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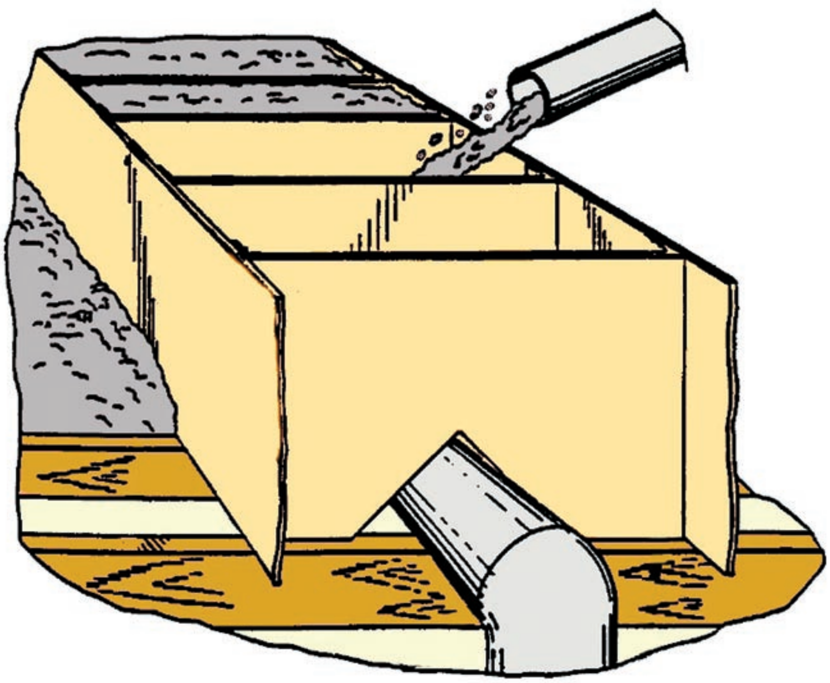
Duct Systems in Southwestern Homes: Problems and Opportunities

August 2004–August 2005



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U.S. Department of Energy
Energy Efficiency and Renewable Energy
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Building Technologies Program

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Preface

This report on duct systems in Southwestern homes is one in a series of technical briefs prepared by the Southwest Energy Efficiency Project (SWEEP) in support of the U.S. Department of Energy's Building America Program. Its intended audience is builders and design professionals interested in employing technologies that will reduce energy costs in both new and existing housing stock. Feedback from all readers on the form and content of this report is welcome. A companion report, "Policies and Programs for Saving Energy through Enhanced Duct Systems," is aimed at energy program policy makers, planners, and analysts. It includes information on energy and economic analyses associated with various levels of the penetration of energy-efficient distribution technology and associated policy options. Both reports are available for downloading at www.swenergy.org.

Nomenclature

ACCA	Air Conditioning Contractors of America
cfm	cubic feet per minute
CO	carbon dioxide
DOE	U.S. Department of Energy
FSEC	Florida Solar Energy Center
HVAC	heating, ventilation and air conditioning
NREL	National Renewable Energy Laboratory
PIER	Public Interest Energy Research
SWEEP	Southwest Energy Efficiency Project

Duct Systems in Southwestern Homes: Problems and Opportunities

Introduction

Ducts move air back and forth between air handlers and conditioned spaces in buildings. If they, and the HVAC system and building shell of which they are an integral part, are designed and adjusted properly, ducts can do a credible job of maintaining comfort in most spaces during most of the year somewhat efficiently. Ideally, ducts would

- suffer no convective or conductive losses,
- have minimal pressure drops save for those associated with effectively distributing air to a space,
- require only modest fan power to achieve good distribution responsive in each area of a dwelling,
- result in only tiny pressure differences between various conditioned areas and between conditioned spaces and the outside, and
- do their job with little noise and reasonable energy bills while requiring minimal maintenance to achieve long, healthy lifetimes of both the dwelling and those who live in it.

In the real world, such ideals are never achieved and only rarely approximated.

Spaces are occupied and used differently at different times of the day; doors are opened and shut; weather conditions (especially the sun) differentially heat and cool various areas of a home (ACCA 1995). A thermostat controlling a single-zone HVAC system with an air handler that runs at a constant speed cannot possibly achieve optimal temperature distribution in all areas of a modern multi-story home, even if other conditions are ideal. Ducts do leak, pressures and flows change with door openings and occupancy patterns, conductive and convective losses can be substantial when parts of distribution systems are outside of the conditioned envelope, and thermal gradients in conditioned spaces occur as a result of poor supply air terminal sizing and grill design. These problems are frequently acerbated by poor insulation, inefficient fenestration (windows and skylights), and a host of other factors. In short, ducts are part of larger systems in homes that influence comfort—but also create problems. Anticipating at least most of these problems can arm the designer and the installer (or retrofitter) with practical wisdom useful in achieving duct designs that work acceptably well most of the time.

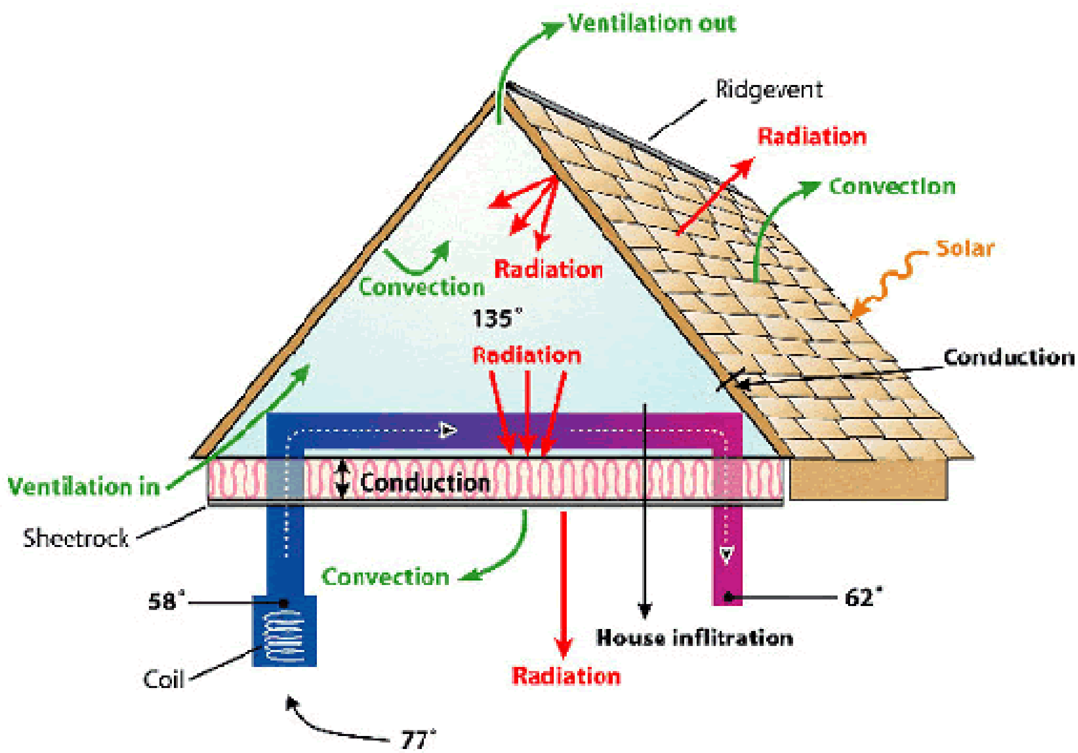
Research, analysis, and recommended practices in the duct area abound and much of it is quite useful. The reader is referred to a recent publication developed by the U.S. Department of Energy as part of the Building America Program, "Better Duct Systems for Home Heating and Cooling" (DOE 2004, Andrews 2003).

Given existing research, this report concentrates on duct-related circumstances in existing and new housing in the Southwest, in which ducts (and air handlers) are frequently located in attics where losses during the cooling season are substantial.

Ducts in Attics

Many homes in the Southwest are built without basements or crawl spaces; slab-on-grade structures abound. A favorite location for ducts is thus the attic, usually above the attic insulation. Most roofs that use conventional roofing material (asphalt shingles or tiles) tend to be very absorptive of solar energy. Accordingly, temperatures in roofs and the attics increase up to 140ºF during the cooling season, so ducts that pass through them are exposed to very hot conditions. If return air ducts in the attic leak, hot air might mix with conditioned air from the space below, thereby raising the temperature of the air that traverses the air-conditioning coil, requiring it to work harder to satisfy the thermostat. Conditioned air leaking into the attic from supply ducts does not get into the conditioned space where it could do some good. Further, leaks from supply ducts in the attic tend to depressurize the home, which causes wasteful infiltration of outside air into the home.

Conductive losses also lower the system efficiency of the HVAC system. A typical installation may have 300 ft^2 of supply duct surface area in the attic. Assuming duct R-values of 4, supply air of 50ºF on a hot afternoon with 140ºF attic temperatures, 6,750 Btus per hour are lost to the attic while the air handler is on, half that number if the R-value of the ducts is 8. Assuming a 2,000 ft^2 attic insulated to R-30, the conductive losses through the attic are smaller (by about 10%) than those through the R-4 supply ducts. Indeed, even when the air handler is off, substantial losses owing to the ducts in the attic still occur. Figure 1 shows patterns of energy flows affecting duct performance in attics.



Source: Danny Parker, Florida Solar Energy Center

Figure 1. Energy flows in attics

Given this state of affairs, a number of responses are possible, individually or in combination:

- **Air seal** the ducts, both supply and return, whether new or retrofit.
- **Insulate** the ducts better than they are conventionally insulated. Two techniques are discussed below, suitable for both new and retrofit.
- **Lower attic temperatures** thereby diminishing the consequences of convective and conductive duct losses. Two strategies are in current use, one which works on the top of the attic ceiling, the other on its bottom. The rooftop can be made cooler by raising the reflectivity of the roof in the solar spectrum or raising the roof's emissivity, preferably both. The first keeps the roof from absorbing as much solar heat as do conventional non-reflecting roofs; the second enhances its ability to re-radiate heat to the sky. Often, the incremental cost for this "cool roof" option approaches zero with new installations or when a roof must be replaced (Parker et al. 2004). A second strategy, dubbed "cathedralizing," requires insulating immediately under the roof rather than at the attic floor. This allows the area of the attic where the ducts are run to become a buffer zone whose temperature approaches that of the conditioned space below. This option is practical only for new construction.
- **Move ducts within attics** to where they are not exposed to severe environments. Several styles of "plenum trusses" have been developed that allow ducts to be installed in the attic floor with insulation on top of them.
- **Move ducts out of attics**. One approach is to install ducts in the space immediately below the attic ceiling in hallways where ceiling heights of 7 ft are not likely to be objectionable. Another places the air handler in a centrally located equipment closet in the home and uses quite short ducts for both supplies and returns.
- **Get rid of ducts largely or altogether.** Because this report is on the subject of ducts, this option is merely mentioned in the interest of completeness. We envision energy-efficient homes that use radiant heating ***and cooling*** systems, circulating conditioned water in slabs or even sidewalls and ceilings. Large cross-sectional areas of radiant surfaces enable achieving good performance via supply water whose temperature is at only a few degrees different from desired space temperatures. This is particularly important with radiant cooling systems because it is critical to keep supply temperatures above the dew point. Low-temperature hydronic heating may be delivered quite efficiently and cost effectively via tankless water heaters or simple solar systems. Hydronic cooling in much of the Southwest may be achieved via nighttime radiant systems such as those developed by the Davis Energy Group (see www.davisenergy.com under "alternatives to compressor cooling") or simple evaporative cooling systems. Zomeworks' Double Play Cool Cell™ system achieves both cooling and heating using sun and sky (www.zomeworks.com).

In all cases, ducts can be reduced to only those used for ventilation, ideally through heat recovery ventilation.

Energy-Savings Techniques

Air sealing ducts makes sense in all cases except when leakage is so small as to be not cost effective to bother with. However, there are advantages and disadvantages, costs and benefits associated with each of the other approaches (insulating, relocating ducts, etc.); they are discussed in the following sections of this report.

Air Sealing

Air sealing ducts is a good idea whether ducts are wholly within the envelope, partially outside (e.g., attics), or have some runs in areas such as unconditioned crawl spaces or basements where losses from supply ducts may be partially recovered. Of course, it is particularly critical to air seal supply and return duct runs that are outside the conditioned envelope. Leaks in returns in attics can directly lower the efficiency and effectiveness of the HVAC by lowering supply air temperature in the winter and raising it in summer. Return leaks in basements or crawlspaces can also contribute to back-drafting combustion appliances and pulling into the home soil gases that may contain radon, essence of lawn fertilizer, pesticides, and other undesirable substances. Leaks in supply ducts lower the amount of conditioned air delivered where desired and also cause infiltration of exterior air because spaces connected to return ducts are driven to be under negative pressure with respect to the outside. Negative pressure of the inside of a home with respect to the outside leads directly to forced infiltration of outside air—summer and winter.

Sealing ducts during construction is the easiest time to get things right because they are easily accessible. A number of tactics for retrofit sealing have also been developed and analyzed (Andrews 2003; Parker et al.1993; Modera et al. 1996; Treidler et al. 1996, Sherman et al. 2000).

Leakage can occur anywhere, but frequently leakage occurs at joints, whether metal to metal (Figure 2), duct board to duct board (Figure 3), or when a plastic flex duct is fastened to a metal collar. Duct tape should never be used because it does not seal well and has a very short lifetime (Sherman et al. 2000). High-quality, UL-Listed duct mastics have been developed that work well, install quickly, clean up easily, are environmentally benign, and have very long lifetimes. Mastic can be put on by hand, brush, or trowel. If openings are larger than ¼-in., fiberglass mesh should be laid down on a bed of freshly-applied mastic followed by an outer coating of mastic. The process goes quickly, so to enhance production, most practitioners work by the rule, "if it looks like a crack, seal it." This is particularly applicable when dealing with returns that "pan" across joists, creating a virtual, albeit leaky, duct. This is a notoriously bad duct design feature that nonetheless is found all too frequently in older homes and is still employed in some new ones. The best tactic is to detach the panning, seal all sides of the "return" completely (imbedding fiberglass in the mastic as appropriate), lay down a bead of mastic over the edges of the joists, reinstall the panning over the mastic, then touch up any remaining holes on the outside (Figure 4).

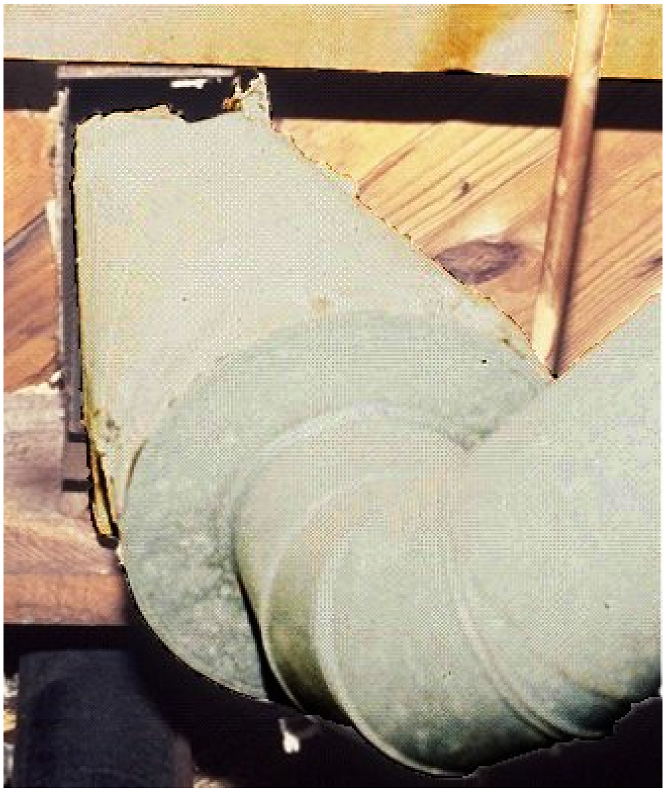


Figure 2. Ducts disconnected from boots are surprisingly common. Mastic with imbedded fiberglass results in a strong, long-lasting repair.

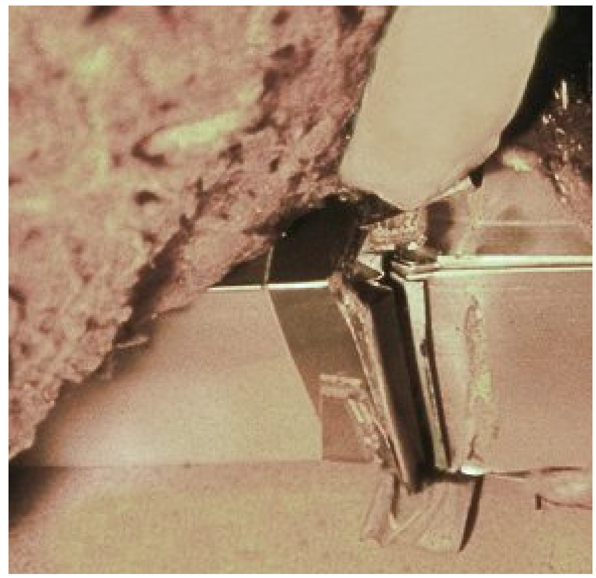


Figure 3. Failed duct tape on this joint under attic insulation could have gone undetected for the life of the home.

Figure 4. Panned duct repair needs to be thorough, though not necessarily aesthetically pleasing.

Source: Pedalino, 2005

Figure 5. This is what a weatherization crew found on a job in Phoenix. The air handler was mounted on a platform in an unconditioned garage. The platform served as the return air plenum for the home.

Figure 6. The results of repairs to the situation in Figure 5. The crew was able to achieve a 50% reduction in duct leakage.

Figures 5 and 6 depict the successful results on a weatherization program in Phoenix, where a crew found and sealed a very large return-air leaks close to an air handler in a garage. The platform served as the return air plenum for the home. The weatherization crew achieved 832 cfm, 50% reduction in duct leakage on this job, which was roughly 80% of the total flow of the air handler. Initial pressure pan leakage totaled 56.8 pascals; the final measurement was 0.9 Pa. In addition to energy savings, comfort and indoor air quality were also improved dramatically.

Aeroseal

A unique approach to duct sealing was invented by Mark Modera of the Lawrence Berkeley National Laboratory. Called "Aeroseal,™" the technique involves producing a fog of sealant particles and using that fog to pressurize a duct system when the grilles are temporarily blocked off. By maintaining appropriate particle sizes, duct air-flow rates, and duct pressures, the particles are transported to the leaks with very little deposition on the walls of the ducts (Figure 7). Because of the acceleration of the air and particles at the leaks, the particles tend to leave the air stream and impact on the edges of the leaks and then upon the previously deposited sticky particles. As holes are filled by the process, flow from the injecting fan is impeded and pressure in the ducts increases. Adjustments are made to optimize flow and pressure as the sealing process progresses, and a laptop computer is employed to monitor relevant parameters, calculate sealing achieved, and provide information useful in deciding when to stop. Every sealing job produces a minute-by-minute graph of the leakage during the process, all of which are uploaded to a central database at Aeroseal headquarters for archival storage and performance analysis.

Figure 7. This shows the latest generation of "SmartSeal" Aeroseal equipment (left) and pictures joints sealed by the process. The injector heats the sealant solution (right) to the optimal level to form an aerosol, which is blown into ducts to accomplish sealing.

Preparing for an Aeroseal treatment entails finding and sealing holes larger than 0.5 to 1.0 in. across, temporarily blocking the grilles, and isolating the fan and heat exchanger from the sealant. Given the need to isolate the air handler, the sealing process is accomplished on supply and return ducts separately. The time required for the sealing process is a function of the initial leakage level. In existing homes with construction like that in the Southwest, the average injection time has been 1 to 1.5 hours for the supply and return; however, in markets with rectangular sheet metal ductwork average injection times are 2 to 3 times as long.

In February 2005, Aeroseal began shipping new equipment that demonstrated a factor of 5 reduction in injection times in the field. Using the first-generation equipment, set up and clean up have typically required several hours, depending on circumstances, resulting in one or two systems being sealed per day in existing homes and three to four new systems per day in the California market (where construction is similar to that in much of the Southwest). A pilot program on 350 light commercial rooftop systems demonstrated sealing rates of two to five rooftop packaged systems per day for one crew.

Retrofits tend to be more complicated than sealing in new homes, but the Aeroseal technique has the advantage of sealing ducts in inaccessible areas. If a whole group of new homes can be treated in a production manner, there are economies of scale both because marketing is a one-time affair for a number of homes, and technicians can work much more efficiently in unoccupied homes that are close to one another. Accordingly, costs can be as low as $400 per air-seal job for new homes. For retrofit work that entails both a sales process and more extensive testing and set-up time, costs typically run from $900 to $1800 (Modera 2005, Lubbers 2005). Duct leakage of 600 cubic feet per minute (cfm) at 25 pascals can frequently be reduced by 90% using the Aeroseal technique, realizing annual savings of $200 to $300 per year in many locations. The company's web site includes a number of details on the process, including videos, as well as the results of case studies in a variety of climate zones (www.aeroseal.com).

Aeroseal was bought by the Carrier Corporation, which formed a limited-liability corporation, Carrier Aeroseal, LLC, to further develop and market the duct-sealing concept. As of the present writing, the spring of 2005, ducts in more than 12,000 homes in the United States and Canada have been sealed using the process. There are 51 certified Aeroseal contractors in the United States (eight in the Southwest; they are listed in Appendix A), and Carrier's existing distributors will soon become involved in the business. In addition, with the introduction of the new injection technology, the process is now available for commercial ducts systems, both new and retrofit. (The new injection technology was used to seal a 75,000-ft^2 building, demonstrating a sealing rate 5-10 times faster than the generation-one equipment.) Presently, there is a homebuilder in central California who routinely has ducts sealed by an Aeroseal contractor on all new homes, and several other production builders are considering adopting the technology in some of their market areas.

Estimating Savings Associated With Air Leakage

When a blower door is used to estimate air leakage rates in homes, it creates circumstances that may not normally be experienced during heating or cooling system operation. When a home is depressurized, typically there is a single pressure difference between all parts of the inside of the envelope with respect to the outside, and every hole (except the opening where the blower is installed) becomes an infiltration hole. By analogy, when a Duct Blaster™ (or Aeroseal fan) is used to pressurize a duct system, all of the registers are sealed, and all of the ducts are brought to close to a common pressure with respect to the rest of the dwelling, typically 25 pascals with a Duct Blaster. Yet under operating conditions, pressures within ducts tend to vary inversely with distance from the air handler as well as a host of other variables reflective of the geometry of plenums and pick offs, damper settings, etc. Accordingly, holes in the far end of a system tend to leak less than holes of the same size and geometry close to the fan where pressures are highest. In consequence, just as estimating annual energy savings based on lowered flow rates of a blower door at a constant pressure as a result of air sealing is subject to substantial errors, estimating savings from lowered flow rates at a constant pressure with a Duct Blaster or similar technique is similarly error prone.

A number of building scientists are at work developing techniques for more accurately estimating the consequences of duct leakage under operating pressures and estimating actual duct efficiency based on field measurements. For example, a team from Ecotope has examined three methods for quantifying leakage-related duct efficiencies that hold promise for aiding the understanding of what circumstances of ducts merit which kinds of remediation that is cost effective (Kruse et al. 2004).

In an attempt to estimate energy saved by air sealing ducts in the Southwest, we elected to employ Energy 10, an hourly simulation tool, which allows for specifying percent supply duct leakage both inside the envelope and to the outside, as well as percent return leakage to the outside, under normal operating circumstances. Table 1 shows the results of an Energy 10 simulation of air leakage losses of typical 1500-ft^2 homes in six cities in the Southwest. Each home shown is identical save for changes in patterns of duct leakage. The ***base case*** assumes 20% supply leakage to the outside, 10% supply leakage to the inside, and 20% return leakage in from the outside. The ***better case*** assumes 10% supply leakage to the outside, 5% supply leakage to the inside, and 20% return leakage from the outside. The ***best case*** assumes 2%

supply leakage to the outside, 2 % supply leakage to the inside, and 2% return leakage from the outside. Data shown are duct-related energy consumption and consequent annual costs.

Table 1. Simulations of Three Scenarios of Duct Air Leakage in Six Cities in the Southwest

City	Case	Cooling season duct loss (kWh/yr)	Duct-leakage-related fan energy (kWh/yr)	Heating-season duct loss (therms/yr)	Duct-related cost for cooling and fan ($/yr)	Duct-related cost for heating ($/yr)	Duct-related annual cost heating and cooling ($/yr)
Albuquerque	Base	835	511	333	$112	$330	$441
Albuquerque	Better	356	208	131	$47	$130	$177
Albuquerque	Best	69	41	22	$9	$22	$31
Cheyenne	Base	237	786	699	$66	$657	$723
Cheyenne	Better	102	306	272	$27	$256	$282
Cheyenne	Best	20	55	46	$6	$43	$49
Denver	Base	479	697	573	$76	$527	$604
Denver	Better	204	272	222	$31	$204	$235
Denver	Best	40	49	37	$8	$34	$42
Las Vegas	Base	2,665	568	131	$291	$139	$430
Las Vegas	Better	1,111	237	52	$121	$55	$177
Las Vegas	Best	198	46	9	$22	$10	$32
Phoenix	Base	3,665	645	61	$319	$80	$399
Phoenix	Better	1,547	274	25	$135	$32	$167
Phoenix	Best	277	54	4	$24	$6	$30
Salt Lake City	Base	817	737	577	$103	$572	$674
Salt Lake City	Better	342	286	221	$41	$219	$260
Salt Lake City	Best	62	51	37	$7	$37	$44

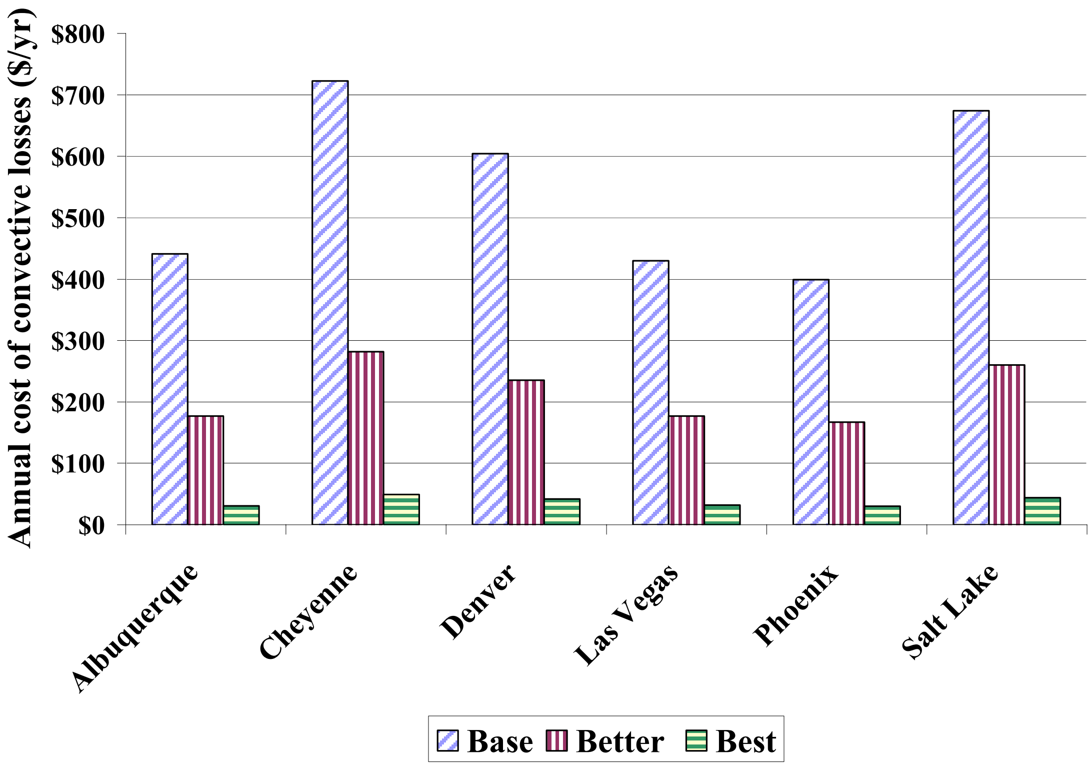


Figure 8. Annual costs at three levels of air leakiness in the six Southwestern homes.

Many homes in the Southwest have ducts that leak than the base case, and quite a few ducts are as tight as the best case. However, the numbers suggest the magnitude of savings possible by careful duct sealing. In spite of lower fuel costs, Cheyenne, with its cold winter, shows the best savings because of good duct sealing of almost $650 over base. However, even in hot Phoenix, savings over base are $370 per year.

Figure 8 shows estimates from the simulation of the annual costs associated at three levels of air leakiness in the six Southwestern homes.

Mobile Homes: A Special Case

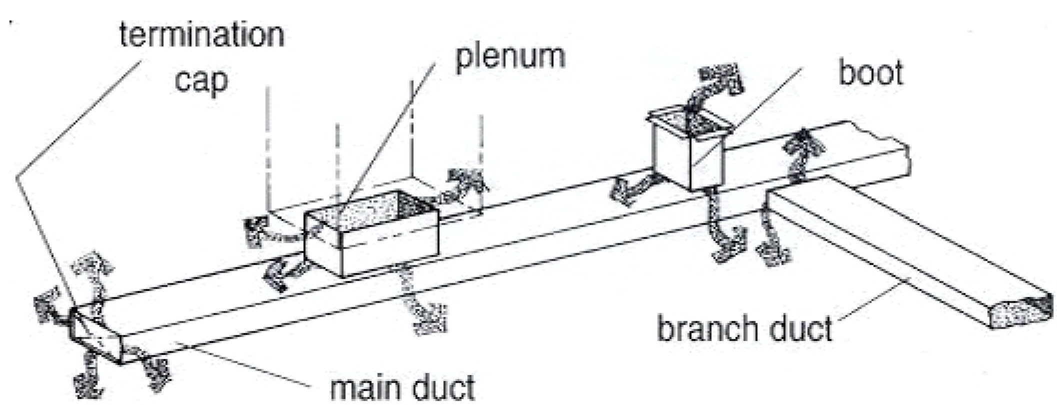
Mobile home ducts are notoriously poorly constructed. This, in combination with the bumpy road from the factory to the mobile home park and subsequent setting up, frequently yields homes with substantial duct leakage. This is particularly true of double-wide homes, which require installing a large, insulated flex duct between the two halves of the home to connect supply plenums.

The trick is to be able to test a mobile home for duct leakage problems, decide if it is worthwhile to air seal, develop a strategy for air sealing, and execute it effectively. Bruce Manclark of Delta T is an old hand in dealing with mobile home ducts and finds that somewhere between 85% and 90% of the homes tested can be cost effectively retrofitted (Manclark 2005).

The initial test involves setting up a duct blaster at the return of the furnace, temporarily sealing supply registers with sticky-back plastic, and pressurizing the system to 50 pascals. At the same time, a blower door is used to pressurize the home and is adjusted to maintain the home at zero pressure difference between inside and out. Under these conditions, flow through the duct blaster in cubic feet per minute (cfm) represents the flow from the ducts to the outside of the home at 50 pascals. If this number is more than 10% of the square footage of the home, it is considered a good candidate for leakage reduction, and the job is immediately undertaken. The aim is to reduce the leakage to the outside (using the methodology of measurement described above) by half. Indeed, this much reduction is a necessary condition for contractors to get paid. In practice, air sealing is routinely even more successful, averaging 65% (Manclark 2005). Figure 9 shows areas where leakage in mobile homes is frequently found.

The juncture between the furnace and the supply plenum is frequently the most important area to treat; pressures and temperatures are at their maximum at this juncture and leakage is usually substantial. Typically, crews temporarily remove the electric resistance heater coil or burner unit and "dive in." If this is not practical, the work must be accomplished from below. The usual tactic is to find leakage areas by means of hands, lights, and mirrors. Then holes are repaired with a combination of aluminum valley flashing fastened with screws and high-quality mastic.

Repairs are also frequently required where the boot is connected to the main duct and interfaces with a sleeve that accepts the grille in the floor. In these cases, repairs are usually made with mastic and fiberglass. In about 5% of homes, there are also leaks at the ends of the main duct, just after the last boot. In these cases, the cure is to secure sheet metal between the duct and subfloor with screws, followed by mastic. Finally, crossover ducts between halves of double-wide units are routinely inspected and sealed; in about 20% of cases they are replaced, being careful to keep them off the ground.



Source: Saturn Resource Management, Inc.

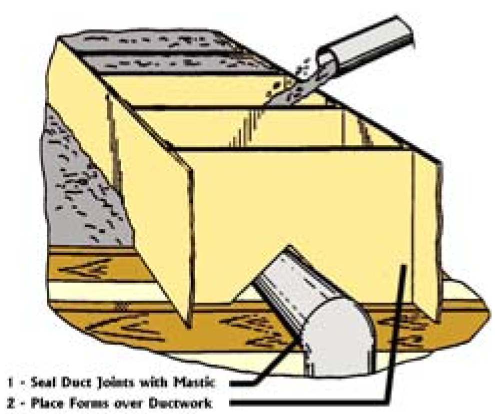
Figure 9. Areas in supply ducts on mobile homes where leaks are frequently found. This graphic is from a detailed specification for the Energy Trust duct-sealing program developed by John Krigger of Saturn Resource Management.

Insulation

The most frequently employed insulation for ducts in attics in new homes in the Southwest is flex duct with a rated R-value of 4. Upgrading to an R-value of 8 has an incremental cost to install that is small, given that labor is effectively identical, and is quite cost effective.

A Building America Program team of researchers from Steven Winter Associates has recently examined the consequences of using cellulose or fiberglass to bury ducts in attics that run close to attic floors. Using three techniques, they discovered in field measurements undertaken in a hot dry climate in northern California that a simple UAΔT technique can be used to estimate conductive duct losses, which are very substantially curtailed as insulation values become large (Griffith et al. 2004). Cellulose was found to be more effective than fiberglass, and importantly, no moisture problems were observed at duct surfaces during extended cooling periods because dew points were never reached.

As a practical matter, the process of burying ducts to achieve R-30 insulation entails blowing a lot of loose-fill insulation, substantially more than is likely to be cost effective in attics in most climate zones. What is more, it is hard to keep it close to the ducts. A solution to the problem is a product whose development was also co-sponsored by U.S. Department of Energy (DOE), "The Ultimate R." Ultimate R consists of some simply engineered cardboard (or other structural material) shapes that form bottomless and topless containers around ducts, allowing cellulose to be blown into the containers without waste—constraining it to the immediate vicinity of the duct runs (Figure 10). Coincidentally, several insulation manufacturers also produce structural (matt or board) forms that could be used to contain loose fill insulation in ways similar to the Ultimate R approach. Installing Ultimate R in new housing with 2,000-ft^2 attics takes on the order of an hour of labor, after which the attic is blown with cellulose, being careful to fill up the Ultimate R containers. Retrofitting attics with Ultimate R is also practical under many circumstances, but time required is extended to several hours because of the need to add time for air sealing the ducts before insulating them.



Source: U.S. DOE

Figure 10. The Ultimate R containment system. Joints are sealed with mastic, forms are placed over the ducts and simply stapled to one another to achieve mechanical stability. Then the forms are filled with insulation ("as easy as 1, 2, 3,"—mastic seal, structural form, insulation fill—says Ultimate R). The system can accommodate a wide range of duct shapes and sizes.

Costs for a typical installation of an Ultimate R system in an attic with 100 feet of supply duct and 30 feet of return in the attic run about $200 for the Ultimate R material, $80 for added cellulose over that required for the attic itself, and $40 incremental cost for semi-skilled labor. Thus, the total cost is about $320 (Crall 2005).

Table 2 shows the results of an analysis of conductive losses in attics of typical homes in six homes in the Southwest. Each has 100 ft^2 of surface area on the return ducts in the attic and 200 ft^2 on the supply ducts in the attic.

Table 2. Conductive Duct Losses and Costs Associated with Ducts in Attics in Six Cities in the Southwest for R-4, R-8, and R-30 Insulating Levels

City	Duct R value	Cooling season duct loss at 2.5 cop (kWh/yr)	Heating season duct loss at 75% HVAC system efficiency (therms/yr)	Annual costs as a result of conductive duct losses ($/yr)	Savings over R-4 ($/yr)
Albuquerque	4	126	106	$115	-
Albuquerque	8	63	53	$58	$58
Albuquerque	30	17	14	$15	$100
Cheyenne	4	24	162	$153	-
Cheyenne	8	12	81	$77	$77
Cheyenne	30	3	22	$20	$133
Denver	4	68	137	$131	-
Denver	8	34	68	$66	$66
Denver	30	9	18	$17	$114
Las Vegas	4	493	59	$107	-
Las Vegas	8	247	30	$54	$54
Las Vegas	30	66	8	$14	$93
Phoenix	4	622	38	$96	-
Phoenix	8	311	19	$48	$48
Phoenix	30	83	5	$13	$83
Salt Lake City	4	113	133	$139	-
Salt Lake City	8	57	66	$69	$69
Salt Lake City	30	15	18	$18	$120

The best summer savings are associated with the hottest climate, Phoenix, where moving from R-4 to R-30 ducts saves 539 kWh per cooling season, and annual savings are $83. In Cheyenne, where heating season savings opportunities predominate, 140 therms of gas per year can be saved by moving from R-4 ducts in the attic to Ultimate R at R-30. Annual dollar savings in Cheyenne are $133, so paybacks for both new and retrofit insulation work are quite short, on the order of 3 to 4 years. Annual dollar savings range from $83 in Phoenix to $133 in Cheyenne, meaning that this measure is cost effective throughout the region.

Figure 11 shows costs savings opportunities graphically. If air sealing is accomplished in addition to lowering conductive losses, savings are increased in proportion to leakage elimination.

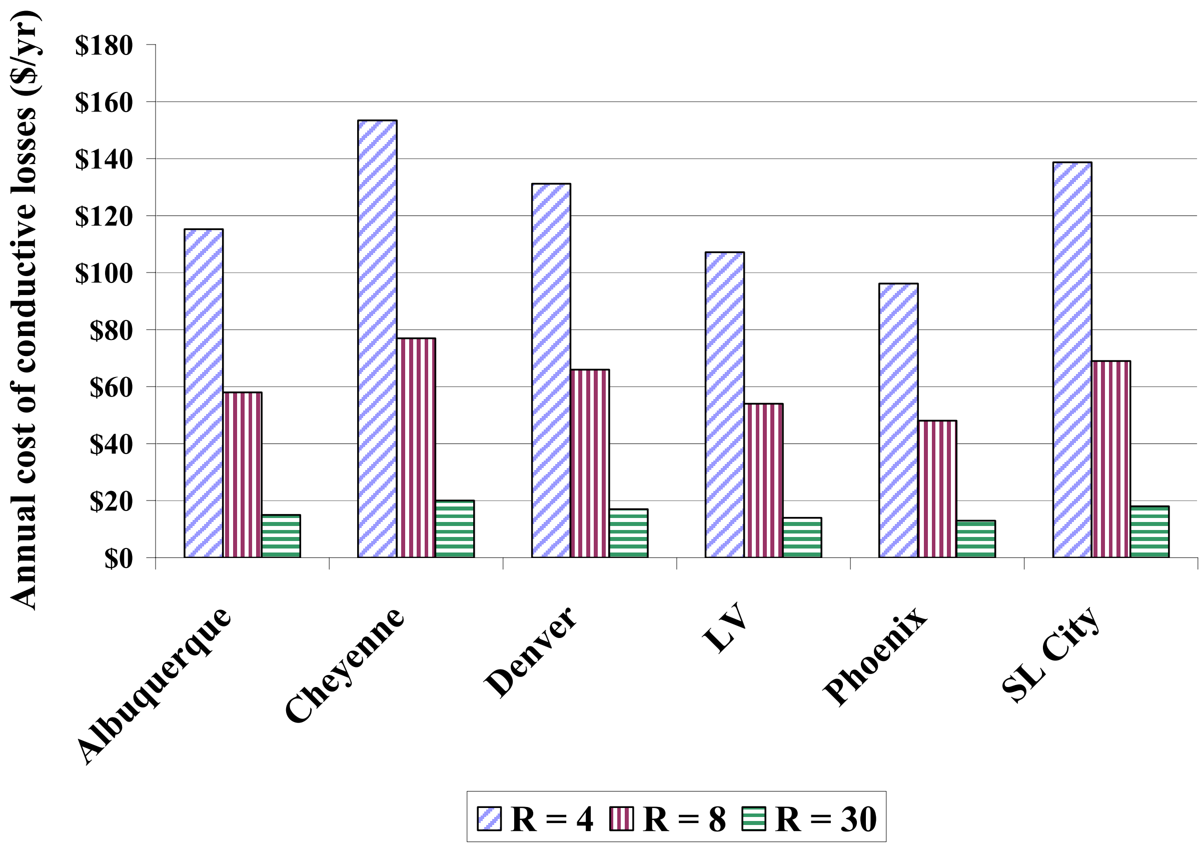


Figure 11. Annual costs resulting from conductive losses of ducts in attics at three levels of insulation in six Southwestern cities.

Lower Attic Temperatures

Danny Parker and his colleagues at the Florida Solar Energy Center (FSEC) have conducted careful research on techniques for lowering attic temperatures. Findings in Florida's hot humid climate are directly relevant to savings opportunities in the Southwest. They involve choosing roofing material with a combination of high reflectivity across the solar spectrum (which tends to keep heat from being absorbed or transmitted) and high emissivity (which tends to radiate heat back to the sky). Appropriate choices of roofing material translates into less flux (radiant heat) being transmitted into attics, ducts, and the living spaces below. A recent paper (Parker et al. 2004) reported on the results from the side-by-side evaluation of a range of roof types using highly instrumented test cells. The material tested, relevant energy-related properties, and savings versus a base case of a conventional roof with dark shingles over a vented attic are shown in Table 3.

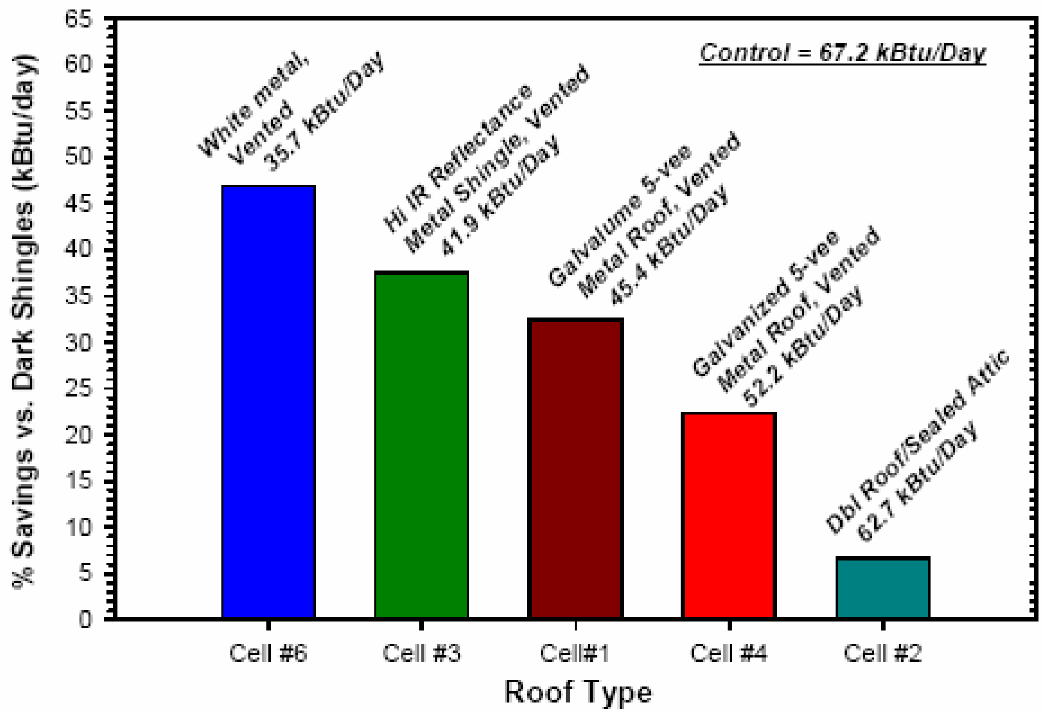
Table 3. Roof Materials, Configuration, and Cooling Energy Performance in Central Florida

Roof type and venting configuration	Solar reflectance (%)	Long-wave emittance	Roof-related savings versus control (%)	Total cooling energy savings versus control (%)
White metal standing-seam, vented attic	67.6	0.83	47	15
High IR, reflective-ivory metal-shingle, vented attic	42.8	0.83	38	12
Galvalume® unfinished 5-vee metal, vented attic	64.6	0.28	32	11
Galvanized 5-vee metal roof, vented attic	70.9	0.04	22	7
Double roof, black shingle, sealed attic	2.7	0.9	7	2
Black shingle, vented attic (control)	2.7	0.9	0	0

Source: Parker et al, 2004

The white standing-seam metal roof showed the best performance, which is also reflected in lowest attic temperature. Although the Galvalume roof has slightly better solar reflectivity, its lower emissivity results in this system being ranked third. The relative cooling savings of the more efficient roof systems would be amplified in direct function of the cross-sectional area of ducts in the attic, particularly if they are leaky or poorly insulated. Peak demand savings are also likely to be more than overall energy savings because of cooler roofs. Of course, the combination of cooler attics with air sealed and well-insulated ducts achieves the best performance. Figure 12 shows the ranking of roofs in the FSEC study along with daily energy use.

In addition to this recent work with various metal roofs, the FSEC team has also examined tile roofs. Findings are similar, with white tile that is both highly reflective and highly emissive yielding the best performance. In sum, white shingles, terra cotta tile, and sealed attic construction produce energy savings of 200 - 600 kWh/yr and demand reductions of 0.05 - 0.5 kW in Florida's climate; similar results can be expected in the desert Southwest. Highly reflective roof systems produce energy savings of 1,000 - 1,600 kWh with demand reductions of 0.8 - 1.0 kW (Parker and Sherwin 1998).

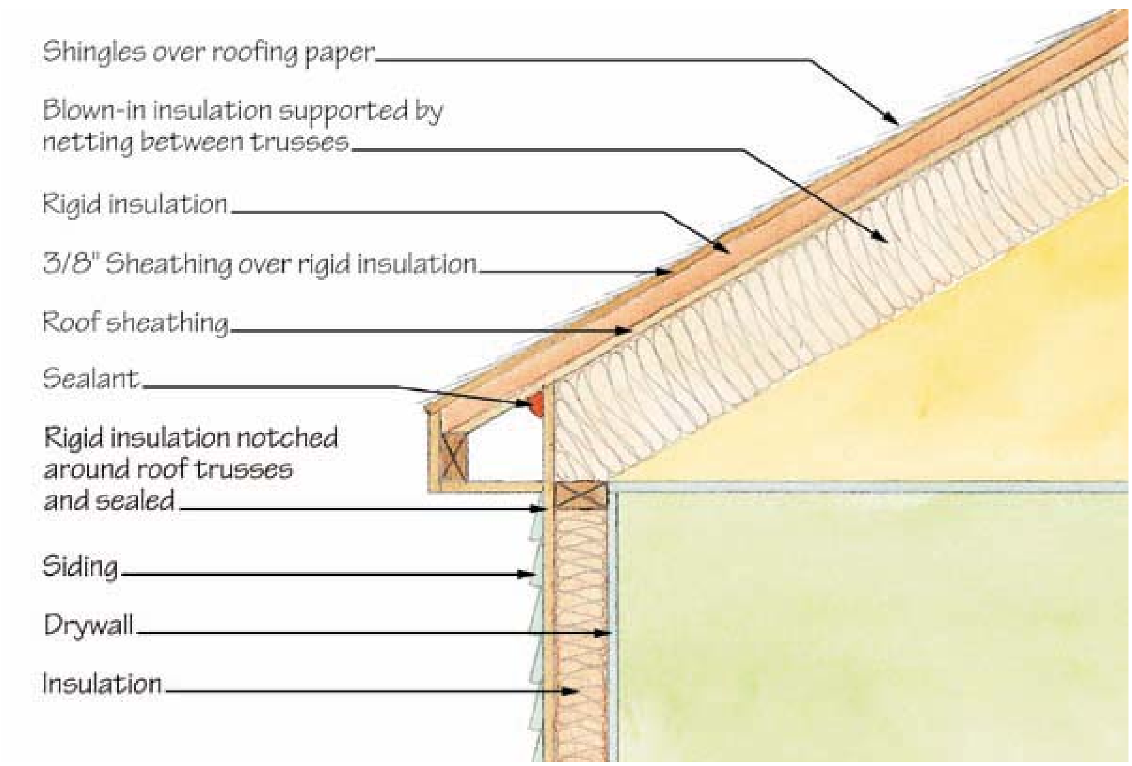


Source: Parker et al, 2004

Figure 12. Daily energy use and savings percentage over the control roof

Cathedralized Ceiling

One way to cool attics is to insulate at the roof deck instead of the attic floor. This makes the attic itself a kind of buffer zone between the fully conditioned envelope and the outside. The resulting lowered attic temperatures make the attic a more congenial environment for the ducts (and air handler, if applicable). Of course, cathedralizing the attic requires keeping the attic itself unvented, and effectively, the volume of the home's conditioned envelope becomes larger. Figure 13 illustrates the technique.



Source: New Buildings Institute; Gard Analytics

Figure 13. The cathedralized ceiling technique

A team from the National Renewal Energy Laboratory (NREL) conducted a study of this approach, which included both simulations and field measurements (Hendron et al. 2003). Field tests with side-by-side homes in Las Vegas, Nevada, one using the cathedralized approach, the other with a conventional-vented attic and attic floor insulation, suggested that there is little overall savings achieved by the cathedralized approach, except when ducts are not well sealed. When the attic is partially conditioned, the penalty for leaks is less than the case in which the attic is hotter, which more than makes up for the larger overall loss from the thermally larger home. Savings of up to 11% were observed with equivalently leaky ducts in both of the homes in the side-by-side test, but when air sealed, differences approached zero.

In summary, the cathedralized attic approach has both advantages and disadvantages. On the plus side, ducts are operated in a less severe environment, and costs for installing vents are zero. Some sloppiness in air sealing ducts is possible without paying much of an energy penalty. In addition, homeowners have access to a storage area that neither runs too hot in the summer nor too cold the winter. On the other hand, it is more complicated (and a bit more expensive for both labor and material) to install insulation at the attic ceiling and do it without thermal losses (Figure 14). The envelope is larger, so conductive and convective losses are larger. Generally if conventional roofing materials are employed, the roof deck itself runs hotter in the summer, which may translate into a shorter lifetime. Finally, if a gas-fired furnace is installed in the unvented attic, it must be closed combustion. Although this raises initial costs, in general, we regard this as an advantage because wintertime gas consumption and heating costs will be lower for the lifetime of the dwelling.

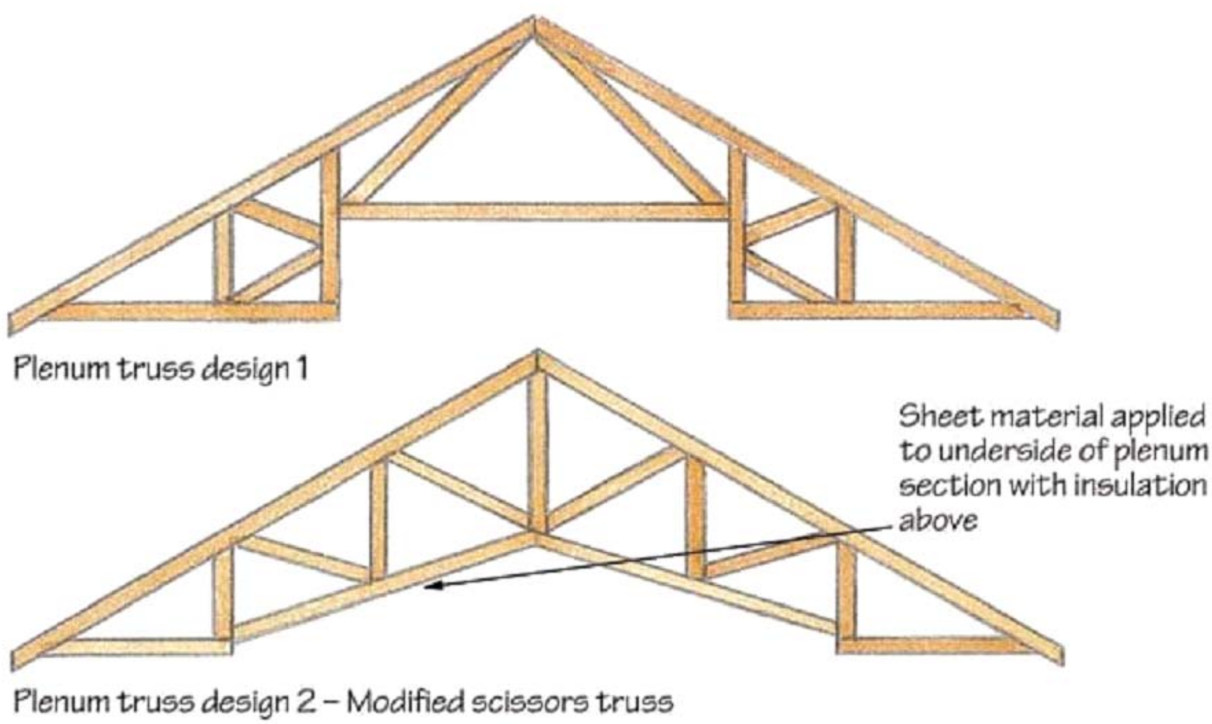
Source: Pulte Homes

Figure 14. Netting is stapled between rafters then the space between the netting and the roof deck is blown tightly with cellulose. Working around framing members is complicated, and the rafters contribute to thermal bridging.

Move Ducts in Attics Under Insulation (Plenum Truss)

It is possible to design trusses in attics that are structurally sound while leaving clear spaces in the attic floor. If the combination of the truss and duct designs are clever, ducts may be run close to the attic floor, below the attic insulation. In practice wood sheets (typically oriented strand board or ½-in. inch plywood) are nailed to the bottom of the trusses and air sealed with urethane foam. This allows insulation to be installed over the area of the trusses along the centerline of the home. The insulation is installed above these boards while the remainder of the attic is insulated in conventional ways (Figure 15). The net effect is that the ducts are operated in a partially conditioned space that is physically and thermally close to the fully conditioned envelope below. Further, the volume of the partially conditioned space occupied by the ducts is substantially smaller than with the cathedralized approach, and the insulation job is substantially simpler and easier to achieve. In addition, the attic can be ventilated, so the roof runs cooler in the summer.

The downside to the plenum truss design is that the trusses themselves are unlike standard building practice—so take some getting used to—and duct runs all have to be within easy reach of the centerline of the home.



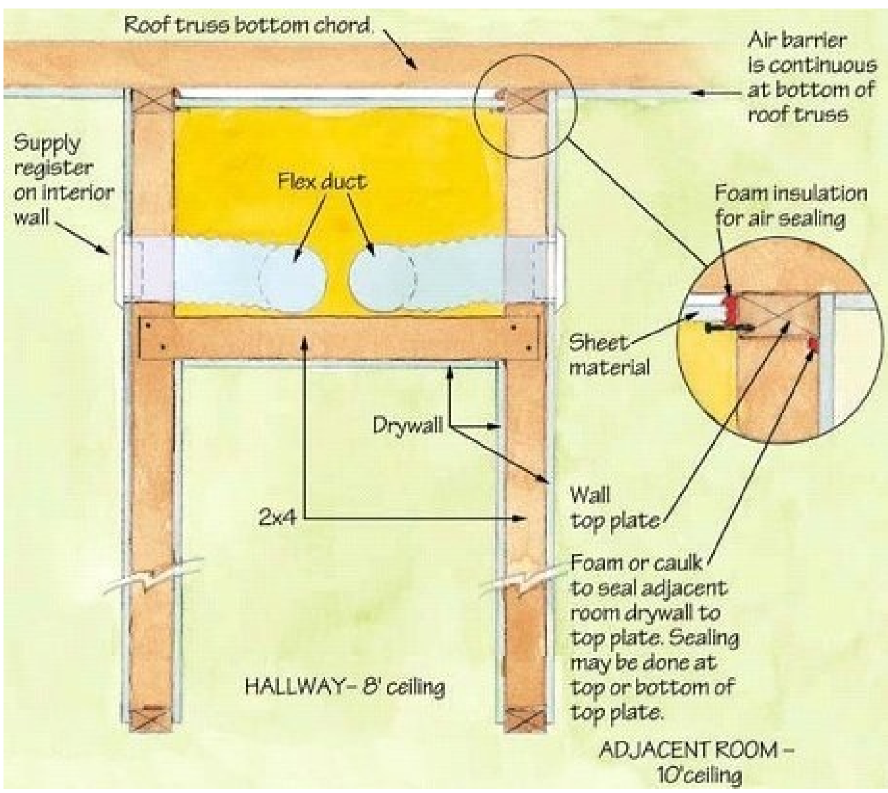
Source: New Buildings Institute; Gard Analytics

Figure 15. Two approaches to truss design to accommodate duct runs under insulation

Move Ducts out of Attics

If ducts can be moved only slightly outside of attics, substantial efficiencies in energy distribution can happen—and attics themselves can be air sealed, insulated, and simplified. A promising technique is called the "dropped ceiling" approach. It involves using about a foot to a foot-and-a-half of ceiling space, mostly in hallways, as passageways to run ducts. This allows ducts to be completely within the conditioned space, so are exposed to much less severe environmental conditions than is the case in the attic—yet they remain largely out of the way.

Home designs with higher than 8-ft ceilings favor this approach, which is illustrated in Figures 16 and 17.



Source: New Buildings Institute; Gard Analytics

Figure 16. Illustration of dropped ceiling approach. Air sealing the duct passageway is important to avoid air flow into the attic and minimize losses

Source: Janet McIlvaine, FSEC

Figure 17. Duct chase installed in an 8-foot hallway. Note finished system is just above door trim.

Each of these approaches to handling duct problems has merit and drawbacks. Getting ducts out of attics is certainly an advantage, but like many other elements of energy-efficient building, the devil is in the details. A useful document for builders contemplating adopting one or another of these approaches was prepared by Gard Analytics and the New Buildings Institute under California's Public Interest Energy Research (PIER), *Building Homes with Ducts in Conditioned Spaces: A Guide for Builders* (Hedrick 2003).

Pressure Differences

A Thanksgiving Story

Imagine a two-story home with well-designed ducts and fairly tight duct work within the insulated envelope. A single large return is located in the family room of the home on the first floor, which is open to the rest of the first floor and the main stairway to the second. The homeowners have recently had a contractor air seal and insulate their home, which has resulted in better comfort than they have experienced before and lower bills for space conditioning. The contractor checked for duct leakage, found it minimal, and decided not to include any duct-related work in the retrofit.

There are a dozen people at the dinner table on Thanksgiving Day. Family and friends enjoy a sumptuous meal, adequate drink, and animated conversations around the fireplace, which, though not used for most of the winter, contributes additional cheer for the festive day. When leftovers are put away and the weary family trundles off to bed, the fire is still burning, so the damper cannot be closed. Bedroom doors are all closed.

As the flame in the fireplace gives way to smoldering embers, both the home and the chimney cool down. In the wee hours, the thermostat calls for heat. When the 1200-cfm air handler in the furnace comes on, the main part of the home experiences strong negative pressures and the bedrooms strongly positive pressures, both because of good air sealing and because there is no pressure relief from the bedrooms to the rest of the home when doors are closed. The negative pressure pulls air down the cooled chimney where it passes over the smoldering embers, which are now producing a good deal of carbon monoxide. The CO-laden air is swept through the return air system and heat exchanger of the furnace and directed through supply ducts into bedrooms, where it enters the lungs of the sleeping revelers. When they awake the next morning (indeed, *if* they awake the next morning), their headaches are not merely the result of overeating or drinking.

The Solution

There are a number of ways to prevent such unhealthy and potentially calamitous circumstances, only a few of which are genuinely elegant. It is always possible to leave homes (or ducts) leaky, open bedroom windows, or leave bedroom doors open. The first two options waste energy, and the third is inconsistent with privacy. Installing air-tight doors on the front of the chimney is a good idea and may resolve the CO problem, but not the pressure differential issue, which will tend to cause infiltration problem in the main portions of the home and exfiltration problems in the bedrooms. The latter are potentially more serious because moisture-bearing warm air will tend to flow into the structure of the walls, where moisture may be released as the air is cooled below dew point, a circumstance that can cause major structural damage. Finally, not solving the pressure problem will lower the flow of conditioned air through the ducts supplying bedrooms with closed doors. Accordingly, the rooms may be uncomfortably cool in the winter and hot in the summer. Adjusting the thermostat in the main part of the house to help alleviate the problem will result in overheating the main portion of the home in winter (and overcooling it in summer), with consequent energy waste.

Solutions for the pressure difference problem include designing each space to have a dedicated return air duct, "jump ducts," transfer grilles, undercutting doors, or a new approach described below, "The deKieffer Bypass."

Dedicated return air ducts and associated runs back to the air handler can achieve good pressure balance and air flow, but only if they are designed carefully and adjusted well at commissioning. Greater cross sectional area of ducts increases the likelihood of wasteful leakage (both convective and conductive), particularly if a portion of the ducts are in unconditioned spaces. Initial costs for material and labor are high with respect to other solutions. Generally, this option is practical only for new homes.

Jump ducts are used in many new homes in the Southwest. These are generally short lengths of 12 to 18 in. diameter flex ducts in the shape of a U that connect a grille in the ceiling of a hallway to a grille in the ceiling of an adjacent bedroom. If designed and installed correctly, they are effective at relieving pressure differences and are somewhat effective in muting sonic transfer. However, because they usually traverse the insulation in an attic, they amount to 5 to 10 ft^2 of surface area that is within R-4 of attic temperatures. This causes energy losses in all seasons (on the order of 200 Btus per hour per jump duct on hot summer days) and discomfort in the winter (because air cooled within the jump ducts descends.) Of course, using higher levels of insulation would help, but this technique is already expensive and labor intensive.

Transfer grilles relieve pressure differences between a space with supply ducts and one that is connected to a return duct. In simplest form, a rectangular hole of half a square foot in cross section is cut in the wall between framing members, typically between a bedroom and the adjacent hallway. A fixed grill is installed on both sides of the wall. The hole is usually placed fairly high on the wall or over a doorway. In addition to air flow, the hole permits easy transmission of both light and sound. Offsetting the grill on the bedroom side from that on the hallway side can go some way towards safeguarding privacy, but this solution to pressure relief is still not very satisfactory aesthetically. However it is inexpensive and consistent with both new and retrofit work.

Return Air Pathways (RAP™) are enhanced transfer grilles manufactured by Tamarack Technologies, Inc (www.tamtech.com). These include a specially engineered baffle between a pair of grilles that limits both light and sound transfer, thereby providing air flow with greater privacy than is possible with conventional transfer grills. Some pressure drop across the system is the inevitable result of the RAP baffle, but the company claims that a foot-square system will allow 69 cfm of air flow back to the return while allowing a pressure difference of only 2.5 pascals, an acceptably low number.

Undercutting doors is also an inexpensive and fast solution to the problem, but when several inches must be removed to ensure adequate pressure relief, the door itself is aesthetically compromised and most homeowners find this solution offensive.

The deKieffer Bypass is a recent invention by Rob deKieffer, principal of the Boulder Design Alliance. As shown in Figure 18, it utilizes the space immediately above the framing members of a door to provide an area for air flow while preserving aesthetics and substantial privacy. The design uses offset trim to provide a gap that is generally unnoticeable, yet the air path is sufficiently curved—and far from the floor—that both sonic and light transfer are minimal.

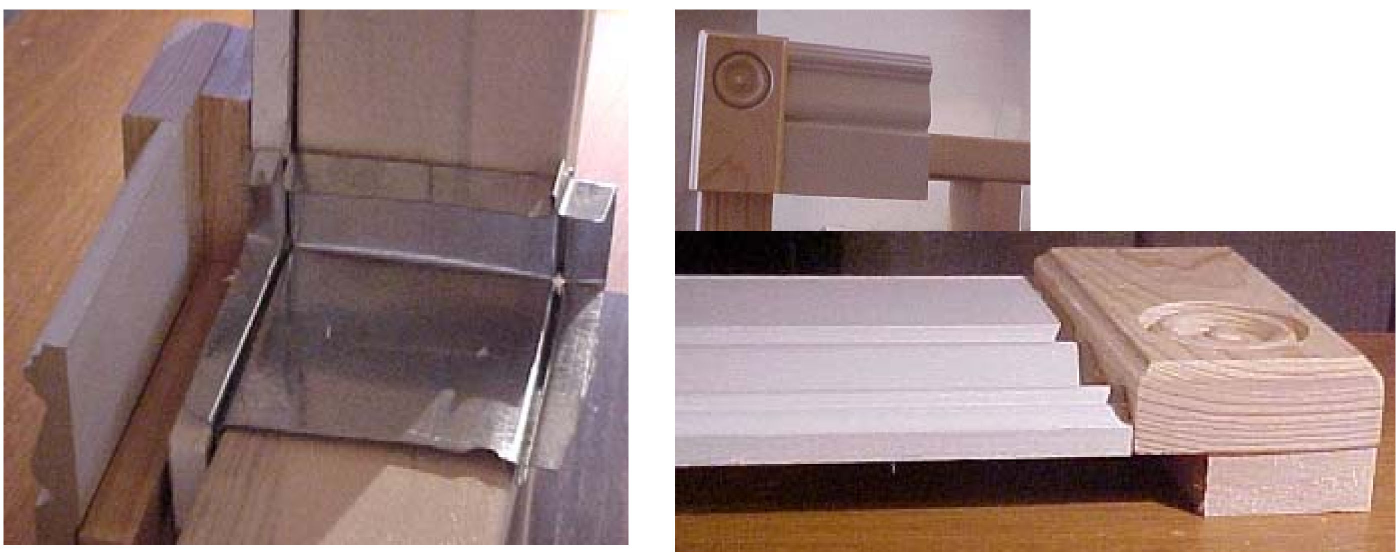


Figure 18. The deKieffer Bypass uses the space between an interior door's header and the beginning of drywall above the door which starts at the height of the trim. The trim on top of the doorway is offset to allow flow. A sheet metal scoop attaches to the drywall on both sides of the opening to provide integrity.

The deKieffer Bypass is being used on several models of energy-efficient homes being built by McStain, a production builder in the Boulder area of Colorado and is under consideration for inclusion in Pulte homes in the Midwest (deKieffer 2004).

Conclusions

Distribution systems—ducts and air handlers—should be sealed wherever they are. Keeping ducts within the conditioned envelope is highly desirable from the energy point of view. Ideally, they should be connected to an air handler toward the middle of the conditioned envelope where they are exposed to environmental conditions that are least deleterious to good efficiency. This allows for both supply and return runs to be short and simplifies the process of balancing flows and pressures. Mechanical rooms can be sonically insulated from living space, and the use of closed-combustion equipment improves overall efficiency and simplifies stack and ventilation requirements and associated installation costs.

It is a good idea in the Southwest to keep attics as cool as practical, especially if ducts run through them. Working from the outside in is optimal, beginning with natural sources of shading such as trees and incorporating cool roof technology. Air sealing and super insulating ducts in attics is good practice and can usually be achieved in retrofit as well as new applications. Techniques for providing special spaces for ducts within attic spaces that are close to indoor air temperatures are meritorious if they don't cause other mechanical or energy problems and the spaces are relatively small.

In retrofitting homes, it is always important to include an analysis and repair of duct systems if needed, particularly if the retrofit work includes air sealing of the envelope. To take the case of HVAC systems in basements, if air leaks in return ducts outstrip those of the supply system (the case in roughly 60% of homes in the United States), there is increased risk of pulling in radon and other substances and in backdrafting hot water heaters or even the furnace itself. Health and safety considerations are primary, of course, but air sealing and balancing the distribution system also enhances its performance, both in comfort achieved and overall efficiency. Insulating ducts that are outside of the envelope—particularly if they are in the attic—is almost always a cost-effective retrofit.

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Appendix A

Aeroseal Contractors in the Southwest

The contractors listed below supply Aeroseal services in the Southwest as of April 2005. They are listed alphabetically by state. New contractors are added frequently. An updated list of contractors (including those in other states) is available at http://www.aeroseal.com/locatedealer.asp

Aeroseal of Arizona
3830 East Indian School Road
Phoenix, AZ 85018
Phone 602.956.9799

Consolidated Mechanical
3802 East Miami Street
Phoenix, AZ 85040
Phone: 602.437.0066
www.consolidated-mechanical.com

Hamstra Heating & Cooling
2035 East 17th Street
Tucson, AZ 85719
Phone: 520.629.9833

Aeroseal of the Rockies
12340 Mead Way
Littleton, CO 80125
Phone: 303.991.SEAL(7325)
www.barrettbarnes.com

Air Flow Solutions
7650 W. 120th Ave.
Broomfield, CO 80020
Phone: 303.635.1010
www.air-flow-solutions.com

Cal Air
5730 Oleta Avenue
Las Vegas, NV 89139
Phone: 702.361.7453

Quality A/C Service, Inc.
3141 Westwood Drive
Las Vegas, NV 89109
Phone: 702.731.1617
www.quality-air.com

Rentmeister & Co.
1956 W. 2250 South
Syracuse, UT 84075
Phone: 801.773.6900
www.rentmeister.com

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

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July 2005	Subcontractor Report	August 2004 - August 2005

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	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) L. Kinney	**5d. PROJECT NUMBER** NREL/SR-550-38068
	5e. TASK NUMBER BET5.8004
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Southwest Energy Efficiency Project 2260 Baseline Rd., Suite 212 Boulder, CO 80302	**8. PERFORMING ORGANIZATION REPORT NUMBER** ADO-3-33469-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	**10. SPONSOR/MONITOR'S ACRONYM(S)** NREL/TP-550-38068
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

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14. ABSTRACT *(Maximum 200 Words)*
Distribution systems should be sealed wherever they are. Keep ducts within the conditioned envelope. Ducts should be connected to an air handler toward the middle of the conditioned envelope. Mechanical rooms can be sonically insulated from living space; use closed-combustion equipment. Air sealing and super insulating ducts in attics is good practice and can usually be achieved in retrofit as well as new applications. In retrofitting, include an analysis and repair of duct systems if needed, particularly if the retrofit work includes air sealing of the envelope. In basements, air leaks in return ducts outstrip those of the supply system (the case in roughly 60% of homes in the United States). There is increased risk of pulling in radon and other substances and in backdrafting hot water heaters or even the furnace itself. Health and safety considerations are primary, of course, but air sealing and balancing the distribution system also enhances its performance, both in comfort achieved and overall efficiency. Insulating ducts that are outside of the envelope—particularly if they are in the attic—is almost always a cost-effective retrofit.

15. SUBJECT TERMS
duct systems, Building America, U.S. Department of Energy, energy efficient homes, air sealing, retrofitting ducts

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Robert Hammon • ConSol • 7407 Tam O'Shanter Drive #200 • Stockton, CA 95210-3370 • 209-473-5000 • fax: 209-474-0817 • e-mail: Rob@consol.ws • **www.bira.ws**

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Davis Energy Group
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