Retrofitting Residential HVAC Systems

In this case study, we show how DOE's Best Practices Guide For Residential HVAC Retrofits *works—as well as some of the installation practice and building code official problems that can arise.*

by Jennifer A. McWilliams and Iain S. Walker

Traditionally, retrofits are done in a piecemeal fashion; individual building components are replaced one at a time, with little thought given to their interactions. This is particularly true for HVAC systems, whose performance can be negatively affected by changes in the building envelope. The systems approach, which attempts to treat the whole building and all of its components together, is a good solution to this problem, and has three major benefits:

- correct system sizing when loads (such as envelope conduction, window solar gain, and infiltration) are reduced by retrofits,
- avoidance of potential problems (such as increased condensation potential when air conditioning is added to previously uncooled houses), and
- total cost can be reduced. The cost of a retrofit using the systems approach is often less than the sum total of the individual retrofits.

Because the current retrofit industry is not structured to use the systems approach, the DOE *Best Practices Guide For Residential HVAC Retrofits* was developed to provide guidance for contractors. In order to simplify the decision-making process, the guide includes preselected packages of changes to the building HVAC system and building envelope that are designed to remove some of the guesswork for builders, contractors, installers, or homeowners about how

LBNL

It's important to seal cavities connecting the house to the attic. Foam was used for sealing small holes and cracks at building component intersections.

Table 1. Recommended Retrofits for Hot-Dry, Mixed-Dry, and Marine Climates

Intervention Level	HVAC System Only	HVAC System Plus Envelope
1	Ducts sealed (leakage decreased to <10% of air handler flow). Ducts outside conditioned space insulated to R-8. Correct refrigerant charge.	Ducts sealed (leakage decreased to <10% of air handler flow). Ducts outside conditioned space insulated to R-8. Correct refrigerant charge. Ducts sealed and buried in added ceiling insulation. New downsized ducts and HVAC equipment. The ducts are installed to minimize the flow resistance, i.e. correct length, good routing, and preferably sheet metal construction.
2	Ducts sealed (leakage decreased to <10% of air handler flow). Ducts outside conditioned space insulated to R-8. Correct refrigerant charge. Added economizer.	Ducts sealed (leakage decreased to <10% of air handler flow). Ducts outside conditioned space insulated to R-8. Correct refrigerant charge. Ducts sealed and buried in added ceiling insulation. New downsized ducts and HVAC equipment. The ducts are installed to minimize the flow resistance, i.e. correct length, good routing, and preferably sheet metal construction. Added economizer.
3	Ducts sealed (leakage decreased to <10% of air handler flow). Ducts outside conditioned space insulated to R-8. Correct refrigerant charge. Added economizer.	Ducts sealed (leakage decreased to <10% of air handler flow). Ducts outside conditioned space insulated to R-8. Correct refrigerant charge. Ducts sealed and buried in added ceiling insulation. New downsized ducts and HVAC equipment. The ducts are installed to minimize the flow resistance, i.e. correct length, good routing, and preferably sheet metal construction. Higher solar reflectance roof. More window shading (or windows with lower SHGC).

best to carry out HVAC changes. The different packages are climate and house construction dependent, and include recommendations regarding materials, procedures, and equipment.

The packages are not meant to be rigid requirements—rather, they are systems engineering guidelines that form the basis for energy-efficient retrofits. The packages are presented at three different levels of intervention, depending on the scope of the retrofit being considered, and for "HVAC only" and "HVAC plus building envelope" scenarios. This approach gives the user considerable flexibility in applying the guidelines. This can be particularly useful, if not make it possible to undertake a given potential retrofit. (Table 1 summarizes potential retrofit packages for three broad climate types.)

A similar systems engineering approach has been used in new construction to develop extremely energy-efficient homes that are comfortable, safe, and durable, and that often cost less than standard construction. The Building America program (www.eere.energy.gov/buildings/building_america/) exemplifies this approach. But the differences between retrofit and new construction tend to limit the changes that one can make to a building, so the *Best Practices Guide For Residential HVAC Retrofits* packages rely on relatively simple and non-intrusive technologies and techniques. The retrofits also focus on changes to a building that will give many years of service to the occupants.

LBNL

Duct board insulation was used to block off large open areas.

Another key aspect of these best practices is the need to know how a house is working in order to find out what parts can be improved. The guide includes a set of diagnostic tools combining physical measurements with checklists and questionnaires. The measured test results, observations, and homeowner's answers to the questions pinpoint the best retrofits applicable for each individual house. The suggested retrofits will depend on the current condition of the building envelope and HVAC system, the local climate, the materials and construction methods used for the house, and the presence of various energy saving systems (such as a heat recovery ventilator).

Occupants Know Best

The importance of addressing any issues raised by the occupants cannot be overstated. Homeowners often cite improved comfort and visual appearance as reasons for retrofitting or renovating homes. These factors are almost always more important than simple payback related to energy savings. On the homeowner questionnaire, occupants can also report problems (such as drafts, high bills, condensation, and mold) and important lifestyle activities that can significantly change building loads and the times when the house needs to be conditioned. Here are some typical questions that should be asked, and that are included in the best practices guide:

How many people live in the house? The more occupants there are, the more chances for excessive humidity and other IAQ problems there are likely to be.

Are there any pets? Like human occupants, pets are a source of moisture and odors. Fish tanks are a source of humidity—particularly if they are large and/or uncovered. Exotic pets may have particular temperature and humidity requirements that make for unusual building loads. Pets may also restrict the use of set-back or setup programmable thermostats.

Are there high energy bills? High energy bills can be a good indicator of HVAC system problems, and the potential to perform envelope upgrades makes more financial sense if there is the potential to save a lot of money. The best practices guide includes references to DOE's Home Energy Saver (www.homeenergysaver.lbl.gov) and the Energy Star Home Improvement Toolbox (http://208.254.22.7/index.cfm?c=home_improvement.hm_improvement_index), to assist in evaluating energy bills.

Table 2. Comparison of Pre-Retrofit Diagnostics and Screening Results for Four California Houses and Four Cold-Climate Houses

Location	Supply Duct Leakage, % of Air Handler Flow	Return Duct Leakage, % of Air Handler Flow	Air Handler Fan Flow, (CFM)	Refrigerant Charge Assessment	Envelope Leakage, (in^2)	Ceiling Insulation (R-Value)
Concord, CA	12	33	805	Undercharged	278	26
Moraga*,CA	22/14	10/n/a	970/540	Both overcharged	335	17
Castro Valley, CA	9	5	1,160	Undercharged	269	25
Larkspur, CA	10	17	1,215	Correct	340	Inaccessible
Arlington, MA	8	25	927	Too cold to test	244	30
Marlborough*, MA	36/31	13/37	515/791	Too cold to test	261	24
Northfield, MN	17	43	1,071	Too cold to test	100	30
Plymouth, MN	8	25	927	Too cold to test	244	30

* Houses had 2 systems

Diagnostics and Screening Results from Eight Test Houses

The guideline diagnostics and checklists were applied to eight houses in three regions of the United States. Two houses were in a heating-dominated coastal climate (Boston, Massachusetts); two houses were in a heating-dominated inland climate (Minneapolis, Minnesota); and four houses were in a hot-dry/mixed-dry climate (different municipalities in Northern California). The houses represented a range of construction methods, HVAC system types and locations, construction materials, foundation types, as well as HVAC system performance. (Some of the key results are summarized in Table 2.)

Retrofit Case Study

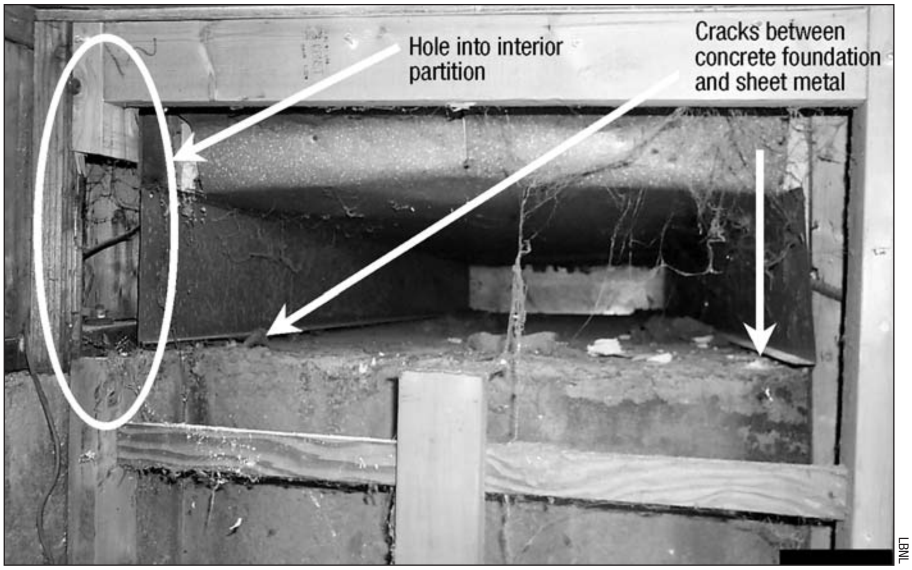
One of the Northern California test houses was selected for the retrofitting case study based on these test results because it showed the greatest potential for improvements. This house was a 27-year-old single-family two-story dwelling of approximately 2,500 ft^2. It was cooled and heated by its original central gas furnace/air-conditioning system, located in the attached garage. The roof was constructed with ceramic tiles on a sloped plywood deck, over a naturally ventilated attic, with R-26 glass fiber insulation between the 2 inch x 8 inch joists on 16-inch centers. The house had the following combination of problems: low-efficiency heating and cooling equipment; leaky and poorly insulated ducts; low air handler flow; low refrigerant charge; and a leaky exterior envelope. In addition, the air handler, furnace, cooling coils, and most of the ductwork were located outside the conditioned space in the garage and attic. A few major components of the shell leakage were easily identified in this house: several large mechanical chases were open to the attic, and a building cavity return was open to the garage and the attic. The HVAC system was undercharged and operating at only two-thirds of its rated capacity. Finally, the homeowner reported problems in cooling the master bedroom upstairs.

ACCA *Manual J* calculations were performed on a room-by-room basis to estimate heating and cooling loads. The existing air flow was compared to the ideal air flow calculated by *Manual J* to see if there were problems with air distribution throughout the house. Downstairs, airflow was slightly lower than required. Upstairs, the results were mixed. The air flow in the master bedroom was too low, but the air flow in the other rooms had higher air flow, so that the total for the upper floor was correct. However, the imbalance between rooms meant that the master bedroom was insufficiently conditioned. This problem was confirmed by the occupants, who complained that the master bedroom did not receive sufficient cooling in the summer.

Retrofit Selection

Based on the results of the screening, the best practices guide indicated that the following retrofit should be undertaken (for the hot-dry/mixed-dry climate of inland California):

- Seal ducts (decrease leakage to <10% of air handler flow).
- Insulate ducts outside conditioned space to R-8.
- Correct refrigerant charge.
- Seal and bury ducts in added ceiling insulation.



This very leaky building cavity return was removed during the retrofit.

• Install new downsized ducts and HVAC equipment. Minimize the flow resistance with correct length, good routing, and—preferably—sheet metal construction.

• Add economizer.

The ducts were sealed using mastic and internal aerosol sealing. The supply ducts were sealed to 4% of air handler flow, but the return leakage was higher than we would like at 9% of air handler flow. The remaining return leakage was mostly at the economizer damper seal because the sheet metal box containing the economizer damper was not installed squarely. The sealing of the envelope was very successful—mostly because this particular house had significant large leaks that we were able to access. We sealed over 1,200 CFM of leakage at 50 Pa—about one-quarter of the total leakage. This included air sealing the attic floor plane (see photo on p. 28), the old cavity return (shown in photo, above), and plumbing penetrations.

The selection of replacement equipment was fairly straightforward, because contractors already install high-efficiency systems with economizers in new construction. Therefore the contractor was able to give us several options from different manufacturers that used condensing furnaces (95% annual fuel utilization efficiency, or AFUE), high-efficiency air conditioners (14-SEER), and air handlers that remain efficient at lower speeds. The contractor also installed a programmable temperature-controlled economizer and a two-zone thermostat controller. The economizer operated independently of the air conditioning system, it used its own thermostat with a setpoint set lower than the house air conditioner thermostat controlling setpoint, and only operated when it was 8ºF (4ºC) cooler outside than inside. The two zones had separate upstairs and downstairs thermostats and used motorized dampers to direct the flow to the two zones. The furnace, air handler, cooling coil, and plenums were relocated from the garage to the attic, because the large ductwork required for the economizer could not be installed in the existing garage location. A pull-down staircase was added for attic access; it included an insulated cover to provide both sound and thermal insulation between the attic and the living space.

The heating and cooling equipment capacity was sized using the ACCA *Manual J* and *Manual S* calculation and engineering considerations derived from the monitored data. A high efficiency split system air conditioning package consisting of a remote condensing unit and an oversized evaporator coil was selected with 36,000 Btu per hour nominal capacity (half a ton downsized from the original equipment), 0.73 Sensible Heat Ratio (SHR), and 14-SEER. The evaporator coil was deliberately mismatched to increase the efficiency for sensible cooling—the latent loads were small for this dry California location. The condensing unit was relocated from a sun-exposed area behind the garage with unstable soil to a shaded area on the opposite (north) end of the house with a new slab on a stable foundation. The heating system was a variable-speed two-stage gas furnace with 66,900 Btu per hour high-fire rate output, 46,400 Btu per hour low-fire rate output, and 95.5% AFUE. The new system used a control strategy that slowly increased the air handler speed at the beginning of each cycle. A two-zone control system was installed for separate upstairs and downstairs control and improved occupant comfort. Air filtration was improved with a 4 inch pleated minimum efficiency reporting value (MERV)-11 air filter at the air handler inlet (for comparison, typical residential filters are not rated, but would be equivalent to a MERV rating of 2-3).

A temperature-controlled economizer was installed through the roof to take advantage of nighttime cooling in this climate. When the set temperature difference is met, the air handler fan is turned on and a vent damper is activated, allowing filtered outside air to cool the house. The damper was designed to close the return air pathway through the upper hallway return grill when it opens the outdoor air inlet. Another damper, installed in the return duct from the downstairs part of the house, also closes off this return air pathway when the fresh air inlet opens. To prevent pressurization of the house, a pressure relief damper opens (to the attic) during economizer operation. When the outside air is cooler than the indoor air (usually at night or in shoulder season), the economizer will use the air outside to cool the house.

The existing return was closed off, because it was very leaky and there was no reasonable way to seal it. A larger upstairs return was installed in a new location (upstairs hallway ceiling) to help reduce temperature stratification, and a second downstairs return was installed in a new location (in the wall at the stairway landing).

Because the ducts, furnace, and air handler were located in the attic, the original retrofit plan was to seal and insulate the attic to bring the system inside conditioned space. Unfortunately, it was not possible to obtain code approval for this retrofit in the time available. As an alternative, it was decided to place the ducts on the attic floor and cover them with blown-in insulation, increasing the effective insulation of the ducts and protecting them from the radiation from the underside of the roof deck (as shown in photo above and photo on p. 33). Thus, the added attic insulation served two purposes—it increased the envelope insulation and it improved the performance of the distribution system. The insulation was blown in to a thickness of about eight inches (approximately R-30) over both the existing attic floor insulation and was mounded over the ducts. With sufficient time and resources, it might have been possible to persuade the code authorities to allow a sealed attic. However, as in most real retrofit situations, time limits meant that the vented attic was retained and the ducts were buried in additional ceiling insulation. Given the strict conservatism of code officials, it is unlikely that these issues can be dealt with on an individual project basis without extensive advance planning.

We hope that research projects like the current study will effect a wider acceptance of innovative building changes.

Problems with the Retrofit

As is true with any novel approach, problems will arise during the retrofit. In this case study, several problems arose as a result of poor communication and equipment failure. The most important of these problems are listed below:

- The zoning system did not decrease air handler speed (or cooling capacity) when only one zone called for cooling. This made the system too noisy and produced unacceptable drafts (with all the air flow going through only half the ducts) in single-zone operation. The control system was operating as designed, and there was no provision in the control system to change the fan speed when one zone shuts down. The zone controls manufacturer (who is neither the contractor nor the equipment manufacturer) plans to market an improved controller that reduces fan speed when just one zone calls for heating or cooling, but it was not available for this retrofit.
- The metal ducts in the attic were replaced with new R-4 flexible ducts (despite clear and repeated instruction to retain the original ducts) because the contractor thought the original ducts were undersized. Initially the contractor hung the flex-ducts from the attic ceiling with smooth bends. However, since the ducts would be covered with insulation, the contractor placed the new ducts on the floor, but unfortunately did not take the time to lay the ducts with smooth bends. The use of flex duct increased the system air flow resistance (that contributes to noise, extra air handler power consumption, and possibly too low a flow through the furnace and air conditioner). This problem was made worse by the many extra bends in the flex duct due to poor layout.

Here we see the poorly insulated sheet metal ducts and blown-in insulation in the attic before the retrofit.

- The retrofit goal was to seal supply and return ducts to less than 10% of air handler flow. The returns were found to have too much leakage to meet this specification. Detailed investigations showed that most of the return leakage occurred through the economizer dampers (mostly due to non-square economizer cabinet installation). Given enough time and money, we believe this could have been improved with some effort to make the box square and install bracing around the box to hold it in shape.
- The air filter has a 1-inch bypass between the top of the filter and the sheet metal housing. Again, with some time and effort, the filter slot could have been fixed using sheet metal to reduce this leakage.
- The condensing unit comes precharged and no more charge was added. The contractor would normally

check the charge with a superheat test, but the weather was not warm enough to do so in this case. This limitation is common for off-season installations of air conditioning systems. Subsequent monitoring results have shown that refrigerant charge is okay.

The new flex ducts in the attic are covered by additional blown-in insulation after the retrofit.

LBNL

• The tension in the springs of the zone selection dampers was incorrectly adjusted so that they were not able to open when the air handler was operating fully. This was later fixed by the contractor.

• The homeowners observed that the upstairs was not receiving enough heat. The contractor installed two sheet metal scoops inside the duct system to direct more air to the upstairs to solve this problem.

• The contractor rectified most of these problems, but some problems required several visits. This shows why it is important to carefully inspect and possibly test the building and all the retrofitted systems after the retrofit. These post retrofit inspections will be particularly important if the contractor, installer, or technician is being asked to do things differently from current practice and procedures. When dealing with problems like those outlined above, it is essential to have a good working relationship with the contractor, to follow up on the problem quickly, to remain good-natured and nonconfrontational, and to listen to any helpful suggestions that the contractor may make.

Building Code Issues

The process of selecting and implementing the retrofits during the field evaluation of the best practices guide raised several issues—these issues illustrate some of the remaining barriers to applying the systems approach to residential retrofitting. The key lessons learned from these issues are (1) that code authorities make it difficult to implement novel construction practices; (2) that changing contractor practices requires a great deal of oversight; and (3) that many pieces of HVAC related equipment do not operate as well as expected. Some of these problems can be overcome through demonstration projects (like the one described in this article) that can be used to show code authorities and contractors how the systems approach can be made to work successfully. If a retrofit is not acceptable by code, the user can look at alternative packages that are less controversial, based on the various intervention levels contained in the guide.

Jennifer McWilliams has been involved in energy efficiency retrofits of residential buildings for over ten years both as a researcher and field technician. She is a Senior Research Associate in the Energy Performance of Buildings Group at Lawrence Berkeley National Laboratory.

*Iain Walker is **Home Energy**'s executive editor. He is a staff scientist in the Energy Performance of Buildings Group at Lawrence Berkeley National Laboratory, in Berkeley, California.*

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies, of the U.S. Department of Energy (DOE). The authors would like to thank Darryl Dickerhoff, Duo Wang, Douglas Brenner, Brian Smith, and Nance Matson of LBNL, Bruce Harley and Mark Hutchins (Conservation Services Group), Rick Wylie (Beutler Heating and Air Conditioning), and Stacy Hunt and Ananda Hartzell (Integrated Building and Construction Solutions).

For more information:

To read this study in its entirety, go to http://ducts.lbl.gov/HVACRetrofitguide.html.

"Case Study Field Evaluation of a Systems Approach to Retrofitting a Residential HVAC System," which focuses on the HVAC retrofit of a single residence in northern California, can be read at http://epb.lbl.gov/Publications/lbnl-53444.pdf.

Home Energy Saver, the first web-based do-it-yourself energy audit tool, can help you save energy in your home and find energy-saving resources. Go to http://hes.lbl.gov to start saving energy.