LBNL 54696

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

A Systems Approach to Retrofitting Residential HVAC Systems

J.A. McWilliams and I.S. Walker

**Environmental Energy
Technologies Division**

May 2004

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

A Systems Approach to Retrofitting Residential HVAC Systems

Iain S. Walker and Jennifer A. McWilliams, Energy Performance of Buildings Group
Lawrence Berkeley National Laboratory, Berkeley, CA

ABSTRACT

A Best Practices Guide for retrofitting residential HVAC systems has recently been completed by DOE. The guide uses diagnostics and checklists to guide the user to specific retrofit packages that maximize retrofit energy savings, comfort and safety potential. The guide uses a systems approach to retrofitting where the interaction of different building components is considered throughout the retrofit selection process. For example, added building envelope insulation reduces building loads so that smaller capacity HVAC systems can be used. In this study, several houses were surveyed using the Best Practices Guide and a single house was selected for retrofitting. The objectives were to demonstrate how a successful system-wide retrofit can be carried out and to provide feedback to improve the guide. Because it represents a departure from current practice, a key aspect of this study was to investigate the interactions with contractors and code officials who are unfamiliar with the systems approach. The study found that the major barrier to the systems approach in retrofits was in changing the working practices of contractors and code officials.

Introduction

Retrofits are an opportunity to use higher efficiency equipment and add features that ensure increased comfort, safety and durability in addition to reduced energy use. Examples include: multiple-speed heating or cooling equipment to better match building loads, added economizers to provide ventilation and reduce electricity consumption, and added zoning to increase comfort (this is particularly useful in houses that have large areas that are poorly conditioned). Traditionally, retrofits are done in a piecemeal fashion, with individual building components replaced one at a time with little thought given to their interactions. Most information (e.g., LBNL's Home Energy Saver (http://homeenergysaver.lbl.gov/), EPA's Home Energy Advisor (http://advisor.lbl.gov) or books such as No Regrets Remodeling (Home Energy (1997)) is targeted at home owners and therefore does not include the things that make the systems approach of this study unique: testing, comparison to targets, the use of integrated systems approach coupled with packaged solutions, etc. Instead, the focus is on very simple general guidance, which means that not all the potential savings are realized. Other guides (e.g., Wendt et al. (1997)) are more weatherization oriented, tend to focus on individual building types, and also treat individual retrofits in a piecemeal fashion. The Best Practices Guide that is the subject of this study was developed by the Department of Energy to be a consensus document that includes input from national labs, Building America teams, contractors, weatherization experts, and other building industry professionals. During its development it was reviewed by many people in these fields, and the authors are grateful for the thoughtful contributions and comments we received.

The systems approach attempts to treat the whole building and all of its components together. This has many benefits:

- correct system sizing when loads (e.g., envelope conduction, window solar gain infiltration reduction) are reduced by retrofits,
- avoidance of potential problems (e.g., increased condensation potential when air conditioning is added to previously un-cooled houses), and
- reduction in total cost compared to summing the costs for individual retrofits.

Because the current retrofit industry is not structured to use the systems approach, a best practices guideline has been developed by DOE (Walker 2003) to provide guidance for contractors. The guide was developed with input from potential users such as contractors and weatherization experts. In order to simplify the guide, it was developed around the idea of having packages of changes to the building HVAC system and building envelope that are climate and house construction dependent. These packages include recommendations regarding materials, procedures and equipment, and are designed to remove some of the guesswork from builder, contractor, installer or homeowner decisions about how best to carry out HVAC changes. The packages are not meant to be taken as rigid requirements – instead they are systems-engineering guidelines that form the basis for energy efficient retrofits. The retrofit packages are presented at three different levels of intervention (depending on the scope of the retrofits being considered) and for "HVAC only" and "HVAC plus building envelope" scenarios. This range of packages results gives the user a degree of flexibility in applying the guidelines. This can be particularly useful if codes provide insurmountable barriers for some potential retrofits. Similar approaches have been taken previously for new construction, where a systems engineering approach has been used to develop extremely energy efficient homes that are comfortable safe and durable, and often cost less than standard construction. This is epitomized by the Building America program whose partners have built thousands of efficient residences throughout the U.S. using these principles. The differences between retrofit and new construction tend to limit the changes one can make to a building, so these 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.

Another key aspect of these best practices is the need to know how a house is working to better define what parts have the potential for improvement. A set of diagnostic tools combining physical measurements and checklists/questionnaires is used in the guide. The measured test results, observations, and homeowner answers to questions direct the user towards the best retrofits applicable to each individual house. The suggested retrofits will depend on the current condition of the building envelope and HVAC system, the local climate, the construction methods used for the house, and the presence of various energy saving systems (e.g., a heat recovery ventilator) and/or materials.

A field pilot study was performed in which the best practices guidelines were applied to eight test houses and a single house was identified for a retrofit case study. The application of the guidelines to these houses gave feedback for updating and improving the guidelines. In order to have an independent assessment of the guidelines, two of the houses were evaluated by an independent energy efficiency contractor. The retrofitted house had the diagnostic screening tests repeated after the retrofit to compare pre and post-retrofit performance. This paper summarizes the field pilot study and retrofit case study. More details of this work can be found in Walker et al. 2004.

Table 1. Diagnostics Screening Checklist: HVAC, Envelope and Occupant Survey.

Measurement/ Observation	Potential Target value	Potential Retrofit Action
Duct leakage	<10% of air handler flow	Seal ducts: Aeroseal/tape/mastic
Duct insulation	RSI 1 (R 6) to RSI 1.4 (R8) for all ducts outside conditioned space	Add insulation to ducts
Air flows at registers	Compare to ACCA manual J (ACCA 2004)	Replace registers, open/close dampers, reduce system flow resistance by straightening existing ducts or replacing them with straight runs of new ducts.
Air handler flow	**Cooling**: >400 cfm/ton in dry climate, or >350 cfm/ton in humid climate **Heating**: 12.5 cfm/kBtu/h	Replace filters, fix duct restrictions, change fan speed, replace fan with high efficient unit, add extra returns in return restricted systems
Filter Condition	Clean and at least MERV 6	Replace with MERV 6 or better. Use 50 mm or 100 mm (2 or 4 inch) filters if possible
Thermostat Setting	Heating: 20°C (68°F) Cooling: 25°C (78°F)	Thermostat raised in summer and lowered in winter to account for better distribution, mixing and envelope improvements.
Spot ventilation	25 L/s (50 cfm) each bathroom 50 L/s (100 cfm) each kitchen	Replace fans, fix restrictive ducting
Spot Ventilation fan power consumption	1.2 L/s/W (2.5 cfm/W). A good source for these ratings is the HVI directory (www.hvi.org)	Replace with higher efficiency unit, remove/reduce duct flow restrictions, clean fan and ducting
Equipment capacity	ACCA Manual S (ACCA 2004b)	Replace with correct size
Refrigerant charge	Use superheat or subcooling tests	Add/subtract refrigerant
Age and Condition of HVAC system	Clean and undamaged. Determine system age.	Clean the system and repair damage or Replace the system if > 15 years old
Location of HVAC system equipment and ducts	Inside conditioned space	Seal and insulates duct locations to make them more like conditioned space, or move system location.
Window A/C units	EnergyStar compliant	Replace with central unit or improved distribution
Multiple systems/zoning	System and controls in good working order and providing good comfort for occupants	Ensure correct damper operation, check capacity of each system/zone matches a Manual J (or equivalent) load calculation
Envelope leakage	Normalized Leakage Area reduction of 0.35	Insulate envelope, seal windows/doors/other openings
Moisture testing	No moisture problems	Source control – better kitchen and bath venting, fix flashing/detailing, seal and condition crawlspaces in high humidity climates, replace windows, add insulation to walls, floors and ceiling
House insulation	Ceiling: RSI 5.3 (R-30) minimum, RSI 8.6 (R-49) in cold/severe cold climate. Floor over crawlspace: RSI 4.4 (R-25). Basement walls: RSI 1.8 (R-10), Basement Floor or slab usually depends on local codes. Walls: Cavity should be completely filled with insulation.	Add insulation to fill cavity. Add semi-permeable rigid exterior insulation in cold/severe cold climates if the wall is 2×4 construction.
Windows	Double-glazed, low-e. Shaded in cooling dominant climates	Replace windows. Add shading.
Window shading	Located on south and/or west facing windows	Add shading to reduce solar loads
Solar radiation control	Radiant barrier in attic, low absorbtivity roof coatings	Add radiant barrier in attic, or low absorbtivity roof coatings
Wall, floor and ceiling construction	Space for ducts/vents	
Evaluate house energy bills (if available)		
Occupant survey Ask occupants to report problems	No problems	Moisture removal strategies, new windows (for condensation resistance), change register type, airflow and location to improve mixing/remove drafts, add envelope insulation, etc.

Diagnostics and Screening Process

The Best Practices Guide includes a checklist to guide the retrofit selection using diagnostic screening tools that combine physical measurements, observations and a homeowner questionnaire. The checklist uses the results of diagnostics tests and observations and compares them to target values. The checklist also includes potential retrofit actions when the target values for various components are not met. A template of the screening checklist is given in Table 1.

Occupant Survey

The importance of addressing any issues raised by the occupants cannot be overstated. Improved comfort and visual appearance are reasons that homeowners often use when retrofitting or renovating homes. These factors are often more important than simple payback related to energy savings. Occupants can report problems (comfort. high bills, condensation, mold, etc.) and important lifestyle activities that can significantly change building loads and the times that the house needs to be conditioned. The following are some typical questions that should be asked and are include in the Best Practices Guide:

- *How many people live in the house?* More occupants indicate that the chances for humidity and other Indoor Environmental Quality problems will be greater.
- *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 setback or setup programmable thermostats.
- *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 (homeenergysaver.lbl.gov) and the Energy Star Home Improvement Toolbox (DOE (2004)), to assist in evaluating energy bills.

Diagnostics and Screening Results from Eight Test Houses

The guideline diagnostics and checklists were applied to eight houses in three regions of the US. Two houses were in a heating dominated coastal climate (Boston, MA), two houses in a heating dominated inland climate (Minneapolis, MN) and four houses in a mixed/hot-dry climate (different municipalities in Northern California). The houses represented a range of construction methods, HVAC system types and locations, construction materials, foundation type as well as HVAC system performance. Some of the key results are summarized in Table 2 (more details are given in Walker et al. 2004).

Retrofitting Case Study

The Concord test house was selected for the retrofitting case study based on these test results because it showed the greatest potential for improvements. The Marlborough house was also a strong candidate, but time and money limits meant that replacing two systems in a house on the other side of the country was not a viable option. The Concord house was a 27-year old single-family two-story dwelling of approximately 230 m^2 (2500 ft^2) and was cooled and heated by it's 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 RSI 4.5 (R-26) glass fiber insulation between the 50 mm by 200 mm (2 by 8 inch joists) on 40 cm (16 inch) centers. The house had the following combination of problems: low-efficiency heating and cooling equipment, leaky (see Figure 1) and poorly insulated ducts (see Figure 2), low air handler flow, low refrigerant charge, and a leaky exterior envelope. In addition, the air handler, furnace, cooling coils and most of the duct system 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. Lastly, the homeowner reported problems in cooling the upstairs of the house.

Table 2. Comparison of 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, L/s (cfm)	Refrigerant Charge Assessment	Envelope Leakage, m^2 (in^2)	Ceiling Insulation RSI (R-value)
Concord	12	33	380 (805)	Undercharged	0.179 (278)	4.6 (26)
Moraga[1]	22/14	10/n/a	460/250 (970/540)	Both Overcharged	0.229 (335)	3.0 (17)
Castro Valley	9	5	550 (1160)	Undercharged	0.164 (269)	4.4 (25)
Larkspur	10	17	575 (1215)	Correct	0.219 (340)	Inaccessible
Arlington	8	25	438 (927)	Too cold to test	0.157 (244)	5.25 (30)
Marlborough[1]	36/31	13/37	243/373 (515/791)	Too cold to test	0.168 (261)	4.2 (24)
Northfield	17	43	506 (1071)	Too cold to test	0.065 (100)	5.25 (30)
Plymouth	8	25	438 (927)	Too cold to test	0.157 (244)	5.25 (30)

1- Houses had 2 systems

Figure 1. Very leaky building cavity return that was removed during the retrofit

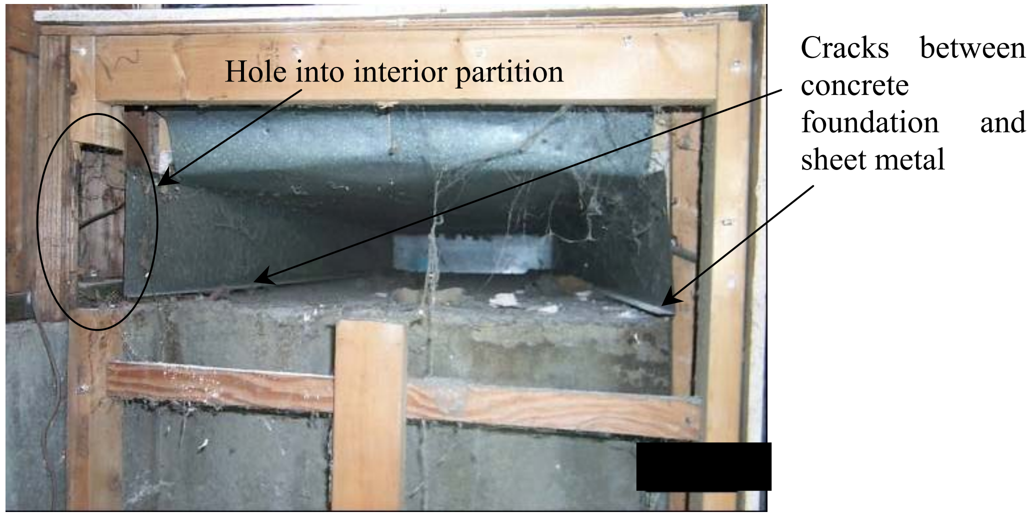

Figure 2. Poorly insulated sheet metal ducts and blown-in insulation in the attic before retrofit

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 airflow calculated by Manual J to see if there were existing problems with the distribution throughout the house. The downstairs of the house had slightly lower airflow than required. Upstairs, the results were mixed: the master bedroom had too low airflow, but the other rooms had higher airflows, such that the total for the upper floor was correct. However, the imbalance between rooms led to the master bedroom being 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 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 RSI 1.4 (R8)
- Correct refrigerant charge
- Seal and bury ducts in added ceiling insulation.
- 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 returns leakage was 9% of air handler flow.

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 570 L/s (1200 cfm) of leakage at 50 Pa (0.2 in. water)) - about one-quarter of the total leakage. The sealing included: air-sealing the attic floor plane (2 large chases) as shown in Figure 3, leaks between the old cavity return (which communicated with the garage) and the conditioned space, and plumbing penetrations in the conditioned space.

The selection of replacement equipment was fairly straightforward because the contractor already installs 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% AFUE), high-efficiency air conditioners (SEER 14) and featured air handlers that remain efficient at lower speeds. The contractor also installed a programmable temperature-controlled economizer and a two-zone thermostat controller. The furnace, air-handler, cooling coil, and plenums were relocated from the garage to the attic because the large ducting required for the economizer could not be installed in the existing garage location. A pull-down staircase was added for attic access that included an insulated cover to provide both sound and thermal insulation between the attic and living space.

Figure 3. Sealing cavities connecting the house to the attic. Foam was used for sealing small holes and cracks at building component intersections (left). Duct board insulation was used to block off large open areas (right)

The heating and cooling equipment capacity was sized using the ACCA Manual J calculation and engineering considerations derived from the monitored data. A one half ton downsized high efficiency split system air-conditioning package consisting of a remote condensing unit and an over-sized cooling coil was selected with the following specifications: 10.5 kW (36,000 Btu/h) nominal capacity, 0.73 SHR, and 14 SEER. The condensing unit was relocated from a sun-exposed area behind the garage with unstable soil to a shaded area on the opposite end (north) of the house with a new slab on a stable foundation. The heating system was a variable speed two-stage gas furnace with a 560 W (¾ hp) blower motor with the following specifications: 20 kW (66,900 Btu/h) high-fire rate output, 13.5 kW (46,400 Btu/h) 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 100 mm (4 inch) pleated MERV-11 air-filter at the air-handler inlet.

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 fan is turned on and a vent damper is activated allowing filtered outside air to cool the house. The damper was designed so that when it opens the outdoor air inlet, it automatically closes the return air pathway through the upper hallway return grille. Another damper was installed in the return duct from the downstairs part of the house to also close off this return air pathway when the fresh air inlet opens. A pressure relief damper opens (to the attic) during economizer operation to prevent pressurization of the house. 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 assist in reducing temperature stratification. 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 available time. As an alternative, it was decided to place the ducts on the attic floor and cover them with blown-in insulation (as illustrated in Figure 4), thus increasing the effective insulation of the ducts and protecting them from the radiation from the underside of the roof deck. Thus, the added attic insulation served two purposes: it increased the envelope insulation and improved the distribution system performance. With sufficient time and resources, it may have been possible to persuade the code authorities to allow a sealed attic. However, as in most real retrofit situations, limits of time 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. Hopefully, research projects like the current study will mean that innovative building changes will become more widely accepted.

Figure 4. New flex ducts in attic covered by additional blown-in insulation.

Problems with the retrofit

As with any novel approach, there will be problems that arise during the procedure. In this case study there were several problems that arose as a result of communication problems and equipment functionality. The problems are listed below to provide guidance for future retrofitters:

- The zoning system did not decrease the air handler speed (or cooling capacity) when only one zone called for cooling. This resulted in the system being very noisy and producing unacceptable drafts (with all the air flow going through only half the ducts) in single zone operation. It was found that 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) has plans to have an improved controller that reduces fan speed when just one zone is calling for heating or cooling, but this 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 they were undersized. Initially the contractor hung the flex-ducts from the attic ceiling with smooth bends. However, to allow covering the ducts with insulation the contractor then placed the new ducts on the floor, but unfortunately did not take the time to lay the ducts with smooth bends.
- The retrofit goal was to seal supply and return ducts to less than 10% of air handler flow, which is the standard for best practices (e.g. DOE (2002)). The returns were found to have too much leakage to meet this specification. Detailed investigations showed that most of the return leakage was through the economizer dampers (mostly due to non-square economizer cabinet installation). Most of this leakage was later fixed by the contractor.
- The air filter has a 25 mm (1 inch) bypass between the top of the filter and the sheet metal housing.
- The condensing unit comes pre-charged and no more was added. The contractor normally would check the charge with a superheat test, but the weather was not warm enough to do one in this case.
- The tension in the springs of the zone selection dampers was incorrectly adjusted so that they opened when the air handler turned on instead of staying closed.
- The upstairs was not receiving enough heat as observed by the homeowners. The contractor installed two sheet metal scoops to affect airflow and heating.

These problems were mostly rectified in by the contractor, but some required several visits. These issues illustrate the need 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 working out any problems with equipment installation and operation, such as those outlined above, it is essential to have a good working relationship with the contractor, follow-up quickly with any problems, remain good-natured and non-confrontational, and listen to any helpful suggestions a contractor may have.

Summary

The DOE Best Practices Guide for retrofitting residential HVAC systems was applied to a range of houses in different climates and locales by a group of researchers and other potential users. Feedback from these field trials was used to improve the guide into its final form. The screening tool in the guide was used to select a single home for retrofitting and assist in the selection of the appropriate retrofits. The process of selecting and implementing the retrofits raised several issues that illustrate some of the remaining barriers to application of the systems approach to residential retrofitting. The key lessons learned from these issues are that code authorities are a significant barrier to implementation of novel construction practices, changing contractor practices require a great deal of oversight and many pieces of HVAC related equipment do not operate as well as expected. Some of these issues can be overcome through demonstration projects (like this study) that can be used to demonstrate to code authorities and contractors how these systems approaches can work successfully. From the equipment point of view, the feedback generated by this project and future applications of the guide are essential for manufacturers and installers to improve their products and installation procedures. If a retrofit is note acceptable by code, then the different intervention levels contained in the Best Practices guide can be used to look at alternative packages that are less controversial.

Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies, of the US Department of Energy (DOE) under contract No. DE-AC03-76SF00098. The authors would like to thank Darryl Dickerhoff, Duo Wang, Douglas Brenner, Brian Smith and Nance Matson of LBNL, Bruce Harley and Mark Hutchins (CSG), Rick Wylie (Beutler Heating and Air Conditioning), and Stacy Hunt and Ananda Harzell (IBACOS).

References

ACCA. 2004. *Manual J - Residential Load Calculation*. Air Conditioning Contractors of America. Arlington, VA.

ACCA. 2004b. *Manual S - Residential Equipment Selection*. Air Conditioning Contractors of America. Arlington, VA.

DOE. 2002. *ENERGYSTAR Duct Specification* http://www.energystar.gov/ia/products/heat_cool/ducts/Duct_Spec_2002.pdf, Department of Energy, Washington, DC.

DOE. 2004. *Energy Star Home Improvement Toolbox.* http://208.254.22.7/index.cfm?c=home_improvement.hm_improvement_index. Department of Energy, Washington, DC.

Home Energy Magazine. 1997. *No Regrets Remodeling*, Energy Auditor and Retrofitter, Inc, Berkeley, CA.

Walker, I.S. 2003. *Best Practices Guide for Residential HVAC Retrofits*. LBNL 53592. http://ducts.lbl.gov/HVACRetrofitguide.html

Walker, I.S., McWilliams, J.A. and Konopacki, S.J. 2004. *Case Study Field Evaluation of a Systems Approach to Retrofitting a Residential HVAC System.* LBNL 53444.

Wendt, R.L., Ternes, M.P., O'Leary, L.A., Berkowitz, P.I., Carroll, E.M., Harmelink, S.M., Hasterok, L.V. 1997. *Retrofit Guide for Military Family Housing: Energy-Efficient Weatherization and Improvements*, Oak Ridge National Laboratory, Oak Ridge, TN.