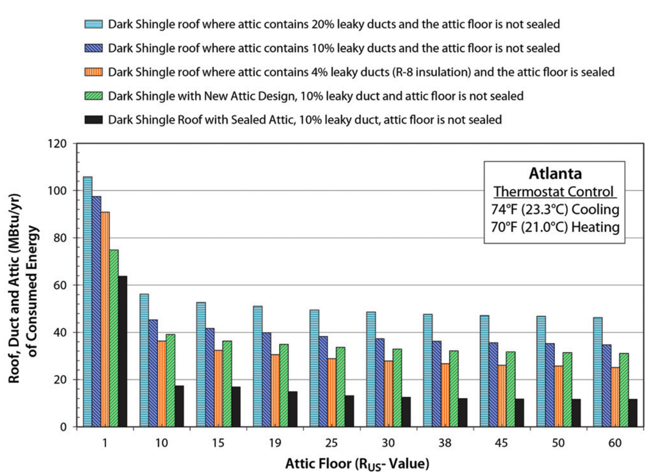


Figure 4 *Energy savings from retrofitting an insulated and ventilated roof deck onto an attic having leaky ducts and a poorly sealed attic floor. Results compared to sealed attic and to improving ducts and also removing ducts.*

The insulated and ventilated roof design is about \$400 less expensive than renovating the ducts and about \$4000 less than sealing the attic.

Converting Attics into Semi-conditioned Space. Sealing the roof deck and gables of an attic with spray polyurethane foam insulation (Figure 5) has gained popularity among many builders and code officials, especially in hot and very humid climates. Sealing recaptures the energy losses from a leaky air distribution system, which can cost \$240 in Miami and upwards of \$725 in Baltimore. The amount of applied foam should at least match the code requirements for the attic floor. Otherwise the system may actually increase heat flows into the conditioned space, especially if there are no ducts in the attic. In fact, the procedure should not be considered unless there is a leaky duct in the attic.

Sealing the attic and eliminating exterior vents is done to exclude moist outside air from the inside, but the sealing must be done properly or a dark attic can become a damp breeding ground for mold and mildew. The foam is sprayed between the roof rafters and over the gable ends of the attic to literally seal the attic from the outdoor ambient, as shown in Figure 5. However, this requires that the insulation be removed from the attic floor because the design makes the attic part of the conditioned space. The roof deck must be sealed to protect against moisture intrusion because the leaky duct will cause pressure imbalances between the attic and the conditioned space, especially if the air handler is in the attic.

Recent data collected from a test facility in Charleston, SC (Miller et al. 2013) revealed very interesting summertime trends in attic humidity for a sealed attic as compared to the conventionally ventilated attics. Asphalt shingles and a semi-permeable underlayment (15# felt paper) protected the OSB roof deck, and the attic was sealed by adhering open-cell spray foam to the deck's underside. Summer field data showed drops in relative humidity as the attic air warmed for all ventilated attics field tested by Miller

Figure 5 *Sealing the roof deck of an attic.*

et al. (2013). He observed that the larger the vent openings in the attic, the higher was the humidity content in the attic air, which peaks around 9 a.m. for the vented attics, as shown in Figure 6.

However, the opposite was true in the sealed attic. Peaks in measured relative humidity from two different sensors[5] in the sealed attic showed values in excess of 80%–90%, and occasionally saturated air (i.e., 100%) occurred around solar noon. In other words, the moisture content in the sealed attic was consistently 80%–100% rh from solar noon to around 6 p.m. for the seven contiguous days shown in Figure 6. Further, the trend was observed throughout the hot summer months.

The temperature and relative humidity data for the sealed attic and the indoor and outdoor ambient were converted to partial pressures to reveal the driving potentials for mass transfer in the sealed attic, as shown in Figure 7. The horizontal irradiance measured at the Charleston site is also included on a secondary *y*-axis of Figure 7. The partial pressure of attic air for the sealed attic lags the peak in solar irradiance by about 2 hours (view blue dashed line versus the black and orange lines in Figure 7). The high moisture content in the sealed attic does not come from the outdoor ambient or the indoor ambient because both have partial pressures during peak irradiance that are less than that observed in the sealed attic air, Figure 7.

Field measurements imply that some of the moisture from a previous rainstorm migrates to the underside of the shingles and underlayment. Irradiance drives moisture from an earlier rainstorm into and through the OSB deck and open-cell foam.[6] As a result, the partial pressure of the attic air and the partial pressure of water at the foam-to-attic air interface occasionally exceed the saturation pressure of water vapor in the attic air, Figure 7. If moisture is coming from the open-cell foam as driven by irradiance, then the partial pressure of water vapor at the foam-to-attic air interface would be higher than the partial pressure of water vapor in the attic, and Figure 7 data shows that this is indeed the case around solar noon. On these particularly hot days, relative humidity measurements showed super saturation (i.e., partial pressure of water vapor exceeded saturated pressure). At this condition, water vapor is in equilibrium with liquid water and therefore all interior attic surfaces are wet! Without a leaky duct, the sealed attic approach actually exacerbates humidity control in attics exposed in hot, humid climates. However, the presence of leaky ducts does not necessarily provide adequate protection from attic moisture. Colon (2011) field tested open-cell spray foam in a home in the hot muggy climate of south Florida. The roof deck was protected by an impermeable underlayment and the air-handler unit and ductwork were contained in the attic, yet moisture levels in the conditioned space increased above that measured *a priori* sealing the attic.

Prototype Sealed Attic Design

Implementing a single retrofit option (adding floor insulation) cannot compensate for the losses incurred by leaky ducts or for air leakage crossing the attic floor. Sealing an attic into a semi-conditioned zone makes good practical sense because the losses from the ducts are recaptured and used to make the attic a semi-conditioned space. The duct becomes part of the conditioned space and losses no longer predominate. These results and those for the insulated and ventilated roof deck have led us to envision another sealed attic design that uses less-expensive insulations and less labor, thereby improving both affordability and simple payback.

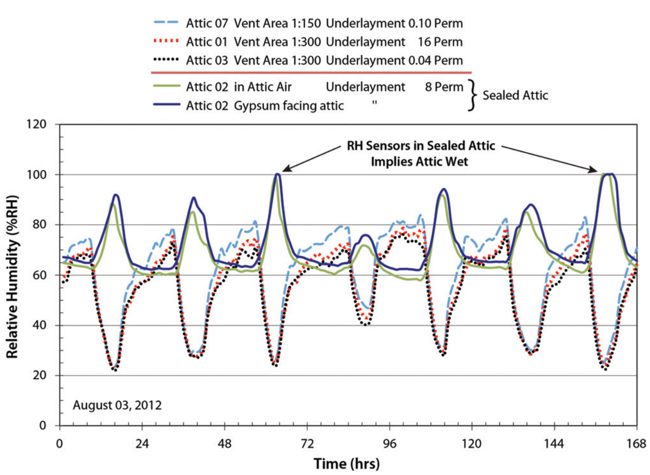


Figure 6 *Relative humidity measured in ventilated and sealed attics field tested in Charleston, SC.*

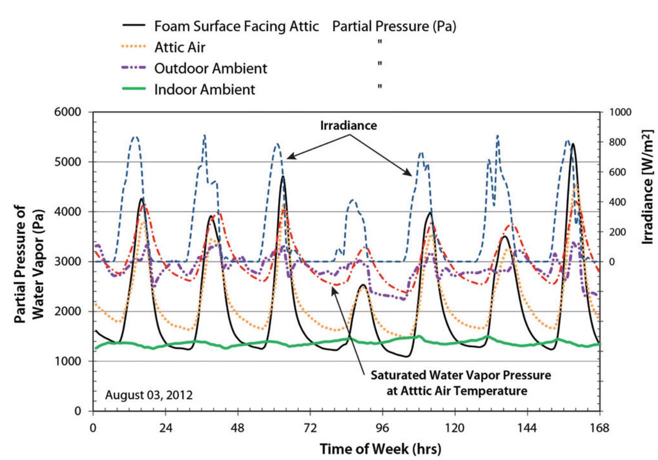


Figure 7 *Partial pressure of water vapor at various locations in and around the sealed attic.*

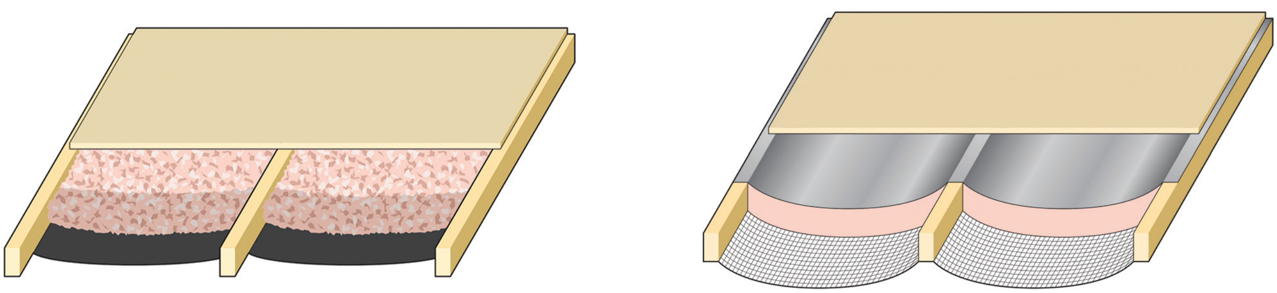
5. Relative humidity measured by thermoset polymer capacitive type sensor. Calibrations in controlled environmental chamber showed the sensor ±0.5 rh at 90% rh, and the sensor's output is fairly linear with increase in RH.

6. Personal communication with Joe Lstiburek of Building Science Corporation.

The prototype design is applicable to new and retrofit work and makes use of roof deck ventilation, which has not been tried in sealed attic assemblies. Blown fiberglass insulation is blown into a spacer fastened between rafters, as shown in Figure 8a. The black liner (Figure 8a) serves as a vent spacer and trough and as the sealing plane (air barrier) for the cathedral design; it is critical to the design. The blown fiberglass insulation is held in place by the black liner whose underside may also have a low-e foil facing into the attic for reducing the radiation heat transfer to the attic floor. The black liner could be either retrofit or new construction, whereas the depicted fiberglass blanket (Figure 8b) is for new construction where the silver lining serves as the air barrier and as a low-e surface and ventilation cavity. A key difference between an attic sealed with spray foam and the proposed sealed attic approach is the inclusion of the inclined air space fashioned between the sheathing and the fiberglass insulation. Heat and moisture driven by irradiance through the permeable felt paper and OSB roof deck will be carried away by free ventilation inside the inclined air space. Each adjacent pair of rafters serves as channels for free ventilation from soffit to ridge, and the inclined cavity is sealed by the spacer (black liner) much like drywall that seals the classical cathedral ceiling. For new construction the fiberglass could feasibly be blanket insulation with a foil facing the underside of the sheathing; it was assumed draped over rafters from the exterior and cut normal to each rafter or truss so that the blanket is not compressed by the sheathing. The R-value of the insulation (whether blanket or blown fiberglass) was preliminarily set at R-38 (i.e., two R-19 blankets). The gable ends of the home are also insulated with R-19 fiberglass blankets.

Computations for Austin, TX show that a conventional attic with R-30 insulation on the attic floor consumes about 3.96 kWh of power per square foot of attic footprint, as shown in Table 8. As compared to the conventional stick-built roof and attic, the proposed sealed roof design reduces energy consumption of the sealed attic from 3.96 kWh down to 2.85 kWh, a 28% reduction in Austin, TX. Including some minor repair to the ducts to drop leakage from 20% to 10% would boost energy savings to 50% of the conventionally built roof and attic.

A 26% energy reduction is estimated for Baltimore, MD; duct renovation increases the energy savings to 43%. For Minneapolis, MN a 22.5% drop in energy compared to the base is computed, and inclusion of some duct repair increases savings to 41% of the control. These results with inclusion of some duct repair exceed a 35% reduction compared to an attic built to IECC 2009 code. The duct repair is a compromise between complete repairs for best heat pump delivery performance and tolerating some leakage to support both the semi-conditioned space and the weather-induced and occupant-generated latent load potentially making its way into the attic.



a) Retrofit Practice

b) New Construction

Figure 8 *Retrofit and new construction making the attic a semi-conditioned space.*

Table 8. Energy Attributed to the Roof and Attic and to the Duct System in the Attic

City, State	IECC 2009 R-Value	Conventional[a] Ventilated[b] Attic	Sealed Attic Prototype R-38 Fiberglass Insulation and Spacer: Duck Leakage 20%	Sealed Attic Prototype R-38 Fiberglass Insulation and Spacer: Duct Leakage 10%	Conventional[a] Ventilated[b] Attic	Sealed Attic Prototype R-38 Fiberglass Insulation and Spacer: Duck Leakage 20%	Sealed Attic Prototype R-38 Fiberglass Insulation and Spacer: Duct Leakage 10%
		Electricity (kWh/ft^2)			Energy Cost (\$/ft^2)		
Austin, TX	30	3.96	2.85	1.98	0.511	0.367	0.255
Baltimore, MD	38	2.87	2.12	1.63	0.418	0.309	0.237
Minneapolis, MN	49	5.25	4.07	3.09	0.507	0.393	0.299

[a] Conventional attic equipped with soffit and ridge vents (1:300 area ratio).
[b] Conventional attic assumes IECC 2009 code insulation on attic floor. Duct with 20% leakage included in attic.

Cost and Simple Payback

For the same R-value, the material and labor charges for sealing an attic are about the same using closed-cell as compared to open-cell foam insulations (Faulkner 2010). Closed-cell insulation has a thermal resistance of about R_{US}-6 (R_{SI}-1.1), whereas open-cell polyurethane is lower at R_{US}-3.5 (R_{SI}-0.6). RS Means material charges for closed-cell foam and blanket insulation are listed in Table 9. The labor charge is based on data gleaned from various contractors and is less than RS Means; Means is based on organized labor rates. Contractor labor charges for foam, however, were comparable to RS Means.

The total cost for foam material and labor ranges from \$3.86 per square foot in Austin to \$6.3 per square foot in Minneapolis as applied to a 1550 ft^2 home with a 4:12 pitch. Table 9 costs for spray foam include R_{US}-10 (R_{SI}-1.74) of foam sprayed onto the gable walls each of 513 ft^2 (47.2 m^2). Initial material and labor cost for Austin is \$7900, and in Minneapolis to seal the roof to R_{US}-49 (R_{SI}-8.5) would cost about \$11,800. The application is very expensive and the proposed off-the-shelf materials (except for the spacer) can substantially reduce costs especially in the colder climates. The new sealed attic design costs about \$3900 for Austin, which includes duct repair. The repaired ducts have bladders installed on the supply and return to control air circulation to maintain the semi-conditioned space. The technique will also roughly set a minimal pressure drop across the attic floor to limit air and moisture movement across it. Simple payback for the proposed sealed attic with inclusion of duct renovation is 10 years in Austin to 12 years in Minneapolis. Note that the new design shows superior performance to the spray foam attic and is estimated to cost \$8000 less than the spray foam application for a footprint of 1550 ft^2 (144 m^2), Table 9.

NEW CONSTRUCTION

Figure 9 illustrates that new construction should always keep the ducts out of the attic. The black bars represent energy use for a roof and attic where the roof is dark and the attic has code level of insulation, but the attic contains an inspected duct with 4% leakage and is well insulated with R_{US}-8 (R_{SI}-1.4) insulation. The home's roof and attic total load is about 15 MBtu/year more than all other systems that do not contain ductwork in the attic. This translates to about \$100 to \$150 cost due to heat gains and losses in the conditioned air. So, comparing the attic containing inspected ducts with the newly designed insulated and ventilated roof deck (Table 10) will yield savings incurring simple paybacks as low as 5–10 years (Table 10). Material and labor assumed the added cost of the profiled and foil-faced EPS insert and the labor to install it.

But the key point of Figure 9 is seen by the prototypes against an attic containing no duct, the attic floor sealed, and with code level of insulation (Figure 9 blue bars with white cross hatching). Incremental savings are very small because a properly constructed roof and attic lose very little heat and there is not that much improvement for a new roof design. Hence for new construction, keep the ducts out of the attic, seal the attic floor, and add insulation to at least code level for the climate zone.

Assuming IECC 2012 code of R_{US}-38 (R_{SI}-6.7) and new housing starts at about 700,000,[7] new housing would save annually about 0.2 quads of energy. In comparison, a proactive roof maintenance program that retrofits sealed attics (Figure 4) in 50% of the existing homes would yield annual savings of 2 quads.

CONCLUSION

Building heat transfer gains and losses are low-grade energy; therefore, retrofitting a single component is not effective in substantially reducing energy use attributed to the roof and attic. For example, a radiant barrier foil or the addition of R_{US}-20 (R_{SI}-3.5) insulation to an attic with R_{US}-10 (R_{SI}-1.8) insulation saves about the same amount of money, but both

7. The U.S. Census Bureau and the Department of Housing and Urban Development jointly announced the following new residential construction statistics for April 2013.

Table 9. RS Means Material Costs for Closed-Cell Spray Foam and for Fiberglass Insulation[a]

	IECC 2009	Sealed Attic Costs, \$			Energy Savings,[b] \$	
		Spray Foam[c]	R-38 Fiberglass and Spacer[d]		R-38 Fiberglass and Spacer[d]	
			No Duct Repair	Duct Repair	No Duct Repair	Duct Repair
City, State	RUS Insulation	Material and Labor, \$/ft²			Attic Footprint of 1550 ft²	
Austin, TX	30	5.08	0.83	2.53	222	396
Baltimore, MD	38	6.16	0.83	2.53	169	280
Minneapolis, MN	49	7.65	0.83	2.53	177	323

[a] Cost of energy savings as compared to conventional roof and attic design. The attic contains 20% leaky ducts.
[b] Savings for sealed attic based on conventional roof and attic with IECC code insulation on floor.
[c] Spray foam costs based on R-value needed in roof rafters to meet IECC Code.
[d] Fiberglass blankets each R-19 in roof rafters plus R-19 on gable walls.
[e] Duct repair does not include new wrapped insulation. Repair assumes only leakage reduced from 20 to 10% of fan flow.

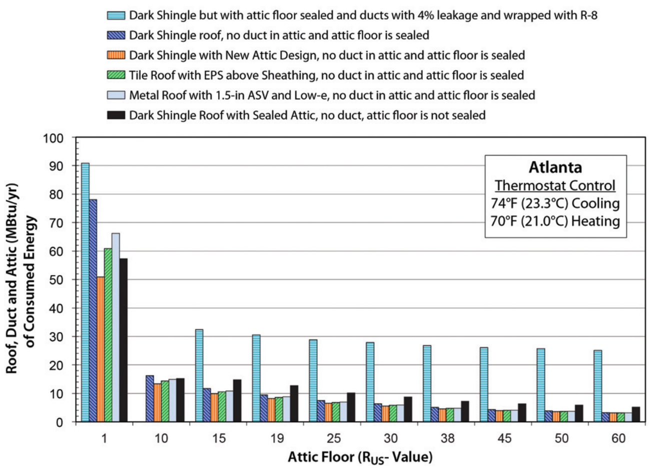


Figure 9 *New roof designs applied to new construction. Design described in Table 10.*

Table 10. Simulated Yearly Cost ($) of Energy Attributed to Roofs and Attics for New Homes as Compared to a IECC 2012 Compliant Home but with Inspected Ducts in the Attic

	New House[a] Compliant with IECC 2012	New Design 1[b]	New Design 2[b]	New Design 3[b]
Location	Roof and Attic Energy Cost	Annual Homeowner Savings from the New Designs Reducing Whole-House Energy Use		
Miami	100	80	70	80
Austin	190	140	130	135
Atlanta	170	115	110	115
Baltimore	860	760	750	750

[a]IECC-compliant home has ducts in attic. Ducts wrapped with R_{US}-8 (R_{SI}-1.4) insulation; duct leakage 4%.
[b]The new designs assume the duct system is in the conditioned space.

Design 1: Foil-faced 1 in. (0.0254 m) EPS insulation fitted between roof rafters; ventilation from soffit and attic to the inclined air space; radiant barrier in attic, two low-e surfaces in air space.
Design 2: Cool-color metal roof offset-mounted from roof deck 1½ in. (0.038 m); low-e surface in inclined air space covers non-breathable membrane; radiant barrier in attic.
Design 3: Peel-and-stick vapor barrier, 1¼ in. (0.032 m) EPS insulation above deck with high-profile tile; spray foam adhered EPS foam and tile to roof deck (no fasteners required).

retrofits have long payback periods. Savings for installing cool-color shingles (solar reflectance of 0.25 or 0.40) yields meager results if this is the only retrofit made to the house. Results show that a systems approach must be used to achieve a cost-effective repair of the roof and attic. Installing a ventilated and insulated roof deck with no other effective repair saves energy but does not compensate for the losses incurred by leaky ducts in an unconditioned attic.

The sealed attic approach and the insulated and ventilated roof assembly are very competitive to one another. Both approaches have paybacks ranging from 10 to 20 years with payback improving as the climate becomes more heating dominant. However, the attic moisture management reported herein led to a conceptual design that includes an inclined air space in the roof deck and controlled recirculation of air in the attic supply and return ducts. Simple payback for the prototype sealed attic design is about 10–12 years in hot and cold climates, and its initial cost is about half that spent for a conventional spray foam installation.

For new construction, the best option is to keep the ducts out of the attic, make sure the attic floor is sealed, and add at least code level of insulation to the ceiling. The advanced attic systems save some energy, but the total load attributed to the roof and attic is so low that the incremental savings are too low to be cost effective. However, even with inspected and sealed ducts having 4% leakage and wrapped in R_{US}-8 (R_{SI}-1.4), the homeowners pay about $100 to $150 more to comfort condition their home. In this scenario, a ventilated and insulated roof deck design with ducts not in the attic would yield simple payback in less than 10 years.

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