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Spray Foam in Accessible Spaces: Best Practices and Case Studies for Retrofit in Mixed-Humid Climates

October 2011

Prepared by
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UT-BATTELLE

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Energy and Transportation Sciences Division

SPRAY FOAM IN ACCESSIBLE SPACES: BEST PRACTICES AND CASE STUDIES FOR RETROFIT IN MIXED-HUMID CLIMATES

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ACRONYMS AND ABBREVIATIONS

ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BPI	Building Performance Institute, Inc.
CC1	Campbell Creek House 1
CC2	Campbell Creek House 2
CFM	Cubic feet per minute
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ft	Foot
HDD	Heating degree days
HERS	Home Energy Rating System
hr	Hour
HVAC	Heating, ventilation, and air conditioning
IARC	International Agency for Research on Cancer
IEEC	International Energy Conservation Code
in.	Inch
lb	Pound
LEED	Leadership in Energy and Environmental Design
MDI	Methylene diphenyl diisocyanate
mil	One thousandth of an inch
min	Minute
MSDS	Material Safety Data Sheet
OSB	Oriented strand board
OVF	Optimal Value Framing
oz	Ounce
Pa	Pascal
PET	Polyethylene terephthalate
pMDI	Polymeric methylene diphenyl diisocyanate
psi	Pounds per square inch
pt	pint
RH	Relative humidity
SPF	Spray polyurethane foam
UFFI	Urea formaldehyde foam insulation

1. INTRODUCTION

Heating and cooling a house is one of homeowners' major expenses. Reducing these costs, saving energy, and creating a healthier, more comfortable indoor environment are good reasons to consider improving the building thermal envelope.

Improvements usually include increasing the amount of insulation, reducing the infiltration of outside air, and controlling moisture in existing buildings. This report describes the use of spray foam materials to insulate, seal, and control moisture. This discussion is limited to treating areas that are accessible. What is accessible, however, can vary depending on the type of renovation. If the building has been gutted or exterior surfaces removed, there are more options.

This report will look at areas to consider for spray foam application and discuss the types of spray foams available and their uses. A number of case studies are presented to show the effectiveness of this retrofit in existing houses based on performance data.

1.1 Insulation

Insulation is rated according to its resistance to heat flow from the warmer side to the colder side, measured by a parameter called R-value. The higher the R-value is, the more effective the insulation. The Department of Energy (DOE) recommends insulation levels for attics in the mixed-humid climate (Fig. 1) between R-38 and R-60, with R-25 to R-30 under the floor of the conditioned space. If some insulation is in place, the homeowner may be able to add additional insulation (DOE 2008). Based on the type and condition of any existing insulation, the homeowner may decide to remove the old material and replace it with a new system.

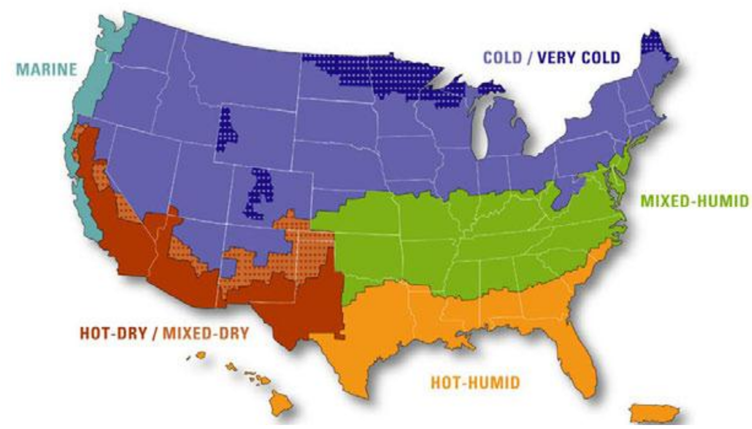

Fig. 1. Building zones in the United States. *Source: Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Mixed-Humid Climate, Building America Best Practices Series: Vol. 4*, NREL/TP-550-38448, U.S. DOE, Washington, D.C., September 2005.

1.2 Sealing

Small openings throughout the building envelope where walls meet each other, where walls meet the ceiling, and around windows and doors allow both uncontrolled and unwanted heat and moisture to move between the inside and outside. Typical locations for infiltration include openings between conditioned spaces and unconditioned attics, crawl spaces and attached garages, and around plumbing and electrical penetrations.

If combustion appliances are present in the home air-sealing may change the building envelope and this leads to the potential need for combustion safety and carbon monoxide protection measures. Additional ventilation may need to be available for specific areas of the house, such as the kitchen. The Building Performance Institute (BPI) has a technical standard that should be followed (BPI 2010), and local building codes have various fire protection codes.

ASHRAE 62.2-2010, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings,* is the U.S. national minimum ventilation standard. It is a consensus document developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). It applies to all single-family houses and multifamily dwellings three stories or less in height (ASHRAE 2010). The standard does allow for other design approaches if they have been approved by a "licensed design professional." Compliant ventilation rates are determined by the following simple calculation.

$$CFM = (0.01 \times \text{conditioned floor area}) + 7.5 \times (\text{number of bedrooms} + 1)$$

1.3 Moisture

Moisture control allows the insulation to stay dry so that it can retain its thermal resistance. Leaky structures and moisture condensing on cooler surfaces can also lead to rot, mold, and mildew problems. Comfortable humidity levels inside a home are sufficient to allow destructive levels of moisture inside the walls due to diffusion or leakage of moist air. Spray polyurethane foam (SPF) acts as a vapor retarder to limit the amount of moisture that can diffuse into the building envelope. Most of the moisture that passes through the exterior envelope (70 to 90%) comes from air leakage (Cozifoam 2011), so the use of foam to seal the structure also provides a moisture retarder. In general the largest single source of moisture in U.S. homes is from the occupants' respiration and perspiration — 10.5 to 13 pt/day for a family of four (Christian 2009). Use of water in the home for cooking and cleaning adds another 11 pt/day (Christian 2009). In the summer of 2010 at the Campbell Creek simulated-occupancy homes, the latent load removal for June, July and August in the typical house measured 28.7 pt/day. At the time, occupant respiration and perspiration was not being simulated, so adding the 11 pt/day suggests that the total moisture generation in this home in the three hottest months of the year averages 39.7 pt/day. This house had an average air tightness of 5.6 air changes per hour (ACH) at 50 Pa. This house had a constantly running bathroom exhaust fan measuring an average of 30 cubic feet per minute (cfm).

1.4 Value of Spray Foam Insulation

Spray foam insulation can help with these problems. The sprayed foam can seal small leaks, add R-value, provide a vapor-diffusion retarder, and serve as an air barrier. Although most spray foams, when properly applied, are effective as air sealants, variations in the components provide a range of R-values and affect the degree of resistance to moisture flow. This report contains blower door measurements taken before, during, and after various parts of the exterior envelope have been sprayed with foam. We have found the ACH at 50 Pa typically goes from about 10-15 to as low as 4.21 after spray foam is properly applied.

It is very important to conduct a BPI Combustion Zone Analysis before and after application of foam sealing to determine whether and how much mechanical ventilation is needed (BPI 2005). The need for combustion safety is also important relative to the flame-spread resistance which will depend on the location and what is planned for the spaces that will be exposed to the foam insulation. Behind drywall is generally no problem. Safe use in the attic and crawlspaces will depend on the presence of combustion sources, and whether the space will be used for storage. Almost all foams can be covered with intumescent paint and fire-retardant coatings. Some foams have inherent flame-resistance properties and require no coatings to meet ASTM E84 (2010) and other combustion safety standards.

2. TYPES OF SPRAY FOAM INSULATION

This section discusses some of the spray foams that are currently available or may be encountered during the retrofit process.

2.1 Latex Foam

Latex foam insulation is most commonly sold in aerosol cans. A spray nozzle and trigger assembly is used to squirt the foam into cracks and open spaces. The latex expands to form a tight seal. Excess material can be cleaned up with soap and water before the material cures. Latex foam will adhere to most surfaces.

Latex foam reaches 75% of its volume as soon as it is applied. This makes it particularly useful for sealing the gaps around window and door frames, where much additional expansion could distort the frames. Latex foam can be shaped and smoothed while it cures and remains somewhat pliable after curing (NAHB 2001).

Latex foam should be applied to clean surfaces when the temperature is between 45ºF and 90ºF. Foam cans should be shaken for a minute or more before dispensing. The can should be held upright. Spaces should be filled about 90% full, allowing some room for final expansion. Foam hardens in about 10 minutes and cures completely within about 21 hours, depending on temperature and humidity.

Latex foam is very flammable when being applied, and the vapor is heavier than air. All ignition sources should be extinguished before spraying. If used around the exterior of electrical boxes, the power to the box should be turned off while spraying. The foam should not be used inside an electrical box.

Vinyl acetate is used in the production of latex foam, so foams are listed by the International Agency for Research on Cancer (IARC) as possibly carcinogenic to humans (NAHB 2001). However the foams are considered safe for use by homeowners who use gloves and eye protection. Breathing the fumes should be avoided while spraying, and the area where the latex is applied should be ventilated until the odor is gone.

Latex foam costs $5 to $10 per 12-20 oz can. A 12-oz can yields about 500 ft of ¼-in bead. The straw and nozzle should be cleaned with warm water so it can be reused with any remaining foam. Reapplication may be needed after an extended time.

EnergyComplete™ (Owens Corning 2009, 2011) is a sealant-insulation system that consists of a sprayed foam sealant topped with conventional fiberglass insulation. The foam for the sealant is acrylic latex which is combined with a proprietary ingredient before application. Once applied, the material retains a flexible seal and is an effective noise barrier. The foam provides protection against infiltration.

On the other hand, the foam alone provides little insulation. The EnergyComplete™ foam does not expand greatly after the original application, so it can also be used around window and door frames. The material is mixed and sprayed with a heated product-specific spray system. The spray pattern can be broader than that allowed by the nozzle and straw system of aerosol cans, making it easier to seal more types of cracks. The force of the spray tends to displace dust in the target area, so the area may not have to be carefully cleaned before starting.

Spraying should not be done around any flame sources. Workers must wear eye protection, chemical protective gloves, long-sleeved shirt, and dust mask, if in dusty location. Although the latex side of the sprayer can be cleaned with water, the other side requires a special cleaner.

Please see the case study on the Summit house in the section of this report describing the ten deep-retrofit homes.

2.2 Spray Polyurethane Foam Insulation

The most common spray foam insulation is polyurethane foam. This foam comes in several different forms, which determine its insulating and moisture-diffusion properties. The foams are described by their density and whether they have closed cells or open cells (see Table 1).

Closed-cell foam forms bubbles as it cures. Most of these bubbles have solid walls, so that gases are enclosed within the foam. Closed-cell foam has a higher R-value per inch of thickness than open cell foams and is more resistant to moisture.

Open-cell foam also forms bubbles, but these bubbles have broken walls, so that air fills the bubbles. Open-cell foam allows moisture to diffuse through more easily.

Table 1. Comparison of closed cell and open cell foam

	Closed Cell	Open Cell
R-value (h-ft^2*°F/Btu)	About 6.0 per inch when new*	About 3.5 per inch**
Moisture permeability	Lower	Higher, but controlled
Infiltration	Good air barrier	Air barrier, if layer is sufficiently thick
Strength and rigidity	Higher	Lower
Water resistance	Resists water	Should not be used in direct contact with water
Typical Density (lb/ft^3)	Medium (1.75–2.25)	Low (0.4–1.2)
Sound absorption	Absorbs sound	Absorbs sound very well

Source: "How Does Spray Polyurethane Foam (SPF) Insulation Work?," American Chemistry Council, 2010, http://www.spraypolyurethane.org/spf_basics (Mar. 17, 2011).

*2009 ASHRAE Handbook of Fundamentals, Ch. 26, Table 4, states 1.5 inch thick layer is 9.09 h ft^2 °F/BTU which is 6.06 per inch@75°F

** 2009 ASHRAE Handbook of Fundamentals, Ch. 26, Table 4, states 3.33 per inch@75°F

To create a polyurethane form, two liquids are combined and interact chemically. The two liquids usually arrive in different containers (often called the "A side" and the "B side"). The A side of a spray polyurethane system is commonly comprised of methylene diphenyl diisocyanate (MDI) and polymeric methylene diphenyl diisocyanate (pMDI). The B side is typically a blend of polyols, catalysts, blowing agent, flame retardant, and surfactant. While the polyols chemically react with the A side to make the foam, the other B side components help control the creation of the foam bubbles (the cells) and provide other properties such as flame-retardance (ACC 2010).

Polyurethane also comes in a "one-component" form, in small aerosol cans (for example, GREAT STUFF™). In the can, the two foam components have been partially reacted and finish forming when the foam is sprayed. The cans are used by both professionals and homeowners to seal small gaps and spaces around windows and doors. The foam comes in several formulations designed for different uses (windows, larger gaps, etc.) Most building supply houses sell this type of canned spray foam. Users shoulde careful not to overfill the available crack space, because this material is very sticky and the overflow can be hard to remove.

Most polyurethane foam is sprayed using either low-pressure (usually less than 250 psi) or high-pressure systems (800–1600 psi). Low-pressure systems are more often used to seal and insulate small areas.

High-pressure spray foam systems are used by professional foam contractors for new construction or major renovation. The contractors generally have 55 gallon drums of the ingredients, air supply systems, heaters, generators, spare parts, and protective gear in a truck or trailer (Fig. 2) that they move to the site.

Fig. 2. High-pressure spray foam rig.

The isocyanate component of spray polyurethane foam is a hazardous material (CDC 2004, 2010). The National Institute for Occupational Safety and Health describe the health effects of isocyanate exposure as irritation of skin and mucous membranes, chest tightness, and difficult breathing. Isocyanates include compounds classified as potential human carcinogens and are known to cause cancer in animals. Application of large quantities of foam requires professional equipment, training, and protective clothing, including respirators and skin protection. Unprotected people should not be in the area when the foam is applied, and adequate ventilation is necessary. A best practice is to allow only the person applying the foam in the house during spraying. The building may need to be vacated while the foam cures. It is always a good idea to read and understand the Material Safety Data Sheet (MSDS) for the product being used. They should always be available at the site from the spray applicator. A copy of the MSDS for all foam materials used on the retrofit job and installed in the home must be kept with each crew and vehicle and made available to all workers and homeowners upon request.

Some polyurethane foam manufacturers advertise their products as "green." Some foams, such as Demilec Heatlok Soy®, use recycled polyethylene terephthalate plastic (PET) as part of the ingredients (Demilec 2007). The polyol component of the B side of the mixture may also include sucrose-based (e.g., corn, sugar beets, sugar cane) or oil-based (e.g., soy) agricultural polyols, but these generally only make up 10 to 20% by weight of the ingredients of the foam (Dwyer

2004). Other brands may claim green credentials by replacing the chlorofluorocarbon propellants with more environmentally friendly chemicals.

Icynene makes several water-blown polyurethane-free foams. Carbon dioxide, created by the chemical reaction, is used to expand the foam, avoiding the use of ozone-depleting chemicals. These foams are available in both low-density, open-cell and medium-density, closed-cell varieties (Icynene 2011). There are also "renewable based" foams in both densities; these foams use castor oil as part of the polyol component. Areas sprayed with these foams are safe for occupancy after 24 hours and produce no detectable emissions after 30 days (Thom 2009).

2.3 Urea Formaldehyde Foam

Urea formaldehyde is a thermosetting resin made from urea and formaldehyde, which are heated in the presence of a mild base. The resin is typically used as an adhesive in manufacturing but when mixed with foaming agent forms foam insulation. The liquid is sprayed into areas needing insulation, where it sets up within minutes. Urea formaldehyde foam insulation (UFFI) was widely used during the 1970s in drill-and-fill wall cavity applications.

UFFI releases formaldehyde as it cures, with most being released in the first few months. With time, the foam shrinks and may become dry and crumbly. Removal of the foam can be expensive and requires special procedures for removal and disposal. In the 1980s, concern grew about the safety of exposure to formaldehyde from UFFI. In 1982 the Consumer Product Safety Commission banned the use of UFFI. Although the ban was eventually overturned in court, UFFI is no longer a commonly used home insulation. (CPSC 1997)

Older UFFI insulation in homes is unlikely to release formaldehyde and is considered safe. Home owners considering additional insulation will choose a newer product, but they may be forced to decide whether to remove the existing insulation or to find a type of insulation that can be added to the UFFI to increase R-value and to fill in areas where the UFFI shrank.

3. BEST PRACTICES FOR RETROFIT

3.1 First Steps

In new home construction, one can plan the measures to be used to add insulation and reduce infiltration and install them at the appropriate times during the construction sequence. Retrofit presents other challenges, as all areas one might want to insulate cannot be easily reached.

The first step for a homeowner should be to get an energy evaluation of the house to help determine the priorities for retrofit. A first and very important step is to try to eliminate excessive air leakage. The best way to do this is to perform a blower door test, which may be available through a contractor or energy service firm. The blower door apparatus seals the door in which it’s installed except for a fan which provides a negative pressure inside the house relative to the outside. The flow out from the house produced by the fan is measured, and when combined with an estimate of the interior volume of the house, provides an estimate of the ACH. The ASHRAE standard to maintain healthy indoor air is about 5 ACH when the indoor air pressure is 50 Pa (0.0073 psi) below that outside (ASHRAE 1989).

As part of a deep retrofit research project, ten older homes (15-110 years old) in the Knoxville, Tennessee, area were selected. Blower door tests found leakage rates from 8 to 28 ACH at 50 Pa. Leakage rates significantly above the standard of about 5 ACH can greatly undermine energy efficiency. If leakage rates are reduced below this standard, the necessary level of air changes for safe indoor air can be achieved using mechanical ventilation; mechanical ventilation with provisions for energy recovery can provide even greater energy efficiency. While the blower door is operating, a person can often feel the air leakage and identify areas that should be sealed. If no blower door is available, consider some of the common leakage areas, and look into options for air-sealing. If you have existing insulation, decide whether you should increase the R-value. Application of spray foam generally requires removing the old insulation first (InspectAPedia 2011), or at least pushing it to the side to gain clear access to the air leakage sites. The final system should protect against air leaks, moisture damage, mold, and pests.

3.2 Checklist for Air-Sealing

A DOE report, *Retrofit Techniques & Technologies: Air Sealing, A Guide for Contractors to Share with Homeowners* (PNNL 2011) contains the following air-sealing checklist with 19 specific locations that should be checked. These locations are identified in Fig. 3.

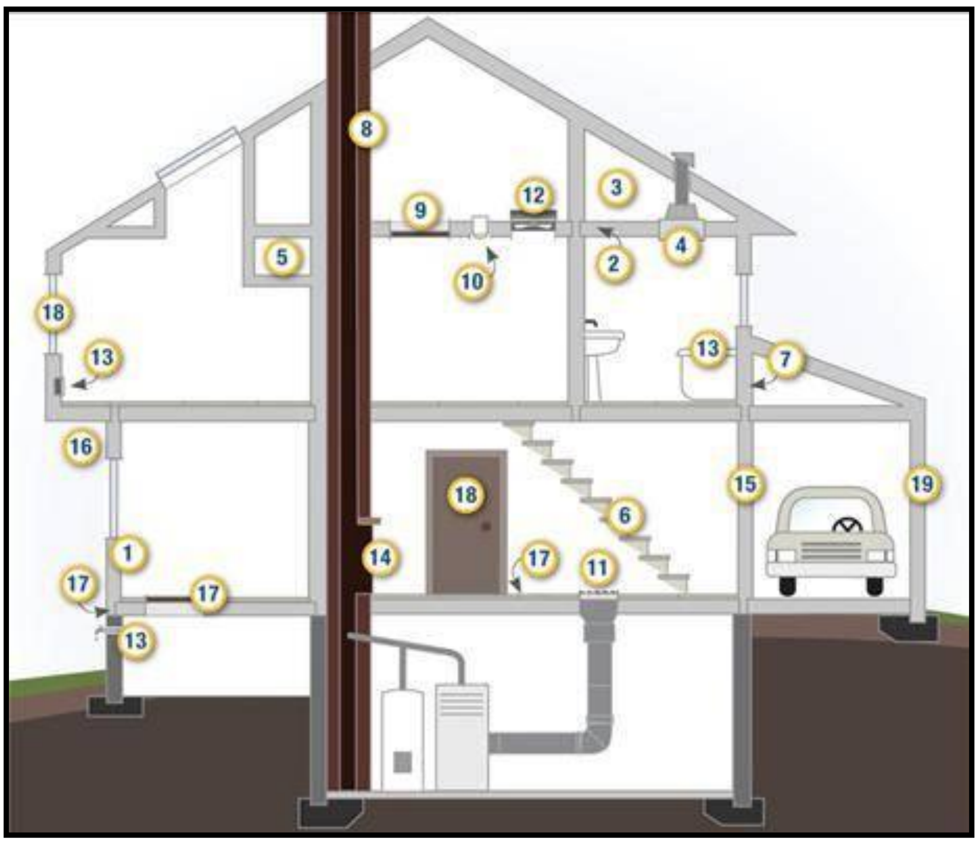

Fig. 3. Areas where air sealing can improve energy efficiency, comfort, and building durability. *Source: Retrofit Techniques & Technologies: Air Sealing A Guide for Contractors to Share with Homeowners*, PNNL-19284, Pacific Northwest National Laboratory and Oak Ridge National Laboratory, Apr. 12, 2010.

1. **Air barrier and thermal barrier alignment:** The air barrier is in alignment with the thermal barrier (insulation).

2. **Attic air sealing:** Top plates and wall-to-ceiling connections are sealed (Fig. 4).

3. **Attic kneewalls:** Air barrier is installed at the insulated boundary (kneewall transition or roof, as appropriate) (Fig. 5).

4. **Duct shaft/piping shaft and penetrations:** Openings from attic to conditioned space are sealed. These quite common construction flaws are called "attic bypasses."

5. **Dropped ceiling/soffit:** Air barrier is fully aligned with insulation; all gaps are fully sealed. They are commonly found in kitchens above cabinets and bathrooms where ceilings are dropped to enclose shower stalls.

6. **Staircase framing at exterior wall/attic:** Air barrier is fully aligned with insulation; all gaps are fully sealed. The typical construction sequence is to construct the stairs before installing insulation. Once the steps are built, it is hard to get access to all the areas on the outside walls to air-seal and insulate. Consequently, breaks in the air barrier and uniform layer of insulation are often present.

7. **Porch roof:** Air barrier is installed at the intersection of the porch roof and exterior wall.

8. **Flue or chimney shaft:** Opening around flue is closed with appropriate (metal) flashing and remaining gaps are sealed with fire-rated caulk or sealant. This flashing should be sealed to all surfaces, flue, and neighboring structural wood members with fire-rated sealant. Do not use nails (Fig. 6). Build a metal flashing dam higher than final insulation layer depth and maintain a 3 inch gap between the insulation and flue.

9. **Attic access/pull-down stair:** Attic access panel or drop-down stair is fully gasketed for an air-tight fit (Fig. 7).

10. **Recessed lighting:** Fixtures, if properly rated, are provided with air-tight assembly or covering. For all remaining non-insulation-contact recessed lighting fixtures, build a metal dam higher than final insulation layer depth and maintain a 3 inch gap between the insulation and the non-insulation-contact-rated fixture.

Fig. 4. Contractor seals an interior wall top plate in the attic. Photo: Chad Greene.

Fig. 5. Foam sealed knee walls. *Source*: Jeff Christian et al., *Tennessee Valley Authority's Campbell Creek Energy Efficient Homes Project: 2010 First Year Performance Report July 1, 2009–August 31, 2010*, Fig. 86.

Fig. 6. Gap around flue as it enters attic should be sealed with sheet metal on the floor of the attic. Follow all fire code requirements—these vary depending on type of flue (single, double, insulated, etc.).

Fig. 7. Insulated and sealed attic opening.

Fig. 8. Insulated, sealed cover for whole house fan. *Source*: http://www.batticdoor.com.

Fig. 9. No backing behind shower.

11. **Ducts:** All ducts should be sealed, especially in attics, vented crawlspaces, and floor rim joist areas (Boudreaux 2011, EPA 2009).

12. **Whole-house-fan penetration at attic:** An insulated cover is provided that is gasketed or sealed to the opening from either the attic side or ceiling side of the fan (Fig. 8).

13. **Exterior walls:** Service penetrations are sealed and air-sealing is in place behind or around shower/tub enclosures, electrical boxes, switches, and outlets on exterior walls (Fig. 9). The tub/shower surround routinely is installed at an earlier point in the construction process, before air-sealing and insulation installation. This requires that the areas which will be covered up must be sealed and insulated before the remainder of open cavities are treated.

14. **Fireplace wall:** Air-sealing is completed in framed shaft behind the fireplace or at fireplace surround.

15. **Garage/living space walls:** Air-sealing is completed between garage and living space. Pass-through door is weather stripped (Fig. 10 and Fig. 11).

Fig. 10. Wall between garage and kitchen and close-up of electrical box. (Notice electrical switch boxes form a potential short leakage path.)

Fig. 11. Wall between the garage and kitchen in energy-efficient house. (Flash-and-batt walls form good air seal between garage and kitchen.)

16. **Cantilevered floor:** Cantilevered floors are air-sealed and insulated at perimeter or joist transition (Figs. 12, 13, and 14).

17. **Rim joists, sill plate foundation, and floor:** Rim joists are insulated and include an air barrier. Junction of foundation and sill plate is sealed. Penetrations through the bottom plate are sealed. All leaks at foundations, floor joists, and floor penetrations are sealed. Exposed earth in crawlspace is covered with Class I vapor retarder overlapped and taped at seams (Figs. 15 and 16).

18. **Windows and doors:** Space between window/door jambs and framing is sealed (Figs. 17 and 18).

Fig. 12. Cantilevered floor improperly insulated and sealed.

Fig. 13. Improperly insulated cantilevered floor from outside.

Fig. 14. Flash-and-fiberglass insulation under cantilevered floor system provides air-tight construction in high-energy-efficiency house.

Fig. 15. Uninsulated rim joists.

Fig. 16. Rim joist (at top of picture) is well-insulated and sealed.

Fig. 17. Foam insulation around windows.

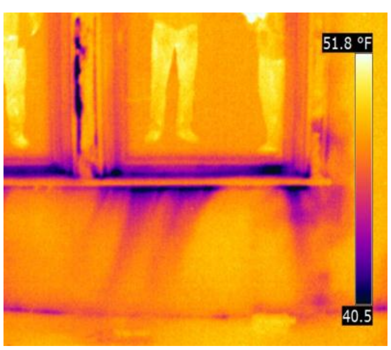

Fig. 18. Infrared image showing colder air drawn in around window by blower door. (Note wispy fingers-like extensions of purple color indicating air intrusion.)

19**. Common walls between attached dwelling units:** The gap between a gypsum shaft wall (i.e., common wall) and the structural framing between units is sealed.

A closed-cell spray foam can be used in most of these locations. Properly applied spray polyurethane foam (SPF) will ensure that the infiltration barrier and thermal barrier align (item 1 on the list) because the polyurethane foam provides both sealing and insulation. The application, climate, and type of spray foam chosen determine whether an additional vapor-diffusion retarder should be added.

In areas such as around recessed lighting and near fireplaces or heat sources, one should check the fire resistance of the particular foam to determine whether it is a suitable choice. Manufacturers of recessed lights (Fig. 19) and electrical boxes and equipment may provide guidance as to which, if any, spray foams could be used to seal around their products. Look for a label (Fig. 20) that says it is suitable for direct insulation contact (IC rated).

Local fire codes may require that a fire-retardant material be added to the top of the foam for some uses. The insulating ability of polyurethane and polyisocyanurate foams can lead to rapid heat build-up.

Fig. 19. Recessed lighting installed before ceiling is finished and insulated.

The Spray Polyurethane Foam Alliance recommends that all interior applications of SPF receive a thermal barrier as soon as possible after initial insulation, except when specifically approved by building code authorities based on fire tests specific to the application (SPFA 2005). The foams should not be used adjacent to or above furnaces, fireplaces, or other sources of very high temperatures. While no more flammable than other types of insulation, contact with flame can cause the foam to ignite, releasing toxic and combustible gases. Remember that live electrical connections should be turned off when foam is sprayed in the area.

Fig. 20. Label showing electrical fixture is "approved for direct contact with thermal insulation."

The guidelines for thermal barriers are not uniform. Some local jurisdictions require a thermal barrier if combustion products are within sight of the foam; others require the thermal barrier if the area is to be used for storage. The local requirements should be investigated thoroughly before choosing the foam product for a specific application in a specific jurisdiction.

3.3 "Hybrid" Applications of Spray Foam

Closed-cell spray polyurethane foam has a high R-value and can be used alone to seal and insulate, but using only closed-cell SPF is sometimes not the least expensive method to get the desired R-value. Spray foam is often used in hybrid applications. After a base layer of 1–3 in. thick closed-cell foam is sprayed, a layer of open-cell foam, fiberglass, cellulose, or other material is added. This application is often called "flash and fill" (Fig. 21) or "flash and batt" (Fig. 22), depending on the type of insulation added to the base foam layer. Figures 23 and 24 show the application of two foam layers.

In cold climates some sources (e.g., Munns 2011) suggest that the base layer of closed-cell foam should provide at least 50% of the total R-value to avoid condensation issues. Because the closed-cell foam is a good moisture barrier, any condensation in that layer is contained. If the condensation occurs in open-cell spray foam or fiberglass batts, you can get condensation between the insulation layers.

Fig. 21. Flash-and-fill done correctly in cantilevered floor. (Note the closed-cell foam under the second floor right above the blown in fiberglass.)

This advice may be more appropriate for a colder climate than for the mixed-humid area. One of the retrofitted houses described later (Green House) used only 10 in. of low-density, open-cell foam. The performance of foam in different combinations is being monitored during 2011–2012 in an Oak Ridge National Laboratory (ORNL) deep-retrofit study (Christian et al. 2010). The study will continuously measure the temperature and relative humidity (RH) in various layers of foamed roof systems to determine how well different foam combinations perform in the mixed-humid climate.

3.4 Precautions for Applications

It is important to determine the specifications for the foam you use. The manufacturer will specify the proper ranges of temperature, humidity, and wind speed for outside application for the particular foam. Failing to pay attention to these limitations can give a poor result. The surface for application needs to be dry and reasonably clean, i.e., a “paintable” surface. Outside applications include spraying foam over siding or filling wall cavities from the outside when the siding has been removed. Spraying foam on a low-slope roof is probably the most frequent outside application. Overspray precautions include making sure all vehicles are away from the site.

Fig. 22. Flash-and-batt insulation.

Fig. 23. Attic was first sprayed with 1 in. of closed-cell foam.

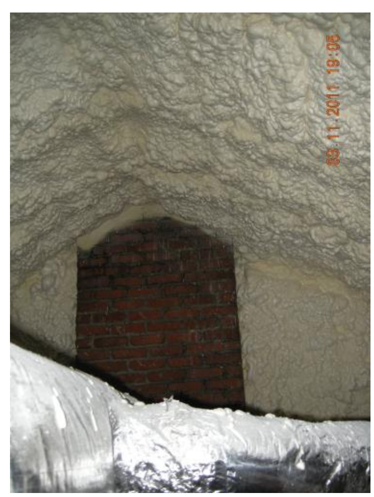

Fig. 24. Attic with 1 in. of closed-cell foam was covered with 8 in. of open-cell foam.

Check the MSDS for precautions and first aid instructions. Have a fire extinguisher nearby. Clear the area of all persons not directly involved in the work, and isolate the area being foamed as much as possible. It is a good idea to create temporary no parking zones around an external spray foam application, so that cars in the area do not get sprayed with traces of foam. Attics and crawl spaces may create additional hazards and need to be treated as a confined space for safety purposes, with requirements for full suits and respirators. Eye glasses and camera lenses are easily damaged if exposed to the foam application process.

Polyurethane foams are subject to more rigid safety requirements than some other materials because of their ingredients. The protective equipment requirements increase when SPFs are applied to large areas using high-pressure spray systems. The Center for Polyurethanes Industry provides a safety manual which contains descriptions of good safety practices for SPF (CPI 2010). A summary of guidance for protective equipment from this manual is shown in Fig. 25.

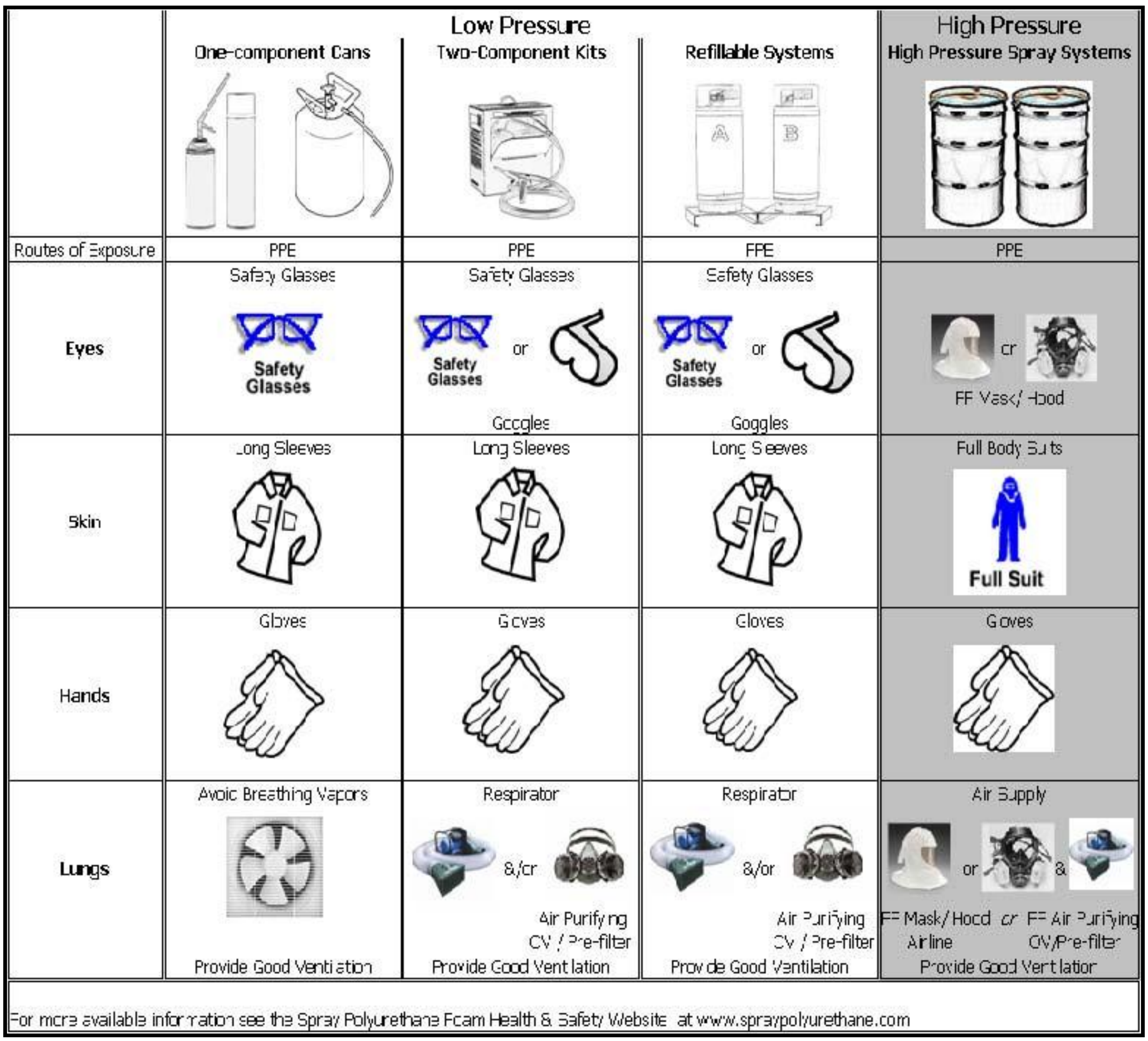

Fig. 25. Personal protective equipment guidance for SPF applicators and helpers. *Source: Health and Safety Product Stewardship Workbook for High-Pressure Application of Spray Polyurethane Foam (SPF),* Center for the Polyurethanes Industry, The American Chemistry Council, Mar. 15, 2010, Fig. 7.

The spray foam insulation should be inspected before any covering material is applied. Unfortunately, lack of attention to the ratio of the mixtures, the functioning of the mixing gun, the temperature of application, relative humidity, and condition and temperature of the surface being foamed can affect the final product. Foam should not be sprayed when the ambient temperature is within 5°F of the dew point (Knowles 2010). Professional spray rigs monitor the mixtures and temperatures to reduce these problems. Moisture and an occasional “bad batch” of chemicals can still cause problems, but the experienced applicator can usually detect these problems from the behavior of the foam (Ernst 2011).

Closed-cell foam gives off heat from the exothermic reaction as the foam cures. Too much heat can cause the foam to crack and shrink. To avoid this problem, foam is usually applied in “lifts” about 1.5 in. thick. Allowing 10 to 15 minutes between these lifts gives the excess heat time to dissipate before more foam is added. Foam should be applied in overlapping passes from side to side. When spraying cavities, spray the foam around the edges (“picture framing” each cavity) and then fill in the middle, working parallel to the edge.

Open-cell foam can usually be applied in one lift. The edges of cavities are again sprayed first before the area is filled in, generally starting at the bottom. The expansion of open-cell foam is less predictable. Some trimming is usually necessary before adding the surface covering, such as drywall.

Small problem areas in the foam can usually be repaired by cutting away the bad foam, leaving a 45° angled surface so the patch will adhere. After cleaning and preparing the surface underneath, additional foam can be added. If the application has to be waterproof (such as a roof), caulk may be used around the seam as well as a waterproof paint (Knowles 2010).

Prior to spraying, all surfaces not intended to be sprayed need to be covered. This includes all windows and doors, furnishings pulled away from the spray target areas but left in the house, HVAC supply and return registers, and all light and electric fixtures and boxes.

A common problem with spray foam is ensuring that the specified thickness of the foam has been attained. It is best if the homeowner and the foam contractor agree in advance on how the depth of the foam will be checked. For example, every third cavity could be checked high, low, and at half-wall or half-roof-span height. These readings are representative of the surrounding area within 2 feet of the sample point. Additional foam may need to be added before batting or additional materials are added. The adequacy of the foam installation can also be checked if a blower door and infrared camera are available on site (and there is sufficient difference between the indoor and outdoor temperatures). It is expensive to bring the spray foam rig back to a site, and much more efficient to ensure that the job is done to the satisfaction of all before the foam contractor leaves.

Another thing to remember is that once the infiltration through leaks into the house has been reduced, special arrangements may be necessary to ensure that enough fresh air circulates in the house. It may be necessary to add mechanical ventilation with energy recovery capability to obtain the optimal ventilation. ASHRAE Standard 62-1989 (ASHRAE 1989) requires at least 0.35 ACH or at least 15 cfm per person. This standard can be used until July 1, 2013. The new ASHRAE Standard 62.2 (ASHRAE 2010) defines sizing for continuous ventilation fans and spot ventilation. The 2010 standard is reflected in the Home Energy Auditing Standard published by the Building Performance Institute, Inc. (BPI 2010).

4. NEW WORKFORCE GUIDELINES

DOE will release *Workforce Guidelines for Home Energy Upgrades* (DOE 2010) later this year. This document has been developed for DOE by the National Renewable Energy Laboratory to promote a high-quality energy retrofit industry with well-trained workers and clear standards for quality work. The guide addresses standard work specifications, a technical standards reference guide, and identification of the essential knowledge, skills, and abilities of workers.

The standard work specifications are organized by the different systems found in residential buildings. Under each system, there are subtopics and details that provide the specifications for quality work. The material is referenced to applicable laws, regulations, and standards. The work specifications that involve spray foam are spread across sections dealing with home performance assessment, combustion appliances, ventilation, air-sealing, heating and cooling, insulation, crawl spaces and basements, and base load.

DOE developed this document at the same time that the U.S. Environmental Protection Agency (EPA) was developing *Healthy Indoor Environment Protocols for Home Energy Upgrades* (EPA 2010). The two documents were coordinated so that the workforce guidelines will at least meet the minimum standards set by the EPA document.

These guidelines have several purposes:

- Enable residential retrofit program administrators to strengthen their field guides and other work manuals by incorporating these standard work specifications
- Assist in development of academic and job training course content and curricula corresponding to the job task analyses and knowledge, skills, and abilities necessary for these jobs
- Build confidence among consumers and financial suppliers that any retrofit work will be of high quality and produce the expected energy savings
- Facilitate technical standards development by appropriate groups
- Increase workforce mobility by establishing the essential knowledge, skills, and abilities upon which worker credentials should be based
- Lay the foundation for an effective worker certification and training program accreditation

A second public review of DOE's *Workforce Guidelines for Home Energy Upgrades* is anticipated in the fall of 2011 (NREL 2011). The document should be checked periodically to gather updates on best practices for retrofit spray foam application. Volunteer committees have been formed to maintain this very important document (DOE 2010).

5. DEEP HOME RETROFITS USING SPRAY FOAM: EXAMPLES

In 2009 ORNL and the Tennessee Valley Authority (TVA) began a program to look at several homes in East Tennessee to determine how extensive retrofitting of older homes could reduce the homes' energy use and peak electricity demand. With the exception of two houses that were part of a research effort described below, the homeowners were volunteers, generally energy-conscious and eager to upgrade their dwellings. Although the program received federal funding for monitoring and documentation, homeowners paid for most of the suggested upgrades themselves. A number of these homes had spray foam applications. This section discusses the lessons learned and some of the performance measurements.

The houses discussed in this report are at various stages of retrofitting, so differing amounts of information are available at this time. The goal of the project is to collect at least a year's worth of performance data on the houses. Several houses are only in the beginning stages as the home owners decide which improvements to make. In these cases, only the potential energy savings can be discussed at this time.

There is an ongoing program with the Tennessee Valley Authority to compare the performance of three similar houses in the Campbell Creek community in west Knox County, Tennessee. The house used as a baseline is an all-electric home built (and certified) according to the 2006 International Energy Conservation Code (ICC 2009). This baseline house is similar to a house that a builder would have built for sale in 2005–2008. However, at the time of construction, no energy inspections were being conducted in this area. The first energy inspections began in Knox County on October 1, 2010. The second house was identical, except that it includes upgrades that a homeowner would be able to make after construction. For example, spray foaming the attic could be done to investigate the retrofit energy savings. The third house is an advanced energy-efficient house with "flash and fill" insulation, which is instrumented with heat flux transducers, temperature thermistors and relative humidity (RH) sensors in multiple locations. All three houses are programmed to simulate "average U.S." occupancy for a three-bedroom house with 2400 square feet. In all three houses the lights go on and off, the refrigerator doors open, washers and dryers run, etc., all at the same times.

The second Campbell Creek house, called CC2, is the first example of a retrofitted house presented in this section. One full year's worth of data has been collected on the performance of the house. The other example houses are all going to be occupied and are in various stages of retrofit, and full performance data is currently being collected on the ones that have been completed.

The changes on all the houses' envelopes are quantified with the measurement of ACH at a reference pressure of 50 Pa. Two computer programs, RemRate and EnergyGauge, were run independently to simulate the energy use of each house and produce a Home Energy Rating System (HERS) rating. A HERS rating of 120-135 was found to be typical for an existing house studied under the ORNL Deep Retrofit Project, and a 0 would technically be a "zero energy" house.

Campbell Creek Retrofit House (CC2)

Fig. 26. Campbell Creek retrofit house, CC2.

CC2 (Fig. 26) is a 2400 ft^2, two-story, south-facing dwelling. The house has three bedrooms, living-dining room, kitchen, laundry room, two-and-a-half bathrooms, and a bonus room over the attached garage.

The walls and roof are made of typical 2 × 4 frame construction. The walls are rated R-11 with the attic ceiling at R-30. The attic ceiling was insulated with 2 in. of closed-cell and 3 in. of open-cell foam, covered with 2 in. of Spider insulation. This combination was not originally intended, but the important specification was that the insulation should attain a final average value of R-30. Researchers experimented with the attic insulation in CC2 during construction. At one point a large amount of insulation was actually removed from the house before the final set of insulation layers was installed. The slab is insulated along the perimeter with 1-in. thick × 24 in. horizontal R-5 extruded polystyrene on all sides except adjacent to the garage.

Fig. 27. Air conditioning unit inside attic insulated with spray foam and spray fiberglass.

The baseline standard "builder" house (CC1) measured 5.7 ACH at 50 Pa on a blower door test. The blower door test of CC2, reflecting the retrofits, measured 3.43 ACH at 50 Pa. Both houses had the air conditioning supply and return ducts located in the attic. In CC2, the attic was sealed and insulated with 2 in. of closed-cell and 6–8 in. of open-cell spray foam and covered with 2 in. of sprayed fiberglass (Fig. 27). The knee walls in the bonus room were backed, sealed with 2 in. of closed-cell foam, and insulated. The process of foaming the attic led to about a 40% decrease in whole-house air infiltration.

Simulation software produced a HERS index of 101 on the baseline house, CC1. In comparison, the HERS index calculated for CC2 was down to 66. CC2 had a number of energy-saving retrofits compared to the baseline house, so not all the improvement in energy efficiency can be attributed to the foam. The foam improved the air-tightness of the house by 40% and enclosed the HVAC system in the conditioned space, decreasing the energy used for space heating and cooling by 17%. Compared to the baseline house, this is a savings of 4768 kwh per year (Christian 2010).

Several problems were identified in the process of retrofitting. Sealing was needed in the area around the electrical box on the wall between the house and the garage (Fig. 28). Another potential problem identified involved the box beam from the front porch that penetrated the house envelope. Additional foam for sealing could have been applied around the beam shown in Fig. 29 and Fig. 30.

Fig. 28. Electrical box compressing insulation and lacking seal.

Fig. 29. Front porch box beam.

Fig. 30. Box beam penetrating house.

CC2 was fitted with 90 sensors to help document the performance of the house. There is a year's worth of performance data from CC2, as well as from the standard builder house (CC1), which was used as the control. This work has revealed some interesting results in the CC2 attic that was sealed and insulated with spray foam.

The temperature and relative humidity in the sealed attic did not vary much from the conditioned living areas of the house. The attic temperature in the summer remained lower than 83°F, and there were no air conditioning supply or return ducts serving the CC2 attic. The temperature in the vented attic in the control house reached 133°F (Christian et al. 2010)**.** These maximum monthly temperatures are shown in Fig. 31.

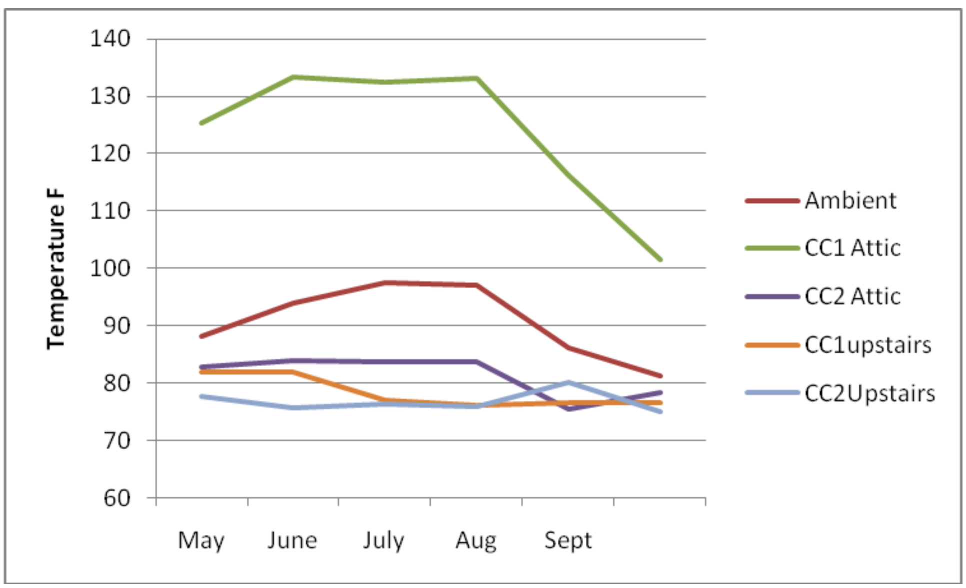

Fig. 31. Maximum monthly attic temperatures compared to the maximum ambient temperature and the maximum air temperature in the top floor for CC2 and control (CC1). *Source*: Jeff Christian et al., *Tennessee Valley Authority's Campbell Creek Energy Efficient Homes Project: 2010 First Year Performance Report July 1, 2009 – August 31, 2010*, ORNL/TM-2010/206, ORNL, Oak Ridge, TN, Nov. 2010, Fig. 109.

Figure 32 shows the average monthly temperatures of the attic air spaces in CC1 and CC2, along with the average ambient temperature and the upstairs space temperature. The average temperature in the sealed and insulated attic in CC2 was not much different from that on the upper floor. The average temperature in the vented attic of CC1 tracks the ambient temperature but remains somewhat warmer than the outside air due to heat loss from the ducts and the house in the winter and from solar gain during the summer and the winter.

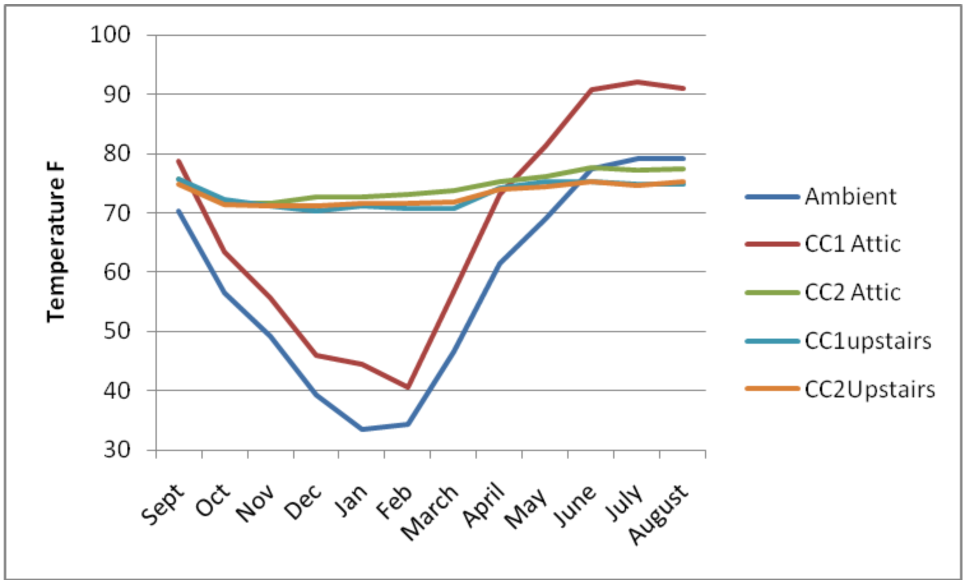

Fig. 32. Average monthly attic, ambient, and top floor air temperatures measured in CC1 and CC2. *Source*: Jeff Christian et al., *Tennessee Valley Authority's Campbell Creek Energy Efficient Homes Project: 2010 First Year Performance Report July 1, 2009– August 31, 2010*, ORNL/TM-2010/206, Oak Ridge National Laboratory, Oak Ridge, Tenn., November 2010, Fig. 110.

The largest retrofit energy savings for homes with ductwork outside the building envelope was accomplished by enclosing the conditioned space to enclose the ducts, as in CC2. Using spray foam to convert the attic to a conditioned mechanical room cost $5,916 compared to the total cost before rebates and incentives of $9,132. The thickness of the high-density foam and other insulation must be optimized for the climate.

Moisture sensors were installed in the north- and south-facing roof assemblies. The maximum RH is found in the north roof between the oriented strand board (OSB) sheathing and the closed-cell foam layer in January. In January 2010 the average RH at this location was 70.3%. In January 2011 the average RH was 62.3%. The average temperature at this same location for the two months was the same, 34°F. The maximum RH measured in January 2010 and 2011 was 89%. There is no concern about moisture levels accumulating in the OSB in this roof assembly. In the summer months the average measured RH is 11–16% at the same north-facing roof assembly location.

During the three hottest summer months (June, July and August), the maximum roof sheathing temperature is around 180°F, 30°F higher in the roof assembly with the spray foam compared to the conventional vented attic in CC1, at around 150°F. The highest roof sheathing temperatures are found on the south-facing roof. The average monthly temperature of the south-facing roof sheathing in CC2 (insulated with foam) is 98.6°F, compared to 93.6° in the conventional vented attic in CC1. The shingles on these houses are the same weathered wood (gray) color with a solar reflectance of 8.2. In general the higher the roof membrane temperature, the shorter the life, but it is felt that peak and average summer temperatures under a black roof on CC1 would be as high or higher than found on CC2 with R-30 insulation sprayed on the underside of the roof sheathing.

When an attic with existing insulation is retrofitted in this way, the spray foam insulation contractor will usually recommend removing the insulation in the attic floor to remove the uncertainty about leakage of conditioned air in the summer. If the insulation is left in place this could increase the amount of moisture accumulation in the sealed attic space because less indirect cooling will occur through the attic floor. Table 2 provides a reasonable cost range in 2010 for removing existing insulation and installing spray foam. Christian (2010) discusses in great depth the energy and cost savings resulting from creating a cathedral ceiling in the attic. In this case, improving the air-tightness of the attic and enclosing the ducts and upstairs HVAC system in the conditioned space created a positive cash flow (meaning that if the funds to cover the cost of the retrofit were financed by a ten-year loan at 6%, the monthly loan payment would be less than the energy cost savings).

Table 2. Cost range for true attic retrofit with low-density R-30 SPF, assuming 1354 ft^2 attic floor area and 1763 ft^2, 10/12-pitch roof

	Price range ($/$ft^2$)			Total price range		
	Low	High	Average	Low	High	Average
Remove existing insulation on attic floor	$0.40	$0.75	$0.58	$542	$1,016	$779
Insulate roof deck with 6–8 in. of 0.5 lb foam	$1.50	$1.75	$1.63	$2,644	$3,085	$2,865
Install intumescent paint ignition barrier	$0.75	$1.10	$0.93	$1,322	$1,939	$1,631
Total				$4,508	$6,040	$5,274

Source: Jeff Christian et al., *Tennessee Valley Authority's Campbell Creek Energy Efficient Homes Project: 2010 First Year Performance Report July 1, 2009–August 31, 2010*, ORNL/TM-2010/206, Oak Ridge National Laboratory, Oak Ridge, Tenn., November 2010, Table 13.

Baker House

Fig. 33. Baker house in Oak Ridge, Tennessee.

The Baker house (Fig. 33) is a 3571 ft^2 house in Oak Ridge, Tennessee. The four-bedroom house was built in 1967. The house contains two stories and a conditioned basement.

The initial tests on this house identified significant problems with infiltration and flow of air within the walls and between the floors. The blower door test showed about 15 ACH at 50 Pa, slightly higher than average for existing homes. A HERS rating of 138 was calculated, with an average annual energy cost of $2710.

Fig. 34. Open wall cavities, ductwork, and electrical penetrations support unwanted air flow.

Open wall cavities, ducts, and wiring penetrations allow outside air to move in and around, eventually leaking into the living space (Fig. 34). The initial energy evaluation recommended sealing the rim/band joint on the basement and entry levels to stop air leaks.

The energy simulation programs were rerun assuming that some of the recommended changes had been made, including adding insulation to the basement and attic planes. This simulation resulted in a HERS rating of 83, indicating potential for substantial energy saving after retrofitting.

After work was completed on the house, the multi-point blower door found a final infiltration rate of 7.55 ACH at 50 Pa. The homeowner chose not to insulate the basement walls, which was one of the recommended measures. ORNL installed four sets of heat flux transducers, thermistors and RH sensors to measure the performance of the basement walls. Measurements will be made for one year without insulation. Then four different methods of insulation, including SPF, will be used on different portions of the walls. Measurements of wall performance with the various types of insulation will be made for a year and compared.

Fig. 35. Sprayed foam insulation in porch roof.

Figure 35 shows foam insulation sprayed in an area between the porch roof and the house. This area was exposed by removing some of the front porch ceiling to gain access, which revealed a 1 by 10 ft hole in the air barrier of the house’s envelope.

Green House

Fig. 36. Green House, during the rehabilitation process, with restored exterior.

Green House (Fig. 36) is an old Victorian home in the central part of Knoxville, Tennessee. The house had been renovated with energy efficient measures and displayed as the Energy House during the 1982 World's Fair.

This renovation involved matching historic preservation with energy efficiency. Because the house was first gutted, there was the possibility of a rehabilitation that could earn Energy Star and LEED certification.

The house has 2200 ft^2, with 10 foot ceilings on the first floor and 9 foot ceilings upstairs. The initial blower door reading was nearly 18 ACH at 50 Pa. The balloon framing of the house, which conformed to common construction practices when the house was built, allowed air to flow within the walls from the basement to the attic. The balloon framing, combined with many penetrations (Fig. 37), allowed a lot of airflow, enough infiltration to have about the same effect as leaving a window open all the time.

Fig. 37. Spray foam used to seal band joist, openings in framing, and electrical penetrations.

Fig. 38. Spray foam applied to underside of roof.

The most significant use of spray foam in this house was its application to the underside of the roof (Fig. 38). The biggest innovation here is that the house is designed with all closed soffits and rakes. The air barrier on the walls is the weather wrap fabric. This fabric is extended into the closed soffits and rakes, which were blown full of open-cell, low-density foam. The confirmed thickness of the foam in the roof produced a thermal resistance of R-38. These measures sealed and insulated the top of the attic and enclosed the upstairs ductwork within the conditioned envelope.

The first energy simulation on the house gave a HERS value of 149. In contrast, the last blower door test showed only 4.31 ACH at 50 Pa. Three of the windows had visible air gaps along the lower sash. Sealing these gaps led to a final 4.19 ACH at 50 Pa, measured on Mar. 30, 2011. The final HERs rating for this house is 55. It has been submitted by the architect to the U.S. Green Building Council and is scheduled to attain a LEED platinum rating, one of the first houses that have been gutted and rehabilitated to attain this high ranking.

The renovation of the Green House is complete. The house was placed on the market in March 2011 for $369,000 and sold in three weeks.

Summit House

Fig. 39. Summit House.

Summit House (Fig. 39) is a two-story, 2150 ft^2 home in Knoxville, Tennessee. The house complied with all building codes, but it was not properly sealed during construction. The blower door measured an air change rate at 50 Pa of about 12 ACH. Control of infiltration should reduce energy cost.

The computer simulations of energy efficiency produced a HERS rating of about 114. During retrofitting, on Mar. 28, 2011, EnergyGauge projected a HERS rating of 62 with the recommended upgrades and retrofits in place.

Figure 40 shows the uninsulated chimney enclosure looking down from the attic. Outside air from this area leaks into living room through the wall and fireplace enclosure and into a second-floor bedroom. Uninsulated areas of the basement (Fig. 41) also needed improvement.

Fig. 40. Uninsulated chimney enclosure.

Fig. 41. Uninsulated cinder block basement and band joist.

The owners of this house are very involved in the upgrades. In addition to reducing the infiltration (Fig. 42), they have removed the siding and are insulating the exterior walls by caulking all gaps and cracks from the outside. They then reinstalled the insulation and added ½ in. DOW SIS™ foam board, which is listed as R-3 and was measured by ORNL as R-2.74 in their ASTM C518 apparatus (ASTM International 2011). In addition, they are upgrading windows with Serious Materials Quad and triple-pane glass, replacing heating, ventilation, and air conditioning (HVAC) systems with multiple inverter-driven heat pumps, installing new water heaters, and insulating the walkout basement walls on the exterior with 2 in. of extruded polystyrene. The owner has purchased a solar photovoltaic system with a peak capacity of 5.8 kWh for the south-facing roof.

Figures 42 and 43 show the EnergyComplete™ system applied to the floor of the attic and the wall between the conditioned space and the unconditioned garage. The installation was confirmed by the blower door tests to have been very successful in these two applications. A different crew returned and tried to seal the accessible spaces in the walkout basement with the same product. However, that crew was apparently not trained on the how to properly install the EnergyComplete™ system. Some valuable lessons learned from this application are summarized below:

Fig. 42. **Owens Corning EnergyComplete™ is used to improve the air barrier between the garage and the conditioned space.**

Fig. 43. Sealed and reinsulated attic. (The fiberglass batts were removed and used in the crawl space under the office. The attic was vacuumed, the electric outlets were foamed with GREAT STUFF™, and the remaining cracks sealed with the pink EnergyComplete™ latex foam.) Then new insulation was blown in to create an R-value of 60.

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1. Larger cracks need to be identified, and properly sized backer rod (a flexible foam rope of varying diameter that fits snuggly into cracks wider than 1/4 in.) or equivalent needs to be installed to provide foam backing.
2. The oval spray pattern needs to always be applied with the longer axis of the oval perpendicular to the crack, even in corners.
3. The homeowner removed all old attic insulation and even vacuumed the attic. The manufacturer states that vacuuming is not necessary, since the air pressure of the foam nozzle will push the loose particles away prior to the foam hitting the substrate.
4. The homeowner used canned foam to first seal all electrical boxes penetrating the attic plane. The manufacturer states that this is not necessary; however, all electrical power should be shut off prior to foam application.
5. Obviously all non-insulation-contact-rated canned down lights should be replaced, but if not, follow proper insulation damming practices of providing at least 3 inches clearance on all sides and check local codes for how much area needs to be isolated above the non-insulation-contact-rated cans. In some jurisdictions the can must remain open to the attic space. The insulation-contact-rated cans are much better because they have an on-board temperature sensor that shuts off the light when the temperature of the light fixture gets too high, avoiding the ignition of surrounding combustible materials.

The retrofit is nearing completion. A projection based on blower door measurements suggests the final infiltration rate will fall to around 4 ACH at 50 Pa . The systematic foam air-tightening from attic, to basement, to walls (Fig. 43) has reduced the ACH at 50 Pa from 12 to 5.6, as shown in Fig. 44.

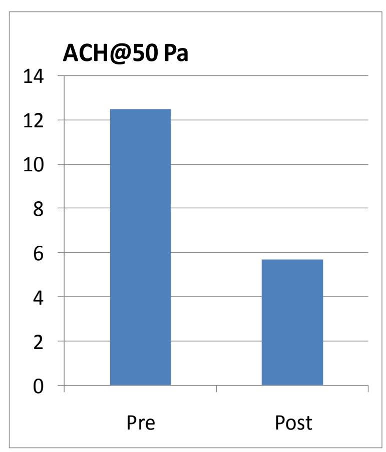

Fig. 44. Application of foam at Summit House reduced the ACH at 50 Pa from 12 to 5.6.

Gaiter House

Fig. 45. Historic Gaiter house was gutted before renovation.

This older house has been a fixture in Knoxville, Tennessee, since 1941. The 2520 ft^2 Gaiter House (Fig. 45) has two stories and a walk-out brick basement. The initial blower door test registered over 17 ACH and before installation of final interior trim the ACH at 50 Pa was 5.

The current owner gutted the house during renovation, leaving many more options for using spray foam as a sealant and insulator.

The house needed drainage improvements and some structural repairs before adding energy conservation measures. The owner decided to condition the attic space and leave a cathedral ceiling in the study on the right side of the house, shown in Figure 45. Ridge and soffit vents were stuffed with fiberglass batts and sealed over with closed-cell foam. One inch of closed-cell foam was sprayed on the underside of the roof and then topped with 8 in. of open-cell foam (Fig. 46). Low-rise foam was used to seal around windows and doors (Fig. 47). The typical minimum thickness of closed-cell foam always applied first by the manufacturer selected by the homeowner for this job is 1 in., so that is what was used on this deep retrofit as well.

Fig. 46. SPF shortly after application to underside of roof.

Fig. 47. Low-expansion foam around window.

In preparation for monitoring the performance of the house, sensors were placed on the exterior wall before the foam was sprayed. Once the insulation was completed, more sensors were placed on the inside of the insulation. Figure 48 shows the first set of moisture, temperature and heat flux sensors placed on the external wall before foam was applied.

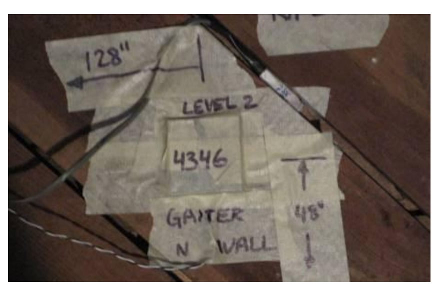

Fig. 48. Sensors attached to wall to monitor performance of insulation.

After each stage of foam application, blower door tests were conducted. The last applications were directed by the blower door test results. The entire foamed surface was checked three times for air leaks, marked with spray paint, and foamed over.

Prior to the fiberglass batts being installed in the above grade walls, the depth of the foam was checked. In several areas it was found that the specified depth had not been attained. It is recommended that the homeowner ensure that the statement of work for the contractor specifies how this depth check will be conducted. It is suggested that every third cavity be checked high low and at half wall or roof span height. The measured depth gage readings can be noted on sketches of each wall, roof, and gable area. The readings should be taken as representative of a circle 2 ft in diameter around the measured points. At the Gaiter house the spray foam contractor did return to bring all depths to the specifications in the contract.

After the fiberglass batts were installed in the wall cavities and drywall had been put in place, researchers returned to the house to conduct a systematic infrared (IR) scan both with and without the blower door fan in operation to check the insulation. In these images, the brighter areas are at higher temperatures. The images were taken on a cool morning after the heat had been turned on in the house all night. The house was scanned from the outside going counterclockwise around the entire perimeter. Then all three floors were IR scanned on the interior going counterclockwise. The blower door was set to cruise at 40 Pa and the same scans were repeated. The following IR shots were some of the most illustrative of remaining thermal and air leakage points in the Gaiter envelope.

Fig. 49. Infrared image of west end of Gaiter house.

Figure 49 shows the west side of the house. The area around the gable vent in the sun room is particularly bright. Figure 50 shows a close-up of the area, which is warmer than the surrounding air. The sunroom is a converted porch, which once had an attic over it. The ceiling had been converted to a cathedral ceiling, with the insulation sprayed on the inside of the roof, and the gable vent had been covered with ½ in. plywood and foamed.

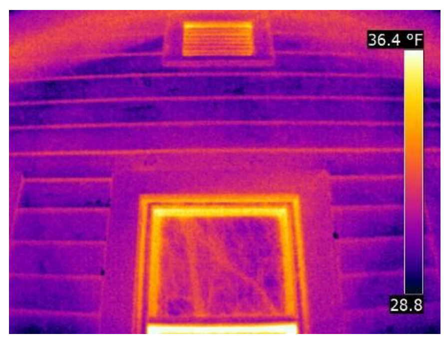

Fig. 50. Gable vent in sunroom area of the west façade.

The framing contractor had to trim some of the foam over the vent to clear the drywall plane. Consequently the foam layer was not as thick over the vent, producing the bright rectangle. The contractor added more insulation to the area from the outside.

Images taken of the same area from the inside show the vent area as cooler (Fig. 51). In Fig. 52, the house was partially evacuated using the blower door set at 40 Pa. Colder air would be drawn into the house through any openings, and the purplish area is deepening and increasing in size. Notice the bulging dark area in Fig. 52, indicating that the colder air is leaking into the home from the poorly sealed gable vent.

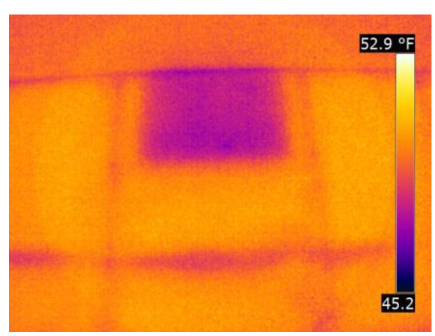

Fig. 51. Gable vent from inside sunroom.

In Fig. 53, there is a bright area under the eave on the east end of the rear of the house. During the retrofit, soffit vents under the eaves were stuffed with fiberglass insulation and then sealed with spray foam. The insulation seems to be missing in this location. The contractor redid this area from the attic.

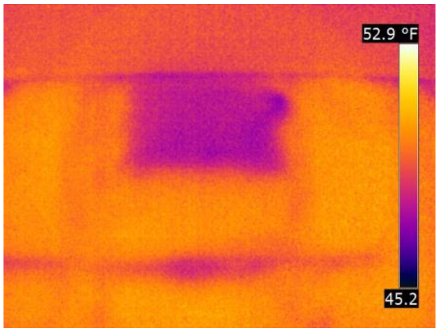

Fig. 52. Cooler air being drawn in through vent area by blower door.

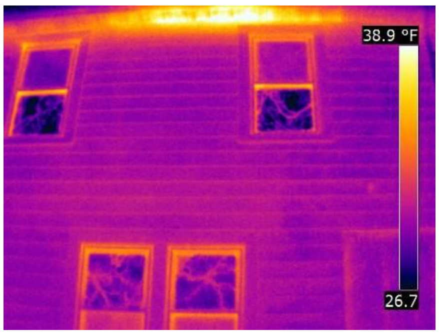

Fig. 53. Bright area indicates less effective insulation and sealing of soffit vent.

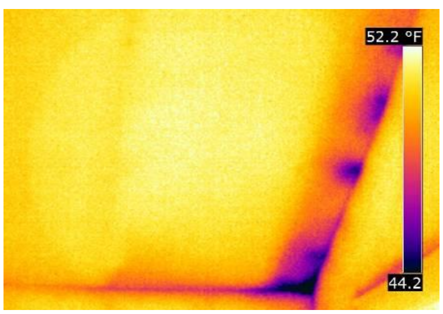

Fig. 54. Ceiling at roof line of sun room without blower door.

Figures 54 and 55 show the ceiling of the sun room at the northwest corner. There are some cooler spots along the junction in Fig. 55, and these areas expand with characteristic wispy finger-like features indicating air intrusions when the blower door is used to lower the air pressure inside the house.

Both Fig. 56 and Fig. 57 show the air intrusion around windows and wall studs, areas with less insulation and not as well sealed.

It would be good to have the blower door and IR on site toward the end of the foam application and to agree in advance on a depth-sampling method that will be used to meet the depth specification. The IR camera identified a few spots where the insulation needed to be redone, locations that would not have been found by visual inspection. (Note that the IR camera is not very useful unless the there is a large difference between the inside and outside temperatures.) Call-backs are costly because the spray rig needs to be hauled back to the site and the heated hoses dragged back into the house, all for what is generally not much added spraying.

The blower door test of the house was repeated, now that the foam and drywall had been installed. This test showed 4.98 ACH at 50 Pa, a considerable tightening of the building envelope from the initial measurement of over 17 ACH.

The reduction of the number of air changes per hour with successive retrofit steps is shown in Fig 58.

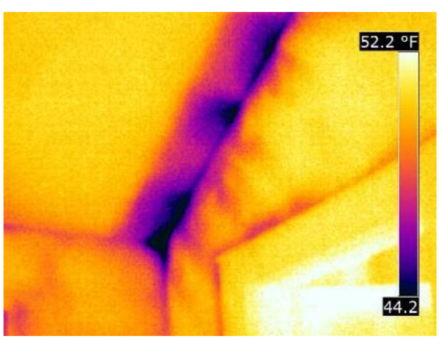

Fig. 55. Ceiling at roof line of sun room with blower door at 40 Pa.

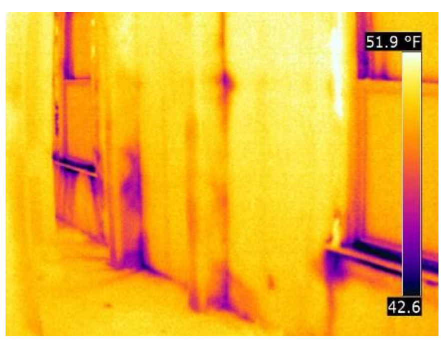

Fig. 56. Air intrusion at junctures and studs with blower door at 40 Pa.

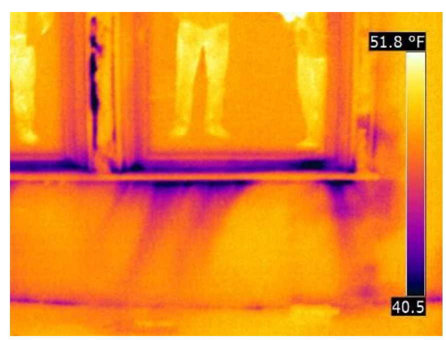

Fig. 57. Thermal "fingers" from air intrusion around windows. **(**Body heat from data takers is reflected from window.)

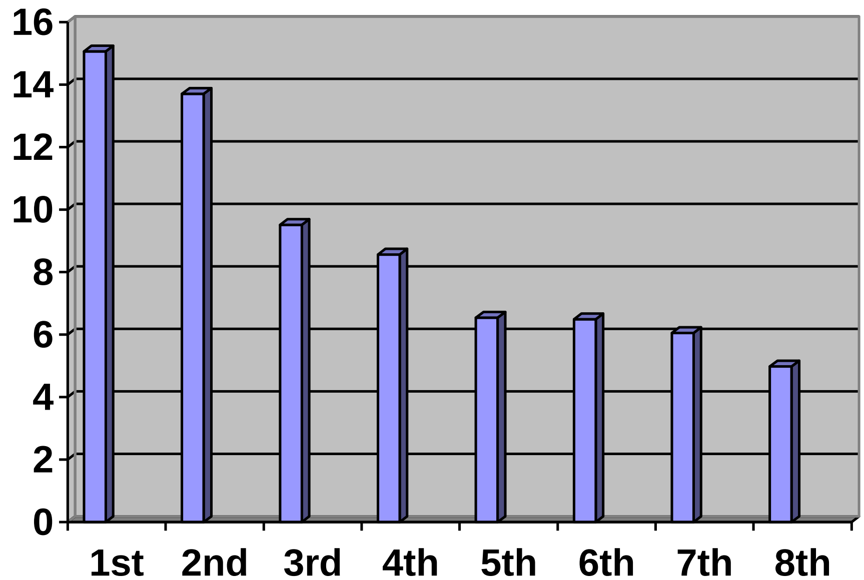

Fig. 58. Blower-door-directed reduction in number of air changes per hour (successive blower door tests) with additional foam retrofits at Gaitor House. (1) Baseline reading, (2) high-density foam in attic, (3) high-density foam in attic and above-grade walls, (4) high-density foam in attic, walls, and basement, (5) additional foam added to walls as result of blower door test, (6) additional foam in attic and walls after call-back, (7) after sealing 8 in. round open flue in basement, and (8) after drywall was installed.

The costs for the foam at Gaiter House are shown in Table 3.

Table 3. Breakdown of costs for spray foam at Gaiter House

Location	Size (ft^2)	Description	Cost ($)	Cost ($\$/ft^2$)
Roof decking and gables in attic	1510	1 in. of 2 lb closed-cell foam and 8 in. of 0.5 lb open-cell foam	6251	4.14
Roof decking in the sun room	255	4 in. of 2 lb closed-cell foam	828	3.24
Exterior walls, sun room gable and framed wall in basement	1655	1 in. of 2 lb closed-cell foam and R-11 unfaced fiberglass batt in 2x4 open wall cavities	2665	1.61
Rim joist in basement	130	Sealed with 2 lb closed-cell foam	280	2.15

The renovation at Gaiter was continuing as of September 2011. The data acquisition system has been installed, and occupancy is scheduled for November 2011. Each of the foam installations will be looked at incrementally as to cost effectiveness.

Country House

Fig. 59. Country House, showing vents in attic and crawlspace.

Country House (Fig. 59) is located in Rockwood, Tennessee. The house has 2300 ft^2 of floor space on the main floor and in the partial finished basement.

The original HERS rating for the house was about 107, but the models predicted that might be reduced to about 64 after all recommended retrofits.

The first blower door tests suggested a great deal of leakage, with 11 ACH at 50 Pa. There was also significant leakage in the existing ductwork.The appliances were older and inefficient. One of the significant areas of leakage was the rim joist/sill area under the first row of siding (Fig. 60).

Windows and appliances have been replaced. The ACH was reduced to 8.29, with most of the insulation and sealing completed. Drill-and-fill foam insulation was pumped into the above-grade wall cavities. The homeowner selected the foam over other available options, but did not solicit cost estimates of alternatives. The old HVAC unit (Fig. 61) has now been replaced with a high-efficiency model. With much insight gained from the blower door, the Country house at retrofit completion was 4.81 at 50 Pa. Because of the way this retrofit was conducted, we were not able to capture the isolated air tightness improvement in the windows. However with the popularity of window replacement as a retrofit measure, this would be a most valuable measurement.

Fig. 60. Rim joist/sill area needs to be sealed and insulated.

Fig. 62 shows the reduction in ACH with successive blower door tests as retrofit progressed.

Table 4 shows the utility usage before and after retrofitting the Country House, while Table 5 lists costs of the improvements.

Fig. 61. Older, inefficient HVAC unit.

All of the data acquisition equipment is installed in this house, and much of the 2010-2011 heating season thermal performance was captured. Figure 63 shows a 41% drop in total electricity usage in March 2011 compared to March 2010. March 2010 had 520 heating degree days (HDD) base 65°F as compared to only 393 HDD base 65°F in March 2011. That is a drop in HDD of 24% which could account for about half of the measured savings during this swing month.

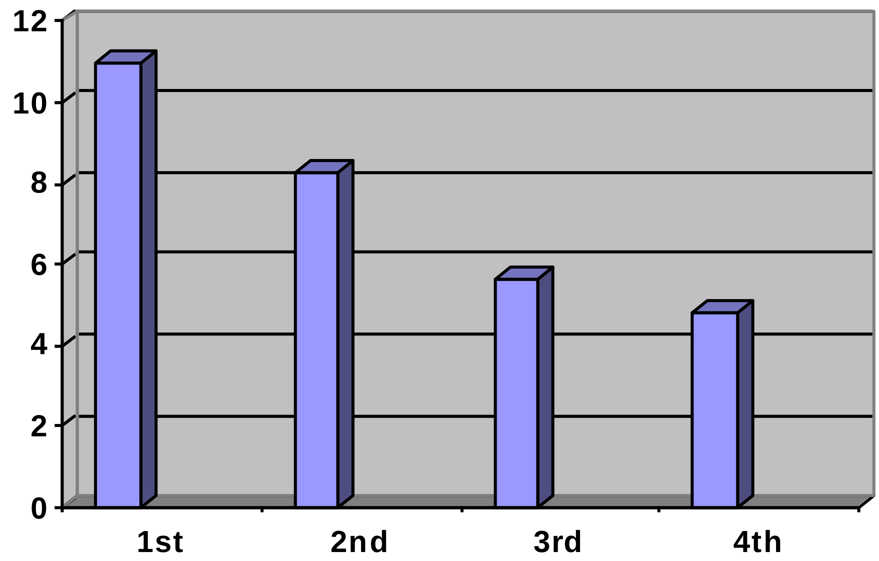

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Fig. 62. Reduction in ACH with additional sealing at Country House. Based on successive blower door tests: (1) Baseline reading, estimated. (2) New windows; drilled and filled above-grade walls with R-2 insulation; backed siding added. (3) Sealed basement rim joist with froth pack, sealed attic knee wall, replaced eight ceiling canned lights with air-tight recessed cans, framed-in the attic hatch, replaced the bath exhaust back-draft damper, with froth pack sealed all top plates in the attic and sealed all electrical and plumbing penetrations in the attic, sealed large attic bypass through the return duct. (4) Replaced heat pump having through-the-basement-wall unitary equipment with split system, eliminating a large leak. With insight gained from the last blower door test, crew sealed missed rim joist in the basement, fixed the leak around the main electrical power entering the basement, and sealed the crawlspace blocks where the blocks went from 10 in. to 8 in., exposing the hollow cores.

Table 4. Utility usage before and after retrofit at Country House (kwh)

	Year			
Month	**2008**	**2009**	**2010**	**2011**
January	1,818	1,925	2,082	1,511
February	1,900	2,201	2,412	1,578
March	1,521	1,725	2,359	1,346
April	1,154	1,361	1,529	1,142
May	1,244	1,288	1,081	995
June	1,255	1,342	1,220	1,074
July	1,669	1,801	1,607	1,042
August	1,563	1,465	1,780	1,193
September	1,640	1,448	1,732	
October	1,300	1,276	1,023	
November	1,044	1,038	934	
December	1,471	1,245	1,041	
Total	17,579	18,115	18,800	4,435

Table 5. Deep retrofit costs at Country House

Retrofit Description	Cost ($)	Area (ft^2)
Closed-cell insulation of kitchen walls	400.00	300
Closed-cell insulation of cathedral ceiling	400.00	300
Aminoplast polymeric foam of remaining exterior walls ($1.29/$ft^2$)	2,757.00	2,143
Insulating of knee wall — fiberglass insulation/foam board/spray open-cell foam	162.00	100
Insulating of rim joist — closed-cell spray foam	760.00	105
Caulking/sealing of cracks — basement walls and crawlspace	92.00	1,196
Caulking/sealing of cracks/fixtures/sheetrock seams — attic	75.00	1,007.5
Attic insulation — blown-in R-50 blown fiberglass	968.00	1,007.5
Energy Star heat pump replacement (packaged unit replaced w/ split unit)	8,705.00	2,400
Energy Star window replacements — 6 single, 2 double	4,160.00	126.35
Vinyl siding w/integral ~R-3 insulation	7,175.00	2,620
Energy efficient blinds — 2 doubles, 1 single	460.00	60
Under-counter spot water heater, electric	168.00	
Energy Star appliances (refrigerator, stove, dishwasher, microwave)	5,484.78	
Labor (self) (80 hours @ $10/hour)	800.00	
Subtotal	**32,566.78**	
Rebates		
TVA rebate	-650.00	
TN State rebate	-250.00	
Federal energy rebate	-1,500.00	
Subtotal	**-2,400.00**	
Grand total (retrofit costs minus rebates)	**30,166.78**	

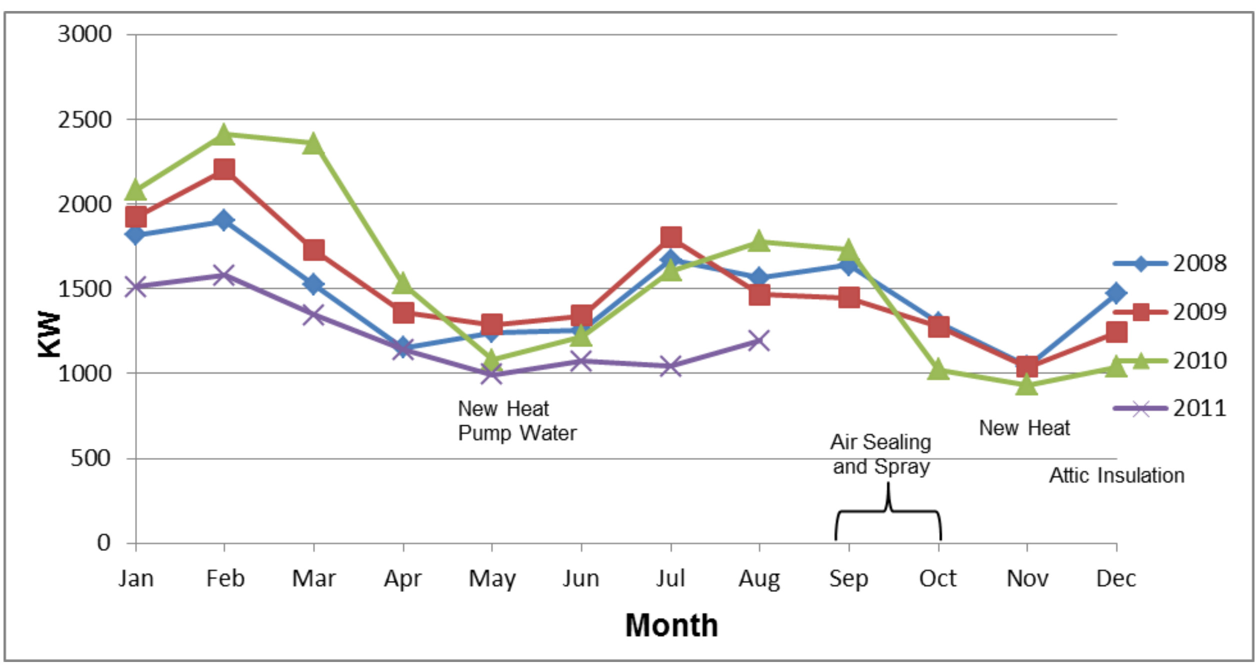

Fig. 63. Total usage of electricity in Country House through August 2011.

Eagle Bend House

Fig. 64. Eagle Bend, in Clinton, Tennessee.

Built in 1939, Eagle Bend (Fig. 64) is a two-story house with some finished space in the basement. The house has 37 windows and 1200 ft^2 of attic space. Earlier upgrades to the house, such as double-pane windows, were done without considering the whole-house impacts.

The house was very porous; the blower door test registered 24 ACH at 50 Pa. The HERS score was 129, about average. With the recommended renovations, the model predicted that the HERS score could be cut in half.

The first step was to reduce the infiltration rate. The whole-house fan (Fig. 65) creates a sizable hole between the conditioned living space and the unconditioned attic. There is also a gap around the chimney that is open to the living area. The soot and dirt on the flooring shows a lot of air movement in the walls and outside of the ductwork (Fig. 66). Some of the recommendations included sealing the electrical and plumbing penetrations, sealing the laundry chute, and removing the fan. The laundry chute is a classic attic by-pass. One can look up and see the roof sheathing and look down into the basement laundry room. SPF could be applied under the roof deck to incorporate the attic into the conditioned space.

Work on this house had not yet begun in earnest as of September 2011.

Fig. 65. Fan and gaps around chimney allow air to move freely between house and attic.

Fig. 66. Soiled flooring from air movement in wall.

Celebration House

Fig. 67. One-story Celebration House.

The Celebration House (Fig. 67) is a 2670 ft^2 rancher in Farragut, Tennessee. The house, built in 1979, sits on a vented crawl space and has the original windows and doors.

Again the big problem is infiltration. The initial blower door test indicated over 13 ACH at 50 Pa. The HERS rating was about 114. With the recommended retrofits, the rating was projected to be closer to 74.

Figure 68 shows the electrical and plumbing penetrations into the house through the crawl space. In addition to providing a path for outdoor air, these openings allow the mold that tends to grow in unconditioned crawl spaces to be drawn into the house. Openings in the attic allow unconditioned air from attic into the interior walls (Fig. 69).

After sealing the electrical and plumbing penetrations and the leaks, the auditors suggested sealing and insulating the crawl space to R-15. The attic is another accessible area in which spray foam could be used for sealing and insulation. A target R-value of 50 would be appropriate for the attic floor.

Work has not started as of September 2011.

Fig. 68. Electrical and plumbing penetration provide airways between the house and the crawl space.

Fig. 69. Opening to interior walls in attic.

Oasis House

Fig. 70. Oasis House, residence for the staff of the Great Smoky Mountains Institute at Tremont.

Oasis House (Fig. 70) is home to the staff of the Great Smoky Mountains Institute at Tremont. Built in 1966, the staff house is typical national park staff housing, simple and utilitarian. The 1800 ft^2 structure; located within the Great Smoky Mountains National Park near Townsend, Tennessee, is built over a crawl space.

The house has problems with infiltration, as shown by the initial blower door test result of 9.93 ACH at 50 Pa. The utility penetrations to both the unconditioned attic (Fig. 71) and to the vented crawlspace allow conditioned air to escape and outside air to leak in. The initial HERS rating was 127, about average for existing houses. After installation of the energy conservation retrofits, the air change rate is predicted to be 3.75 ACH and the HERS rating should drop to 86.

Fig. 71. Utility penetration into unconditioned attic.

Other obvious problems included older single-pane aluminum-framed windows, blown insulation that had settled in the walls about 2 feet, and little insulation in the attic. Removing the wood stove was advised, as the renovated house should not need the extra heat, and the tighter structure would prevent the stove from functioning efficiently and increase the risk of carbon monoxide buildup.

The first priority is to solve the bulk water drainage flowing through the crawl space followed by sealing the air leaks and then insulating the attic. A layer of spray foam on the attic deck will isolate the living area. Then more foam or other insulation should be added to reach R-50. After new windows are added, insulation can be added to the wall. The siding needs replacement. While that is done, external wall insulation can be added.

In a mixed-humid climate, it is best to seal the crawlspace. After closing the vents, the walls and band joints can be insulated with spray foam or combinations of materials.

Plans are to use this retrofit to develop an interactive video, not only to illustrate retrofit best practices, but also to teach basic science concepts to fourth- through sixth-grade science students from the Great Smoky Mountains Environmental Education Institute at Tremont, to the nearby Ijams Nature Center in Knoxville, to Hawaii, and even as far away as Japan. The DOE Office of International Affairs has provided $25,000 in funding for this effort.

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Capital House

Fig. 72. Capital House in Oak Ridge, Tennessee.

This 2438 ft^2 house (Fig.72) was built in 1993 over a ventilated crawl space. The Capital House has two stories and an attached garage. The windows and mechanical systems are showing their age. This house is of particular interest because of its similarities to the Campbell Creek retrofit house, CC2.

The first blower door test showed 8.29 ACH at 50 Pa. The simulation software showed a HERS rating of about 117. If the recommended retrofits are completed, a HERS score of about 73 might be attained.

As with most of the homes surveyed, the utility penetrations into the attic and crawl space were a source of many leaks. Although there was insulation in the attic, the air flow around the penetrations and the uninsulated attic hatch lowered the efficiency of the insulation. The vented crawlspace allowed mold to grow on the wood (Fig. 73).

Fig. 73. Moisture allows mold to discolor the floor joist.

Fire-retardant foam can be used to seal around penetrations. Then the hatch can be insulated and the attic insulation increased to R-50. After checking for radon and taking care of drainage problems, the crawl space has been sealed and insulated with closed-cell polyurethane to about R-10. Lining the insulated crawl space floor with a 20-mil plastic creates a vapor-diffusion retarder. When the siding is replaced, rigid external insulation can be added. Replacing windows with more energy-conserving ones and replacing the HVAC systems will also help reduce energy use. The very old gas-fired water heater was replaced with a tankless unit.

In June 2011 the homeowner reported he was accumulating funds to attack some of the additional suggested retrofits.

Old Tavern

Fig. 74. Old Tavern house in west Knox County, Tennessee.

Old Tavern (Fig.74), built in 1977, already has a sealed crawlspace. The 3800 ft^2 home is located in the town of Farragut, Tennessee. The initial blower door test revealed 8.21 ACH at 50 Pa. The energy efficiency modeling gave a HERS rating of about 124. With the recommended changes, the HERS rating could be lowered to about 66.

Again the major energy culprit is the leaky building envelope and duct system. There are many openings between the living space and the attic, including around all the recessed can lights.

Fig. 75. Open chase into home from attic.

Figure 75 shows an open chase into the home from the attic. This type of opening allows the unconditioned air from the attic to leak into the house and the conditioned air to escape to the attic.

Loose connections and leaky ductwork cause more problems. The crack in the return plenum (Fig. 76) in the HVAC allows dirty air from inside the wall and the attic to be pulled into the ductwork, forcing the system to work harder to condition the air.

Fig. 76. Crack in return plenum (between metal and wood).

The first recommendation was to seal leaks around doors, windows, and penetrations. The many leaks in the attic suggest that the best approach may be to spray foam under the roof and gables and around knee walls, making the attic part of the building envelope with the duct work inside, insulating it to about R-38. Contractor estimates ranged from \$6,000 to \$13,000. The homeowner is leaning toward cathedralizing the attic, but as of June 2011, he had not signed any contracts. Quotes for installing structural-insulating-panel nail base were solicited after a hail storm took out the shingled roof. Preliminary reaction was that the cost was too high. After the shingles are replaced, foaming the attic will be pursued. Changes in the duct system would improve the air distribution, and the bonus room over the garage could be incorporated to eliminate the window air conditioning unit. Additional insulation and sealing in the crawl space and new, more efficient furnace and air conditioning unit will do a lot to improve energy efficiency.

Scenic House

Fig. 77. Scenic house in Oak Ridge, Tennessee, sits over a ventilated crawl space.

The two-story Scenic House is 44 years old and contains 4400 ft^2 over a ventilated crawl space. The house has the original single-pane windows, and the HVAC system is old and in need of replacement.

The initial blower door tests showed infiltration of 7893 cfm or 12.9 ACH at 50 Pa. The energy efficiency calculation produced a HERS rating of 114. Implementation of all the recommend retrofits would allow a projected 3.09 ACH and a lower HERS rating of 61.

The first step is to seal the air leaks in attic access hatches, recessed lighting, plumbing and electrical penetrations, and leaky windows and doors. The duct system (Fig. 78) in Scenic is also a significant source of infiltration and suffers from poor design and lack of insulation.

Fig. 78. Uninsulated ductwork in crawlspace with crickets feeding on mold growth.

There is no insulation in the walls, and they should be increased to R-14. Drill-and-fill from the inside with dense-packed cellulose was suggested. The existing loose insulation in the attic (Fig. 79) provides little or no thermal protection. The attic needs to be sealed against air, possibly with spray foam, and insulated to R-50. For this house, a horizontal loop geothermal HVAC is an attractive possibility for more efficient heating and cooling. Replacing the old windows with Low-E triple-pane type will add to the comfort of the retrofitted house.

Fig. 79. Patchy, loose insulation in the attic.

As of September 2011, financial concerns had placed the homeowner’s retrofit plans on hold.

The Optimal-Value-Framing House

The Optimal-Value-Framing House (OVF) is not a retrofitted house. OVF is one of four research houses used to test new products and concepts. The project is being conducted by Oak Ridge National Laboratory to test a number of energy-efficient concepts such as “flash-and-batt” insulation.

Fig. 80. Optimal Value Framing (OVF) House.

The construction and insulation methods could also be applicable to some retrofits. The wall cavity was insulated by the flash and batt method with about 1/2 in. of closed-cell SPF topped by R-19 fiberglass batt insulation. In a retrofit in which the interior sheathing is removed, this approach would be applicable to a retrofit situation. For walls with no insulation and a house that is undergoing gut-rehab, flash-and-batt could be a very good solution. This extensive renovation is likely to occur only once in an older home’s service life.

6. KNOWLEDGE GAPS AND RESEARCH NEEDED

As the use of spray foams increases, there are still some areas in which advances and improvements are needed. Many questions remain.

There are differing opinions on the time needed for the foams to cure and for any gas from the process to dissipate. In retrofit applications, people may be living in the house during the process. When should they vacate the house and how long do they need to stay away? Are some people (such as infants, elderly, those with respiratory problems, or those with latex or other allergies) and some types of pets particularly sensitive to foam off-gassing?

Are there newer formulations that are less tricky to apply and less dangerous for those doing the application?

Some questions about the choice of foam are not completely resolved. When should closed-cell foam be used and when is open-cell more appropriate? If closed-cell foam is applied first and open cell foam sprayed on top of the closed-cell, what it the optimal thickness of each area in different climates? One rule of thumb floating around is that for attics 50% of the R-value should come from closed-cell foam applied first. Open-cell foam is then applied over it to provide the remaining 50% of the insulation value. Other experts say that this ratio should be lower in warmer climates. However, there appears to be no quantitative data to support this approach. Heat- and moisture-transfer models should be run to find the best mix in different climates.

What are the best choices for basements and crawlspaces? When should foam be used? What type of foam should be chosen? The guiding principle is to fix all moisture problems before retrofitting insulation. How do you know that the moisture problem is fixed, or that the house has low risk for foundation moisture problems after the retrofit?

How does one determine when it is preferable to spray the underside of the roof and the inside gables of the attic to incorporate it into the thermal envelope as opposed to trying to fix the air leaks between the attic floor and the conditioned interior? ORNL currently has four roofs under detailed heat and moisture monitoring. This data will be used to calibrate WUFI and help answer the age-old question, “To foam or not to foam,” and determine what type of foam to use.

What new combinations of spray foam and other insulating materials could be effective in sealing, insulating, providing vapor barriers, or adding fire retardant to the application? Can all of the objectives be accomplished at a more reasonable price with a combination of materials? If a combination of materials is chosen, what are the optimal thicknesses of each layer?

Can spray foam produce greater post-retrofit air-tightness when used on the exterior or the interior of the house?

Below what level of air leakage is mechanical ventilation required? What reasonable rules of thumb can be developed to lead toward optimal solutions from the perspective of indoor air quality, energy efficiency and cost? The committees maintaining ASHRAE 62.2 are currently discussing these questions for new construction. Some of the ongoing case studies described in this report should contribute to better guidance for retrofit of mechanical ventilation. The current solution should be to install mechanical ventilation whenever the house has a natural pressure air exchange of less than 0.35, but more insight is needed to generate site-specific optimization.

The initial foam thickness measurements in all of the case studies described in this report showed great variations. Can a standard methodology be developed so that the homeowner and the foam provider can agree that that the foam has been installed to the agreed upon contracted depth?

The national building codes allow sealed attics and crawlspaces in new construction. There is no requirement in the 2006 IRC (International Residential Code) for providing conditioned air to the sealed attic nor any requirement for a return air pathway. However, the 2006 IRC requires a supply of conditioned air at a rate of 20 cfm/1000 ft^2 of conditioned crawlspace. Leaks in the floor between the crawl space and the main level above the crawl space is not considered a return air pathway, which is mandated in new construction. In retrofit situations how can it safely and inexpensively be determined that an adequate return air pathway to the conditioned space exists? Cutting a hole in the floor between a crawl space and conditioned space is not a very elegant solution. Pressure pan measurements would seem to be a good solution for commissioning, but how can this be designed into the retrofit prior to completion?

7. CONCLUSIONS

Spray foam insulation is extremely useful in improving the energy efficiency of existing houses. As noted in the descriptions of deep retrofits in Section 5, air infiltration is usually the major problem and the first thing to be addressed. Spray foam has the advantage of providing a seal against air movement as well as adding insulation.

The studies of 10 homes undergoing deep retrofits in the Knoxville, Tennessee, area, located in the mixed humid climate, have found that pre-retrofit air leakage varies from 28 to 9 ACH at 50 Pa. Without use of a blower door, one can reduce the leakage to about 7 or 8 ACH. Using a blower door, one can improve to 4.5-5 ACH. Using infrared imaging during cold weather with a blower door operating will identify additional leaks so that an ACH lower than 4 should be attainable with cost-effective effort on the part of the insulating crew.

The houses discussed show the potential for energy efficiency improvements after sealing and insulating. These houses were in various stages of retrofitting. The effectiveness of the energy conserving modifications was seen in the Campbell Creek House, which had its own control house for comparison. In the Gaitor House, still under renovation, there have been drastic improvements in the infiltration rate since the foam insulation was added.

Data on the performance of these houses will provide more information on how to make the best use of spray foam.

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