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Disclaimer

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A Systems Approach to Retrofitting Residential HVAC Systems

Jennifer A. McWilliams and Iain S. Walker

Abstract

Over the past couple of years, a Best Practices Guideline for Residential HVAC Retrofits (http://www.eere.energy.gov/buildings/building_america/pdfs/db/37801.pdf) has been developed by the US Department of Energy (DOE) to provide guidance for contractors in performing whole house retrofits. Because of the strongly cost-limited nature of retrofits, combined with the wide range of existing home performance, the DOE guideline has several levels of retrofit packages depending on the level of intervention that a homeowner can afford, or is justified by the condition of the home and its HVAC system. The packages are pre-selected combinations of individual retrofit activities that provide simple whole house guidance for contractors. This guideline has been evaluated by potential users such as contractors and weatherization experts. Part of this evaluation included a field pilot study applying the guidelines to eight test houses. The application of the guidelines to these houses resulted in feedback that helped to update and improve the guidelines. In order to have an independent assessment of the guidelines, two of the houses were evaluated by an independent energy efficiency contractor. One of the test houses was chosen to be retrofitted and had the Best Practices Guideline diagnostic screening tests repeated after the retrofit to compare pre and post-retrofit performance, as well as being the subject of extensive monitoring to determine the change in house performance due to the retrofit. More details of these test results and the application and development of the Retrofit Guide can be found in Walker [2003].

Applying the Systems Approach to Retrofitting

Traditionally, retrofits are done in a piecemeal fashion, with individual building components replaced one at a time, with little thought given to their interactions. Much information, such as Lawrence Berkeley National Laboratory's (LBNL) Home Energy Saver (http://homeenergysaver.lbl.gov), although useful, is targeted at home owners rather than contractors, and therefore does not include a systems approach where all aspects of HVAC system performance, including interactions with the building envelope and the occupants are considered. The systems approach attempts to treat the whole building and all of its components together. This has many benefits:

- correct system sizing when loads (such as envelope conduction, window solar gain infiltration reduction) are reduced by retrofits,

- avoidance of potential problems (such as 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, the DOE Best Practices Guideline was developed to provide guidance for contractors. (http://ducts.lbl.gov/HVACRetrofitguide.html) In order to simplify the decision making process, the guide includes pre-selected packages of changes to the building HVAC system and building envelope that are designed to remove some of the guesswork from builder, contractor, installer, or homeowner decisions about how 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—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 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. Tables 1 through 3 summarize potential retrofit packages for three broad climate types.

Similar approaches have been taken previously in energy efficiency certification programs 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 (http://www.eere.energy.gov/buildings/building_america/), whose partners have built thousands of efficient residences throughout the United States using these principles.

The differences between retrofit and new construction tend to limit the changes one can make to a building, so the Best Practices Guidelines 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 availability of various energy saving systems (such as a heat recovery ventilator) and/or materials.

Diagnostics and Screening Process

The DOE 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 4.

Table 1. Hot dry, mixed-dry and marine

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 R8 Correct refrigerant charge	Ducts sealed (leakage decreased to <10% of air handler flow) Ducts outside conditioned space insulated to R8 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 R8 Correct refrigerant charge Added economizer	Ducts sealed (leakage decreased to <10% of air handler flow) Ducts outside conditioned space insulated to R8 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 R8 Correct refrigerant charge Added economizer Higher solar reflectance roof, more window shading (or windows with lower SHGC).	Ducts sealed (leakage decreased to <10% of air handler flow) Ducts outside conditioned space insulated to R8 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 because of increased durability. Added economizer Higher solar reflectance roof, more window shading.

Table 2. cold and severe cold (and subarctic/arctic)

In some severe cold climates summertime humidity levels can be high enough to be uncomfortable for occupants and houses will have air-conditioning. Although the air-conditioning systems in this climate do not use large amounts of energy because they only operate for the hottest few weeks of the year, their design and installation can still be optimized. The air-conditioner should be chosen and operated to maximize humidity control.

This retrofit is suitable for dry summer climates within the colder zones. Air conditioners are removed completely if CDH23 < 1400 (CDH74 < 2500) and mean monthly dewpoint < 15.5°C (60°F). A listing of these data for various locations is given in a Dry Summer Locations table. Cooling is provided by an economizer in these climates.

INTERVENTION LEVEL	HVAC SYSTEM ONLY	HVAC SYSTEM PLUS ENVELOPE
1	Ducts moved inside conditioned space or sealed (leakage decreased to <10% of air handler flow) and insulated to R8. New downsized ducts and replace HVAC equipment. The ducts are installed to minimize the flow resistance, i.e. correct length, good routing and preferably sheet metal construction	Ducts moved inside conditioned space or sealed (leakage decreased to <10% of air handler flow) and insulated to R8. Upgrade windows. Add ceiling/wall/floor insulation.
2	Ducts moved inside conditioned space or sealed (leakage decreased to <6% of air handler flow) and insulated to R8. Replace air-conditioner with downsized unit that has air-handler flow at the lower end of the manufacturers specifications.	Ducts moved inside conditioned space or sealed (leakage decreased to <6% of air handler flow) and insulated to R8. Upgrade windows. Add ceiling/wall/floor insulation. New downsized ducts and replace HVAC equipment. The ducts are installed to minimize the flow resistance, i.e. correct length, good routing and preferably sheet metal construction.
3		1Ducts moved inside conditioned space or sealed (leakage decreased to <6% of air handler flow) and insulated to R8. Upgrade windows. Add ceiling/wall/floor insulation. Add an economizer. Remove air-conditioning if present- this includes outdoor unit, refrigerant lines and indoor coil.

Table 3. mixed-humid and hot humid

In these climates we do not recommend the use of economizers because outdoor air adds a significant humidity load to the building. To control humidity, use a separate humidity control system, for example, a dehumidifier in an internal air handler closet (http://www.buildingscience.com/housesthatwork/hothumid/wood/default.htm) and low flow air circulation fan. Other recommendations about sealing and insulating duct locations (to effectively bring them inside the conditioned space) are important in humid locations to reduce the problems associated with condensation on cold duct surfaces.

INTERVENTION LEVEL	HVAC SYSTEM ONLY	HVAC SYSTEM PLUS ENVELOPE
1	Ducts sealed (leakage decreased to <10% of air handler flow) and insulated to R8 Correct refrigerant charge. Install kitchen and bathroom exhaust fans.	Ducts sealed (leakage decreased to <10% of air handler flow) and insulated to R8 Correct refrigerant charge. Install kitchen and bathroom exhaust fans. Seal and insulate attics and crawlspaces containing ducts.
2	Ducts sealed (leakage decreased to <10% of air handler flow) and insulated to R8. Correct refrigerant charge. Install kitchen and bathroom exhaust fans. Replace air-conditioner with correctly sized unit.	Ducts sealed (leakage decreased to <10% of air handler flow) and ducts outside conditioned space insulated to R8. Correct refrigerant charge. Install kitchen and bathroom exhaust fans. Seal and insulate attics and crawlspaces containing ducts. 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. Replace air-conditioner with correctly sized unit.
3	Ducts sealed (leakage decreased to <10% of air handler flow) and insulated to R8. Correct refrigerant charge Replace air-conditioner with correctly sized unit. Install kitchen and bathroom exhaust fans. Upgrade windows. Add ceiling/wall/floor insulation	Ducts sealed (leakage decreased to <10% of air handler flow) and ducts outside conditioned space insulated to R8. Correct refrigerant charge. Seal and insulate attics and crawlspaces containing ducts. 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. Replace air-conditioner with correctly sized unit. Install kitchen and bathroom exhaust ans. Upgrade windows. Add ceiling/wall/floor insulation.

Table 4. Diagnostics and Screening Checklist

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 exhaust fans, fix restrictive ducting, ensure venting is to outside, not recirculating into room or exhausted into attic
Spot Ventilation fan performance	Less than 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 Manuals J&S	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[1] 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.

[1] Normalized leakage area is equal to the measured envelope leakage area at 4 Pa that is normalized by floor area and the number of building stories. The exact relationships can be found in ASHRAE Fundamentals and ASHRAE Standard 119.

Measurement/ Observation	Potential Target value	Potential Retrofit Action
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
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.

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. Occupants can also report problems (such as comfort, high bills, condensation, and mold) 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 included in the Best Practices Guide:

- How many people live in the house? *More occupants indicate that the chances for excessive 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. Fishtanks 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.*

- 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.homenergysaver.lbl.gov) and the Energy Star Home Improvement Toolbox (http://www.energystar.gov/index.cfm?c=home_improvement.hm_improvement_index), 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 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 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 types, as well as HVAC system performance. Some of the key results are summarized in Table 5. Full results can be found in Walker [2003].

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

1. These houses each had 2 systems

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 230 m^2 (2,500 ft^2) and 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-in x 8-in 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 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.

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. While 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 air flow, such 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 be undertaken (for the hot-dry/mixed-dry climate of inland California):

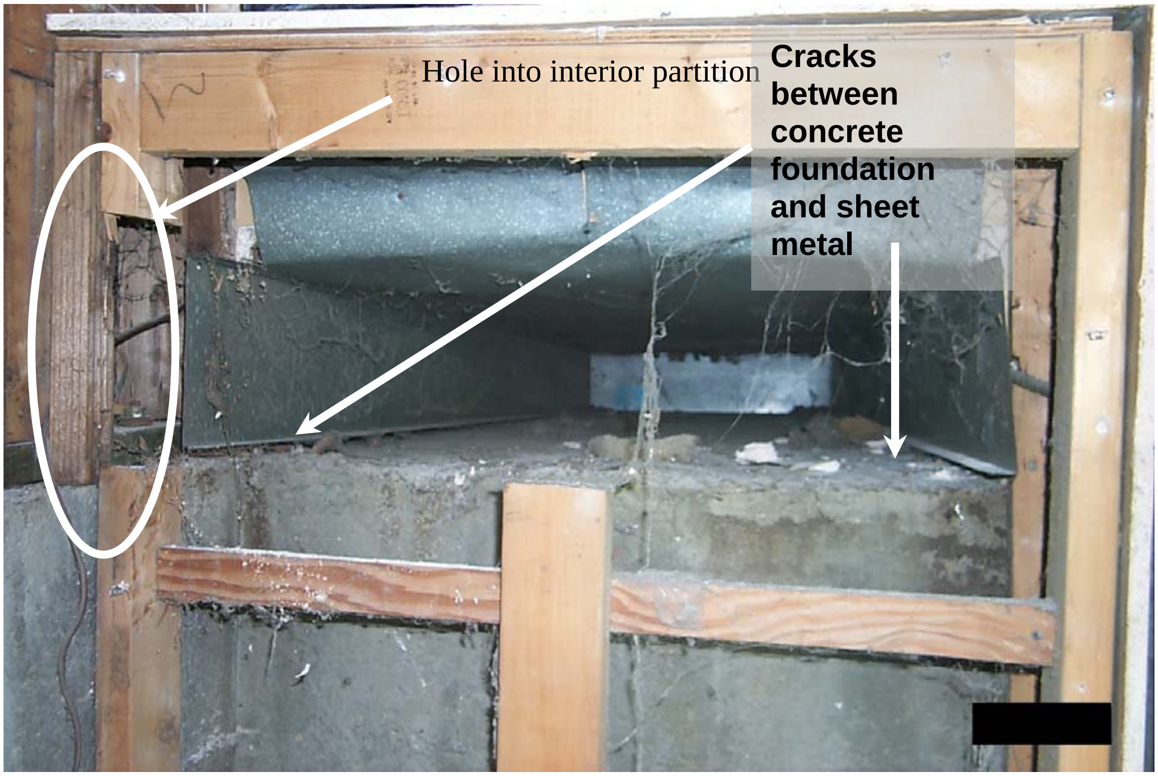
- Seal ducts (decrease leakage to <10% of air handler flow)
- Insulate ducts outside conditioned space to R-8
- Correct refrigerant charge
- Seal and bury ducts in added ceiling insulation
- Install new downsized ducts and HVAC equipment. Minimize the flow resistance with correct length, good routing, and preferably sheet metal construction because of increased durability.
- 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 0.566 m^3/s (1,200 CFM) of leakage at 50 Pa, about one-quarter of the total leakage. The sealing included air-sealing the attic floor plane (2 large chases shown in Figure 1), the old cavity return (shown in Figure 2), 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 (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 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 8°F (4°C) 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 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 1. 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)

Figure 2. Very leaky building cavity return that was removed during the retrofit



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 10,550 W (36,000 Btu/h) nominal capacity (half a ton downsized from the original equipment), 0.73 Sensible Heat Ratio (SHR), and 14 SEER. The evaporator coil was deliberately mis-matched 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 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 66,900 Btu/h high-fire rate output, 13600 W (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 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 assist in reducing 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 available time. 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 Figures 3 and 4). Thus, the added attic insulation served two purposes: it increased the envelope insulation and improved the distribution system performance. The insulation was blown in to a thickness of about 0.203 m (8 in.), approximately 5.25 RSI (R30), over both the existing attic floor insulation and was mounded over the ducts. 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 3. Poorly insulated sheet metal ducts and blown-in insulation in the attic before retrofit

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

Problems with the Retrofit

As with any novel approach, difficulties will 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 a system that was too noisy and produced unacceptable drafts from the registers (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) 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, 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.

- 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 0.025 m (1 in.) 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 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. This limitation is common for off-season installations of air conditioning systems. Subsequent monitoring results have shown that refrigerant charge is OK.

- 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. This was later fixed by the contractor.

- The upstairs was not receiving enough heat, as observed by the homeowners. The contractor installed two sheet metal scoops to affect airflow and heating to solve this problem.

The contractor mostly rectified these problems, but some problems 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 nonconfrontational, and listen to any helpful suggestions a contractor may have.

Building Code Issues

The process of selecting and implementing the retrofits during the field evaluation of the Best Practices Guide 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 requires 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 the one described in this article) that can be used to show code authorities and contractors how these systems approaches can work successfully. If a retrofit is not 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.

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