# Insulating and Air Sealing Low-Pitch Residential Attic Spaces: Cost-Effectiveness Evaluation

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**ABSTRACT**

*Rising energy costs and attractive incentive programs established by the government and/or energy companies continue to fuel the need and desire to increase the energy efficiency of residential homes. Air sealing and insulating attic spaces remains one of the best opportunities to attain these energy-efficiency improvements.*

*Low-pitch attics, though, present unique challenges to effectively insulate and air seal them, especially in retrofit situations where the rafter/truss design is fixed and space constraints exist at the perimeter of the structure. The perimeter space constraints limit accessibility to these areas as well as restrict the amount of insulation that can be installed.*

*This paper quantitatively and qualitatively summarizes the cost-effectiveness of various solutions for sealing and insulating attics under low-pitch roofs, with an emphasis on evaluating solutions in areas with space constraints.*

*Insulation and air sealing materials as well as methods for installing those materials were evaluated in a laboratory setting to determine the cost-effectiveness of each method. In addition to the cost versus benefit of each insulating/air sealing solution, the practicality of each approach is compared.*

## INTRODUCTION

### The Importance of Adequately Insulating and Air Sealing Attics

While adequately insulating and air sealing attics conserves energy and reduces energy costs to homeowners, these actions also result in several other positive outcomes.

First, air sealing slows air movement through the structure due to stack effects. In the cooler months, stack effects invite air containing moisture from the outside in through leaks at the bottom of the house. The air travels up into the attic. In a ventilated attic cool roof design, the moisture quickly condenses on cold objects in the attic and/or the underside of the roof and the potential for moisture damage is heightened. Similarly, stack effects may drag radon gases from the ground into a home. Adequately air sealing the attic space can help limit the stack effect, thereby limiting moisture in the attic and slowing radon intrusion into a home. The overall comfort of the home is also improved since drafts are reduced as well.

Second, in colder climates, if the attic is not sufficiently insulated or has too much warm air leaking in, the roof deck may become warm enough to melt snow. The water from the melted snow runs downward and freezes on the eaves, creating ice dams. As this phenomenon is repeated, the ice dams grow. The water is unable to flow downward to the eaves and instead moves up under the shingles and roof covering. Ultimately, water leaks into the attic and along the exterior walls.

Walls present one of the largest opportunities to improve the air sealing of a building. Between 18% to 50% of a building's air leakage is through the walls, which includes the leaks into the attic at the top plate (ASHRAE 2005).

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## Building Code and Government Program Requirements

The International Codes, ENERGY STAR® Qualified Homes Program, and United States Department of Energy (DOE) have all acknowledged the importance of insulating and air sealing attic spaces and have strived to address the issue by mandating minimum requirements and/or providing recommendations to home owners and builders. The requirements and recommendations for insulating and air sealing attics have increased over the last decade.

**R-Value Minimums for Attic Spaces.** The International Codes and the ENERGY STAR Qualified Homes Program outline minimum R-value targets for insulating attics in new homes. The DOE has published recommended R-value minimums for insulating attics in new and existing homes, indicating a desire and need to address insulation levels in existing residential structures as well as new structures. Table 1 summarizes these minimum R-value requirements.

The International Codes and ENERGY STAR program allow mechanisms other than those identified in Table 1 to satisfy the attic insulation requirements; Table 1 lists the recommendations for a common compliance mechanism providing a sense of the R-value expectations for an energy-efficient home. Note the trend towards higher R-value thresholds in the International Codes. Also, note that the International Codes and ENERGY STAR program requirements openly recognize the space constraints along the perimeter of attics and provide some reduction in the minimum R-value required for this area.

**Air Sealing Requirements for Attic Spaces.** As with insulating attic spaces, the International Codes, ENERGY STAR program, and DOE have placed similar and growing emphasis on air sealing the building envelop of a home.

For example, the 2006 *International Residential Code*'s (*IRC*'s) early call for action requiring that "the building thermal envelope shall be sealed to limit infiltration" and listing ten locations to be "caulked, gasketed, weatherstripped or otherwise sealed with an air barrier material, suitable film or solid material" (ICC 2006) was quickly and vastly improved upon. The 2009 and 2012 editions of *International Energy Conservation Code* (*IECC*) identify two additional locations to be sealed and outline compliance verification requirements (ICC 2009, 2012).

The 2009 *IECC* requires a home to have ≤ 7 air changes per hour (ACH) at 50 Pa or be visually inspected by the code official or approved party independent of the installer (ICC 2009). The 2012 *IECC* mandates even tighter homes and more rigorous compliance verification. Under the 2012 *IECC*, homes must have ≤ 5 ACH and ≤ 3 ACH at 50 Pa for climate zones 1–2 and climate zones 3–8, respectively. Further, the option to only visually inspect for air sealing is removed in the 2012 *IECC*, and all homes must be tested (ICC 2012).

The ENERGY STAR program devotes an entire section, Section 5, of its Thermal Enclosure System Rater Checklist to air sealing. Section 5.2.3 specifically requires that the top plate at all unconditioned attics/wall interfaced be sealed to the drywall. Further, the ENERGY STAR program requires ACH at 50 Pa to be less than or equal to 6, 5, 4, and 3 in climate zones 1–2, 3–4, 5–7, and 8, respectively (EPA 2012).

Lastly, the DOE has sponsored and published many guides and fact sheets to educate and encourage homeowners and home builders to air seal homes (DOE 2000a, 2000b, 2000c, 2008, 2010).

**Table 1. Minimum Attic R-Value Requirements and Recommendations in *IRC* (ICC 2006), *IECC* (ICC 2009, 2012), ENERGY STAR Qualified Homes Program (EPA 2012), and DOE Fact Sheet (2008)**

| Climate Zone | 2006 IRC | 2009 IECC | 2012 IECC | ENERGY STAR, Version 3 (Rev. 06) | DOE Insulation Fact Sheet | | |
|---|---|---|---|---|---|---|---|
| | | | | | New Homes | Uninsulated Existing Attic | 3-4 in. of Insulation in Existing Attic |
| 1 | 30 | 30 | 30 | 30 | 30 to 49 | 30 to 49 | 25 to 30 |
| 2 | 30 | 30 | 38 | 30 | 30 to 60 | 30 to 60 | 25 to 38 |
| 3 | 30 | 30 | 38 | 30 | 30 to 60 | 30 to 60 | 25 to 38 |
| 4 | 38 | 38 | 49 | 38 | 38 to 60 | 38 to 60 | 38 |
| 5 | 38 | 38 | 49 | 38 | 38 to 60 | 49 to 60 | 38 to 49 |
| 6 | 49 | 49 | 49 | 49 | 49 to 60 | 49 to 60 | 38 to 49 |
| 7 | 49 | 49 | 49 | 49 | 49 to 60 | 49 to 60 | 38 to 49 |
| 8 | 49 | 49 | 49 | 49 | 49 to 60 | 49 to 60 | 38 to 49 |

NOTE: Under the 2006 *IRC*, 2009 and 2012 *IECC*, and ENERGY STAR Qualified Homes Program, R-30 is deemed to satisfy requirements for R-38 whenever the full height of uncompressed R-30 insulation extends over the wall top plate at eaves. Similarly, R-38 is deemed to satisfy requirements for R-49 whenever the full height of uncompressed R-38 insulation extends over the wall top plate at eaves.

## Low-Slope Attics: Where Space Constraints Limit Insulating and Air Sealing

While strong driving forces exist to adequately insulate and air seal attics, low-slope attics pose space constraints and make insulating and air sealing a challenge. While many roof designs exist, most designs closely resemble either a hip or a gable roof system. In a gable roof system, assuming a rectangular footprint, the perimeter space constraints presented by the truss/rafter design are largely present on only two sides of the home. By contrast, in a low-slope hip roof system, the attic has truss/rafter design constraints on all four sides and the corners.

Sources conflict on the exact definition of a low-slope roof, with some defining a rise of 3 units or less for every 12 units of horizontal distance (i.e., 3/12 slope) as a low slope and others citing a 2/12 slope (ASTM 2006; Feirer and Feirer 2004; CoolFlatRoof.com 2012). Regardless of the exact definition, roofs with even as much as a 5/12 slope are still significantly space constrained and pose accessibility challenges for installing insulation and air sealing.

Figure 1 illustrates the space constraints. It provides a visual of how the space for installing insulation and physically maneuvering to do installation work in an attic shrinks as the roof slope decreases from 8/12 to 3/12. It also shows the approximate distance from the exterior of the top plate to the interior of the attic required before enough vertical space exists to insulate to an R-30 and R-49 level using a generic R-3.5/inch insulation.

The 2006 *IRC*, 2009 *IECC*, 2012 *IECC*, and ENERGY STAR program all extend some latitude in their insulation requirements for space-constrained areas around the perimeter of the attic (see the note in Table 1). But, even a densely packed insulation can require 8 in. of vertical space before reaching an R-30 level, which is not available along the perimeter of many low-slope attics.

In new construction, several approaches can be used to build a home with a low-slope roof and provide sufficient space to physically access for air sealing and adequately insulating the attic perimeter. Three popular approaches include raised heel truss systems, extended bottom chords, and dropped chord trusses (see Figure 2).

Of the three approaches, the raised heel truss system has been the most popular in recent years. It creates a slightly higher wall as viewed from the exterior of the structure. By contrast, the extended bottom chord approach maintains the traditional wall height appearance; however, it does result in eaves that project further beyond the home's walls than "normal." Finally, the dropped chord truss, like the raised heel

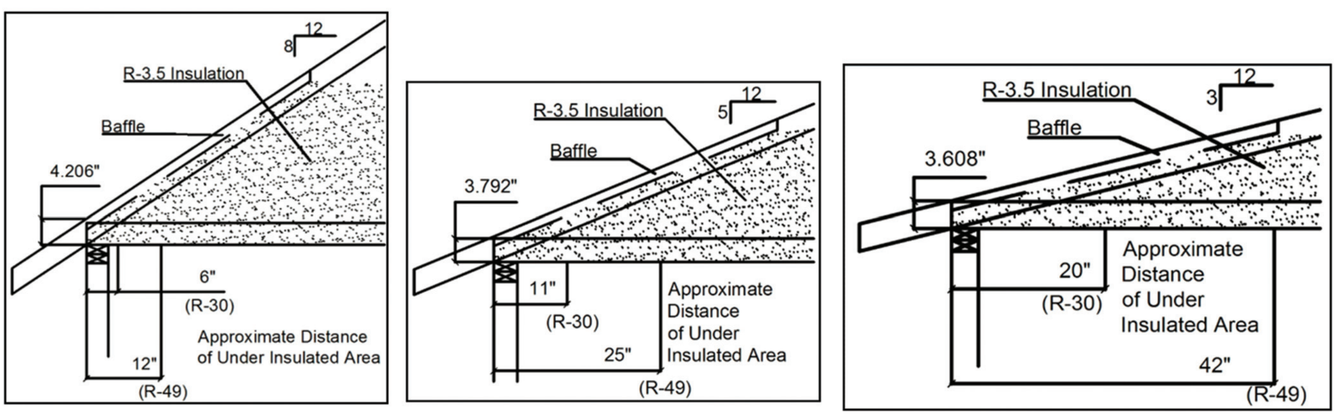


***Figure 1*** *Attic space constraints increasing with decreasing roof slope, negatively impacting the attic insulation levels.*

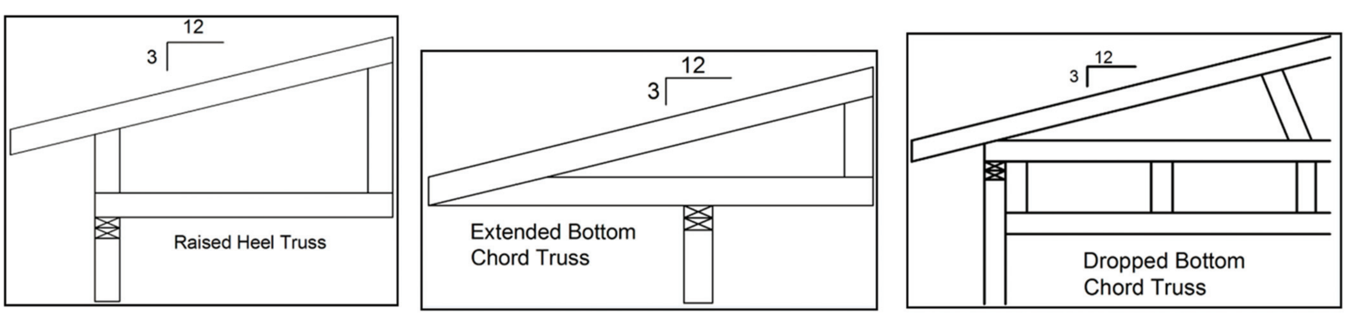


***Figure 2*** *New construction methods for increasing vertical space along the perimeter of a low slope attic: raised heel truss, extended bottom chord, and dropped bottom chord.*

truss, results in a slightly taller wall appearance from the exterior of the home.

In new construction, low-slope roofs and their sealing and insulating challenges can be avoided through the design of steeper roof slopes. Similarly, a hip roof system with its space-constrained corners is an option that can be ruled out in the design phase of new construction. Unlike new construction, though, retrofitting an existing home with a low-slope roof to ensure adequate insulation and air sealing is a challenge that cannot be designed out.

Accordingly, the challenge of air sealing and insulating existing low-slope roofs is the subject of the research presented here. The objectives of this research were to

- understand current methods employed to address this challenge,
- conduct a series of simulated installations to evaluate the methods known today, and
- begin a data-based discussion on the most effective methods to address space-constrained attic areas.

The authors acknowledge that a potential option to address air sealing and insulating an existing, unconditioned, vented low-slope attic is to convert the attic into a nonvented, conditioned space. While this is a viable option that should be considered in a broad discussion on air sealing and insulating homes, for this research nonvented roofs were left out of the scope.

## Current Air Sealing and Insulating Methods Recommended/Employed for Constrained Attic Spaces

**Literature Review and Internet Search.** While the challenge is broadly recognized, a literature review and internet search found limited information on recommendations specific to addressing the challenges of air sealing and insulating existing low-slope attics. The review did reveal generic attic air sealing and insulation instructions specific to the top plate area, which are relevant to the research topic since, as discussed previously, the attic perimeter typically represents the most space-constrained area of the attic.

After first instructing to pull back any existing insulation in the attic and install baffles along the roof rafters when missing, the instructions offered three options, discussed in detail in the following subsections. Only one source offered the second option listed, which, interestingly, offers some potential to increase the R-value around the perimeter of the attic using foam boards, which typically have a higher R/in. than traditional blown-in or loose-fill attic insulation materials (e.g., R-5 to 6.5 verses approximately R-3.5 to 3.8).

**OPTION 1: Air Seal without Improving Insulation (DOE 2010; Lstiburek 2012)**

i. Apply a continuous bead of either one-component foam or caulk sealant to the gaps between the drywall, oriented strand board (OSB), and top plate, with most references only calling for the sealing of the gap between the drywall and top plate.
ii. Place a fiberglass roll at the top plate to provide additional support to the baffle.

**OPTION 2:**
**Air Seal and Improve Insulation (North 2012)**

i. Apply a continuous bead of either one-component foam or caulk sealant to the gaps between the drywall and top plate.
ii. Fit a foam sheet/block extending from over the exterior sheathing to at least the interior drywall.
iii. Install a second foam sheet/block vertically, flush against the outside edge of the attic baffle. Seal around the attic baffle and the vertical foam block seams.

**OPTION 3:**
**Abandon Ventilation in Some Areas to Improve Air Seal (DOE 2010; Lstiburek 2012; Straube 2012)**

i. Place fiberglass in large opening between roof deck, rafters, ceiling joists, and top plate, where baffles cannot be installed.
ii. Apply two-component air sealing spray foam to the top plate area.

All three options concluded with instructions to reinstall previously existing insulation and/or add new loose-fill or blown-in insulation.

**Phone Interviews with and Completed Questionnaires from Experienced Home Performance Retrofitters.** Experienced home performance retrofitters' phone interviews and completed questionnaires revealed several consistent themes:

- Experience matters; solutions often need to be customized to the situation
- One- and two-component spray polyurethane foams are popular, often with customized dispensing guns
- Air sealing is a priority over insulation

Other methods employed by home performance retrofitters to address the top plate and corners of attics included:

i. Reconstructing the roof
ii. Conducting air sealing via the exterior eave area as an access point
iii. Removing/replacing interior drywall
iv. Sealing/insulating the wall cavities with urea formaldehyde urethane foam or dense pack cellulose
v. Doing nothing.

Some retrofitters indicated that in many homes the cost and effort to air seal and insulate attics, especially those with access challenges or located in southern climates, did not return cost savings as high as those from making improvements to other areas of the home.

Like the option to convert an unconditioned, vented attic into a conditioned, nonvented attic, the methods identified in this numbered list to air seal and insulate the attic are viable approaches that should be considered in a broad discussion on air sealing and insulating a home. However, to adequately consider all of these approaches is too large a task with the resources available and under the scope of one research project.

Accordingly, the scope of this research project was limited to employable techniques for air sealing and insulating constrained, vented attic spaces that require no renovations (e.g., replacing the roof deck) and are accomplished from the interior of the attic.

## EXPERIMENTAL DESIGN

### Test Equipment

The laboratory work conducted for this research employed a duct blaster with a digital pressure and flow gauge and two mock attic structures designed to conduct qualitative and quantitative research.

The duct blaster had three flow-ring configurations available, each corresponding to a different airflow range and minimum fan pressure. Based on the differential pressures targeted and the airflows generated during this research, a ring with a flow range of 10–125 cfm and a minimum fan pressure of 3 Pa was employed for all duct blaster testing (EC 2012).

The digital pressure and flow gauge used in conjunction with the duct blaster is capable of pressure measurements that are accurate to ±1% of the reading from –1250 to 1250 Pa. The duct blaster, when used with this specific digital pressure and flow gauge, has a flow accuracy of ±3% (EC 2011).

The first of the two mock attic structures was designed to replicate a section of low-slope, hip roof attic space so that qualitative research could be done on the relative ease of various attic air sealing methodologies as well as some very basic quantitative research on the effectiveness of the air sealing methodologies. Air leakage was not measured using the first mock attic structure. The structure's footprint was 12 × 20 ft with a 3/12 roof pitch and included a simulated hip roof section (see Figure 3).

Construction of the structure in a laboratory setting created differences from in-field practices (e.g., there is an extra 2 × 4 framing layer below the bottom chord). The subtle differences are not believed to materially impact the results of the research.

The second of the two mock attic structures was also designed to replicate a section of a low-slope attic; however, this second structure was designed to perform quantitative air sealing measurements for the top plate area of an attic. Figure 4 shows this second structure.

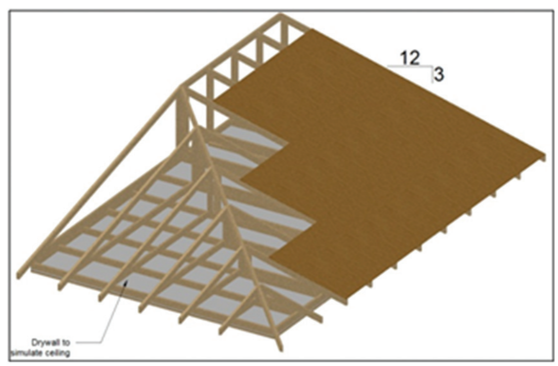


***Figure 3*** *Mock attic structure with 3/12 hip roof and 12 × 20 ft footprint.*

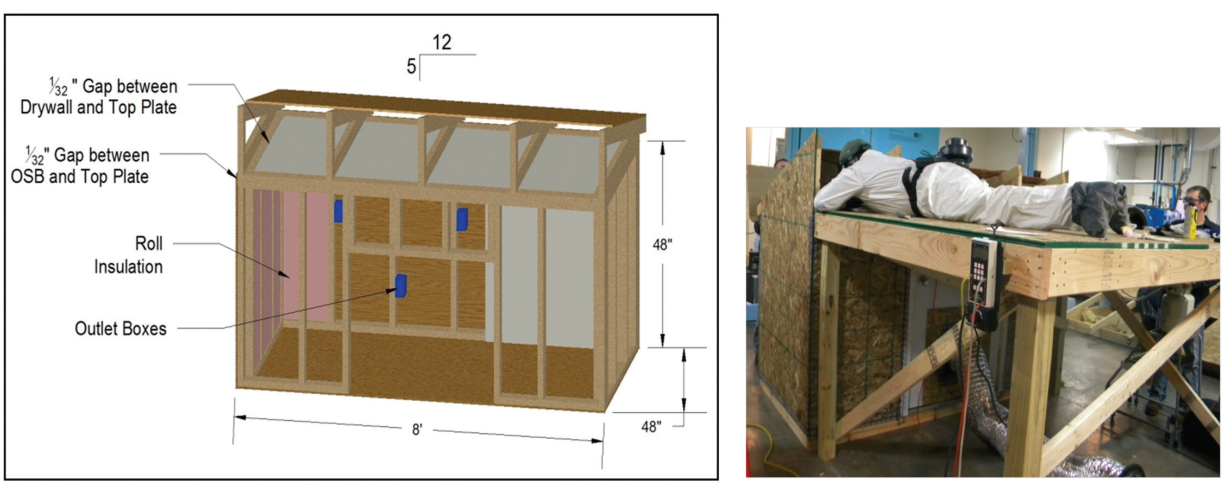


***Figure 4*** *Mock attic structure with 5/12 gable roof, 4 × 8 × 4 ft chamber, door equipped with duct blaster, and working deck.*

The deck on the right-hand side of the structure was strictly to simulate accessing the attic top plate as an installer would do in the field (i.e., it enabled the installer to stay low on his belly to do the installation work). Air infiltration studies were done on the hut-like structure to the left of the installer deck. The hut consisted of a small chamber below an attic. The small chamber provided an area to allow suction by the duct blaster.

The chamber had a 4 × 8 ft footprint. It was built on a 2 × 4 framed floor, with one single 4 × 8 ft sheet of OSB making up the solid floor surface.

The walls were 4 ft in height and framed 16 in. on center with 2 × 4 studs. Kraft-faced R-13 fiberglass batts were installed in the wall cavities with the kraft facer closest to the interior of the wall. Three rectangular electrical outlets were installed in one interior wall. All four walls were sheathed with solid sheets of drywall on the interior and solid sheets of OSB on the exterior. Similar to common construction practices, the exterior OSB sheathing was not flush with the top face of the top plate; rather, the top of the OSB sat approximately 1/2 in. below the top face of the top plate. Washers were placed between the sheathing and the top and bottom plates to introduce a ~1/32 in. air gap to simulate air gaps found in field construction that occur as a result of lumber drying (Onysko and Jones 1989). All drywall seams were taped and mudded. These features were all included to simulate actual construction.

The roof was approximately a 5/12 slope and comprised of ceiling joists and roof rafters spaced 24 in. o.c. The two short sides were sheathed with OSB to the top of the roof deck and constructed to simulate gable ends. One long side had the rafters protruding over the wall edge to create an eave area. The other long side was left open to access the attic from the deck.

The mini-door with the port for attaching the duct blaster was installed using a standard door frame. The floor sill was sealed with silicone and the other edges were sealed with one-component foam. All penetrations used for tubing inserts as part of the pressure measurements were sealed with silicone.

**Air Sealing and Thermal Insulating Techniques Evaluated.** Based on the results of the literature search and home performance retrofit contractor information gathered, three strategies were selected to evaluate:

i. Air sealing without improving insulation
ii. Air sealing and improving insulation
iii. Air sealing and improving insulation at the expense of ventilating portions of the attic

A matching, abbreviated description of the technique found in the literature to undertake each strategy is described in Figure 5 and identified as either1, 2, or 3.

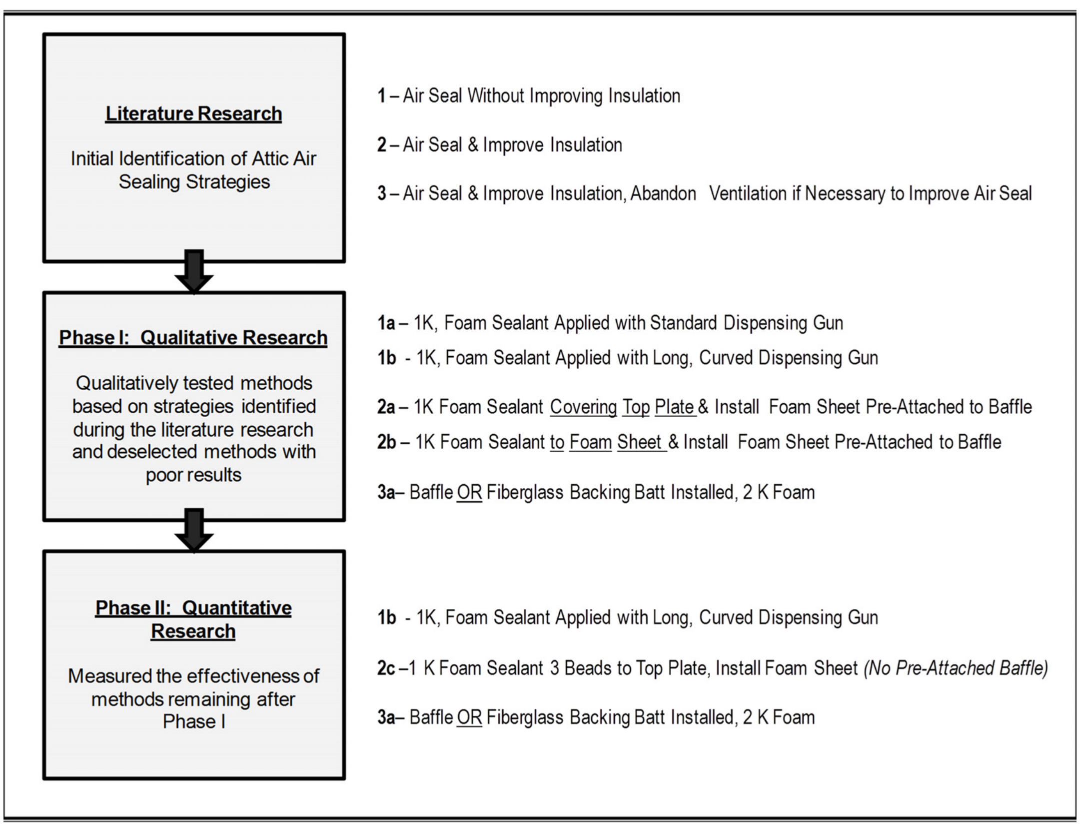


***Figure 5*** *Experimental strategy for investigating air-sealing and thermal-insulating techniques.*

As shown in Figure 5, as the research progressed beyond the literature search into the qualitative and quantitative phases, each technique originally found in the literature was refined. New information was learned in each phase, helping to optimize techniques. Optimized techniques are identified with their original technique number followed by a chronological alpha-character, representing the order the technique was integrated into the research project.

Note that for the first two strategies the literature was fairly broad in recommending a "sealant." To keep the scope of this research manageable, a one-component polyurethane foam sealant was selected to conduct the qualitative and quantitative research under techniques 1 and 2.

Figure 6 shows the difference between the standard length and long, curved dispensing gun used with the one component (1 K) polyurethane foam during phase I.

As explained previously, the foam board used in techniques 2a, 2b and 2c can enhance the R-value along the attic perimeter over more traditional attic insulation materials. In addition, it was hypothesized that the foam board could be pressed down upon by the installer to help compress and distribute the one-component foam, thereby further aiding in air sealing. A 1 in. thick foil-faced polyisocyanurate foam was used in all testing.

The dispensing system for the two-component foam sealant used in phases I and II consisted of a set of hoses, a mixing nozzle, and a cone tip.

## TEST PROCEDURES

As mentioned previously, this research involved the construction of two mock attic structures, which were each used to conduct two separate phases of experiments.

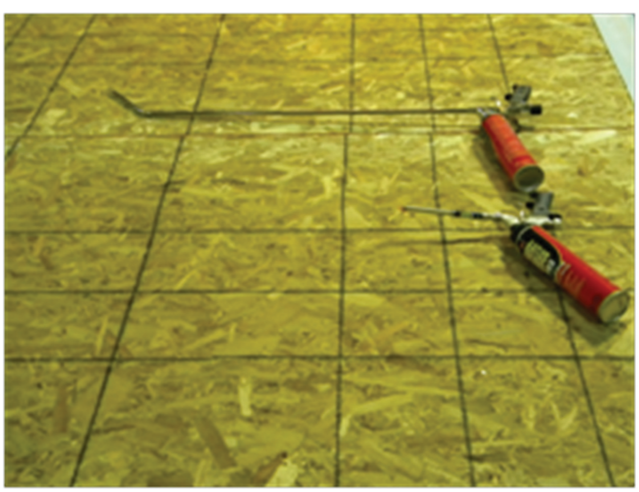

*Figure 6* *Standard-length dispensing gun compared to long, curved dispensing gun.*

### Phase I Test Procedures

Phase I utilized the 12 × 20 ft mock attic structure, which had a tarp installed on the open 12 ft end to help simulate the dark, limited visibility conditions of an attic. The long 20 ft end was left open, as a flood light would most likely be placed in the center of an attic during real-life retrofit work. The research installer's access was constrained to simulate an actual attic access situation. Again, this ground rule was established to help simulate real-life retrofit work. Most of the data collected in phase I was qualitative.

The first task in phase I involved having the installer enter the attic area and mark the point of his furthest physical reach along the perimeter of the entire attic structure. The roof deck was then removed and the distance between the top plate and ceiling drywall joint and the point of reach was measured. Photos were taken to visually document the reach points.

Next, the techniques outlined in Figure 5 for phase I were executed. Note that the same experienced installer was used for all installation tasks in this research program. In addition, all necessary materials for each technique were pre-staged in the attic structure.

Techniques 1a and 1b required the installer to apply one-component foam to the top plate. Two beads were applied. One was targeted between the exterior sheathing and top plate. The second bead was targeted between the top plate and interior drywall. The installer used the standard dispensing gun in two cavities and the long, curved gun in six cavities.

For techniques 2a and 2b, the foam sheet was pre-cut to ~24 in. wide by 16–20 in. long. Foam baffles were pre-attached to the foam sheet by pushing four or five drywall screws through the foam baffle and foam insulation board (see Figure 7). The hypothesis was that having the baffle pre-attached to the foam would ease baffle installation by acting as an extension arm to get the baffle into place. Foam sheets were limited to the 16–20 in. length based on the assumption that greater lengths would be difficult to maneuver in a confined attic space.

For technique 2a, where the one-component foam was applied to the top plate using the long, curved dispensing gun, four cavities were employed. For technique 2b, three cavities were employed and the standard dispensing gun was used to apply the sealant to the foam sheet (see Figure 8).

For technique 3a, foam baffles were installed in all rafter spaces that the installer was able to access. The installer attempted to stuff ~36 in. long by 3.5 in. thick fiberglass into the ends of the cavities where he was not able to install a baffle. A broom stick was used to ball up the fiberglass and push it out over the soffit area. Once the baffles and fiberglass were in place, the installer left the attic space, suited up in a protective suit and full respirator, re-entered the attic space, and installed the two-component polyurethane foam sealant.

For each installation step and technique, installer feedback was immediately captured after the work was completed. Foam was given adequate time to cure, and then the roof deck

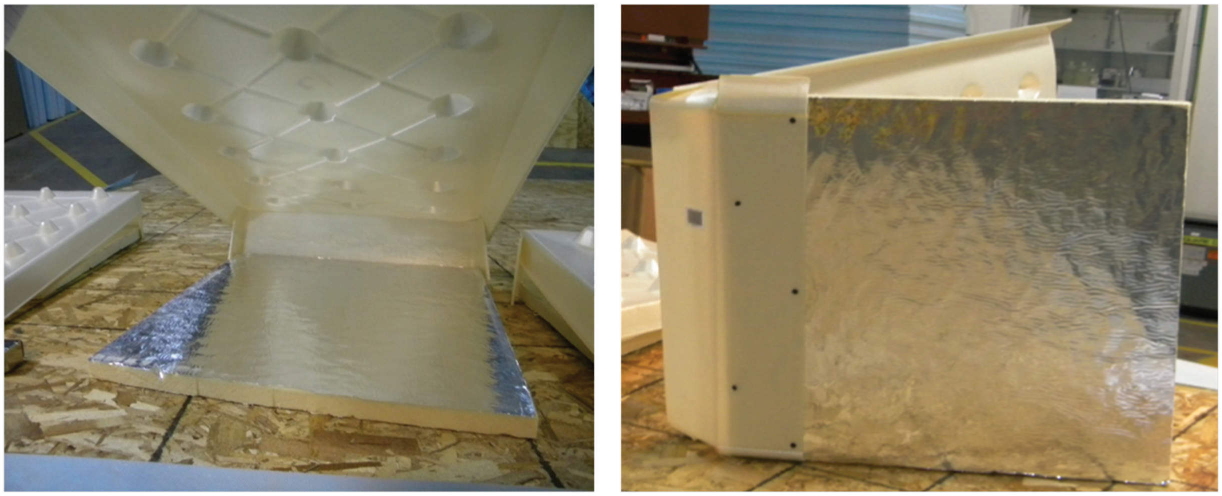

***Figure 7*** *Foam attic baffle pre-attached to 1 in. polyisocyanurate foam insulation board using drywall screws.*

was removed. A qualitative analysis of air sealing effectiveness and photographic documentation was then conducted.

### Phase II Test Procedures

Phase II employed the 4 × 8 ft by 4 ft tall chamber with the ~5/12 slope roof and duct blaster to quantitatively measure air infiltration improvements after three different air sealing techniques were applied to gaps on either side of the top plate (refer to Figure 5). The installer had the same ground rules as in phase I, with no body part allowed above the highest point of the attic structure and all materials required to be pre-staged either in the attic or on the work deck.

For technique 1b, two beads of one-component foam were applied using the long, curved dispensing gun. The first bead targeted the gap between the interior ceiling drywall and the top plate. The second bead targeted the gap between the top plate and exterior OSB sheathing

For technique 2c, the first bead of the one-component foam was applied onto the interior ceiling drywall, slightly forward of the gap between the drywall and top plate. Phase I had shown that as the foam sheet was pushed out over the top plate area it also pushed the foam sealant. Accordingly, by placing the bead slightly forward of the gap intended to be air sealed, it was hypothesized that bead would move to the ultimately intended location. A second bead was still applied along the gap between the interior ceiling drywall and top plate, though. The third bead applied targeted the outer edge of the top plate. This area was identified as the target after technique 1b was employed during phase II. During that step, it was not possible to maneuver the dispensing gun to apply the foam sealant directly to the gap between the top plate and the OSB sheathing with the sheathing sitting 1/2 in. below the top face of the top plate. Thus, the hypothesis was that it might be possible for a bead of foam to be applied to the outer edge of the top plate to "fall into place" as the foam sheet was installed, sealing this outer gap.

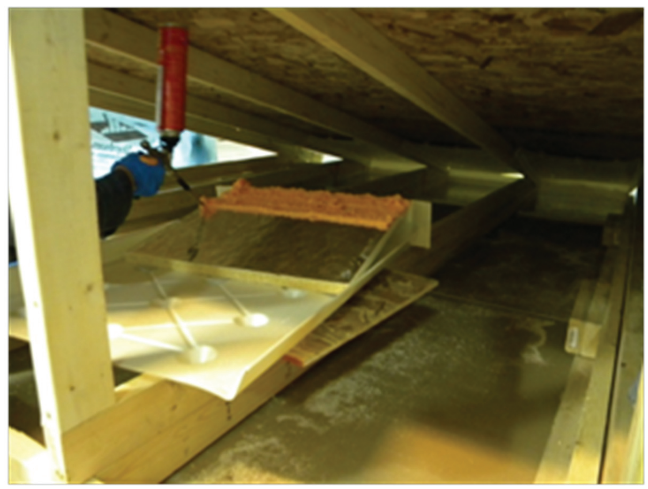

***Figure 8*** *Application of 8–10 in. of one-component foam sealant to polyisocyanurate foam board with attic baffle pre-attached.*

No air sealing difference had been seen in phase I between using baffles or fiberglass batts as a backer material for the two-component foam. Foam attic baffles were selected for phase II, technique 3a, since they would typically be used in most attic cavities.

The measurement procedure for phase II first involved taking an air infiltration measurement with both the interior and exterior sheathing to top plate gaps sealed with construction tape to establish what a very good air infiltration rate would be for the chamber if both gaps around the top plate were sealed. This measurement was noted as the targeted performance level. Note that all other gapped areas were also sealed with construction tape to establish the targeted performance level as well as to determine the performance level of each of the three techniques tested (i.e., researchers taped gaps around the bottom plate, gaps between the OSB sheathing, gaps between rafter ends and OSB sheathing, etc.).

Once the targeted performance level measurements were complete, a baseline measurement with no tape on either side of the top plate was conducted. This was important to do before each new air sealing method was installed since the same structure was to be used for each air sealing method. While the previous air sealing material would be removed prior to installing the next method, no guarantee could be made that all the air sealing material would be removed or that the gap size might not be increased in some areas as the old material was chipped away.

Each technique outlined in Figure 5, as well as the targeted performance level, was tested at 25 and 50 Pa pressure differentials. At each pressure differential, five airflow measurements were collected at 20 s apart. The average of the five measurements was rounded to the nearest whole number and reported.

## RESULTS

### Phase I Results

Phase I results are summarized in Figure 9 and Table 2. Figure 9 illustrates how far the installer was able to physically reach into various areas of the low-slope roof assembly. It provides a visual guide to understanding the constraints an installer faces when air sealing such structures. Table 2 captures both the air sealing observations and the installer feedback for each phase I air sealing and thermal insulating technique. Figures 10–12 provide visual examples of the air seal achieved for the techniques employed in phase I.

Figure 10 exemplifies what a good-quality sealant installation around the top plate looked like using technique 1a or 1b relative to poor installation quality around the top plate. Similarly, Figure 11 shows what a quality sealant installation looked like using technique 2a and a poor-quality installation using technique 2b. In the case of technique 3a, if an installer was able to reach into a given cavity to apply the two-compo-

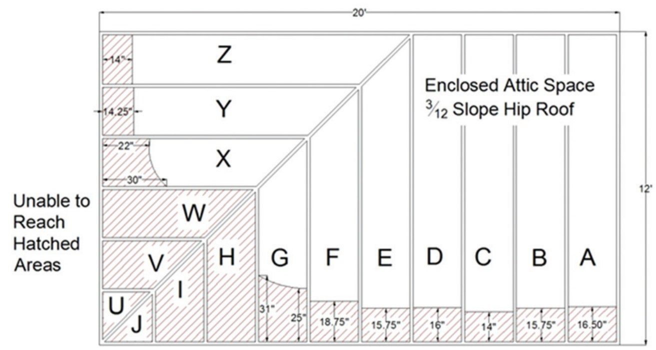


***Figure 9*** *Bird's-eye view of attic mock up: distance between the furthest physical reach point to the interior top plate edge.*

**Table 2. Phase I Testing Summary, Techniques 1a, 1b, 2a, 2b, and 3a**

| Phase I Technique | Sealant Installation Quality Results Summary | Key Learnings |
|---|---|---|
| 1a | • Sealant installation quality was poor. | • Extended-length, curved dispensing gun works better than standard-length dispensing gun.<br>• Design improvement opportunities exist for the extended gun to enable more flexible positioning of the gun in a confined area.<br>• Installation could be optimized if the one-component foam can product could be interchangeably positioned vertically and horizontally. |
| 1b | • Reach was to cavity I.<br>• Sealant installation quality was good to cavity D. | |
| 2a | • Sealant installation quality was good. | • Pre-attached foam baffles to a foam sheet are cumbersome to maneuver, become easily damaged, and limit the reach of the technique. |
| 2b | • Sealant installation quality was poor. | |
| 3a | • Reach was to cavity E installing foam baffle.<br>• Reach was to cavity I installing rolled fiberglass batt.<br>• Reach was to cavity G installing two-component foam.<br>• Sealant installation quality was good in *all* cavities reached, installing the two-component foam (e.g., to cavity G). | • An extension wand at the end of the dispensing hose would enable accessing more areas. |
| Overall | • **Easiest installation, physically:** One-component with the extended, curved dispensing gun.<br>• **Longest reach:** One-component with the extended, curved dispensing gun.<br>• **Best sealant installation quality:** i) Pre-attached baffle to foam sheet with one-component applied to top plate OR ii) two-component spray foam.<br>• **Best sealant installation quality/reach balance:** Two-component spray foam. | |

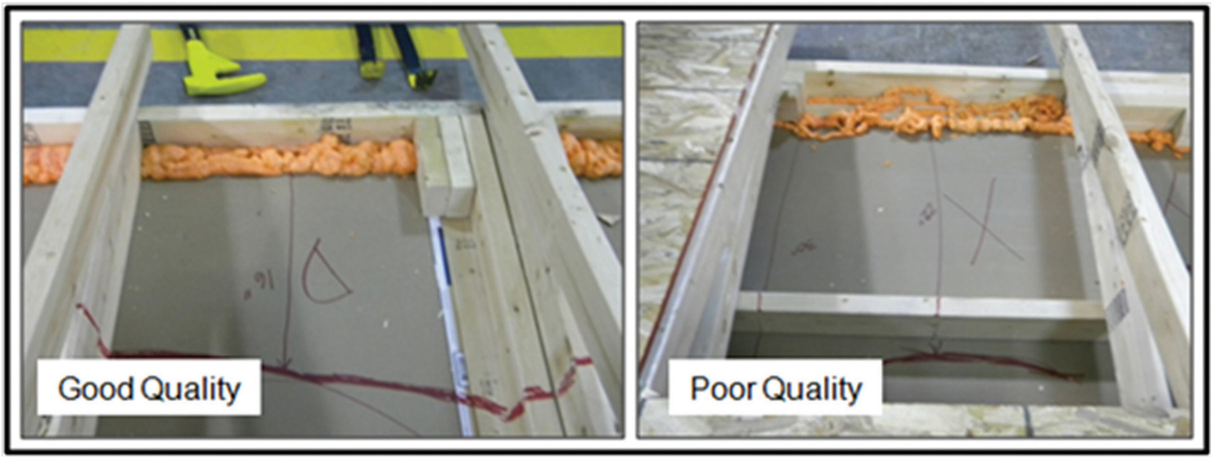


*Figure 10* *Examples of good- and poor-quality foam sealant installations using techniques 1b and 1a, respectively.*


*Figure 11* *Examples of good- and poor-quality foam sealant installations using techniques 2a and 2b, respectively.*

nent foam, the top plate area appeared completely air sealed during post-installation inspection (see Figure 12).

### Phase II Results

Phase II results are summarized in Figure 13. Recall that only the good-quality installation approaches from phase I were tested in phase II. The reduction in air infiltration was generally the same for all three air sealing techniques employed at pressure differentials of 25 and 50 Pa.

All three techniques had a large performance gap relative to the targeted performance level, having air leakage rates 20% to 35% greater than the target. Recall that both the interior and exterior top plate gaps were sealed with construction tape and air infiltration was measured at the outset of phase II, representing the target performance level for each technique employed. A large portion of the delta from the target can most likely be attributed to the inability of techniques 1b, 2c, and 3a to reach and seal the gap between the exterior sheathing and the top plate.

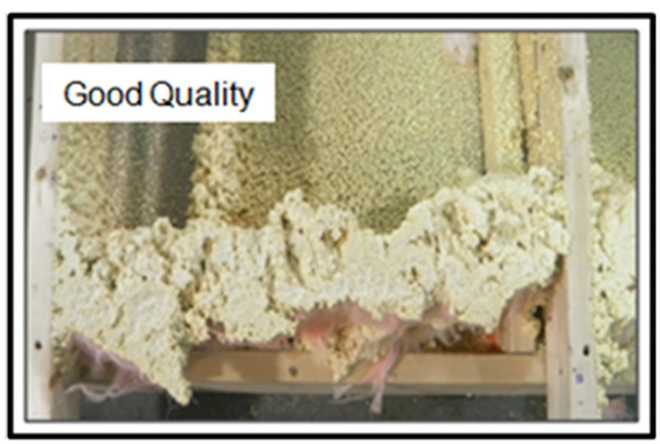


*Figure 12* *Example of a good-quality foam sealant installation using technique 3a.*

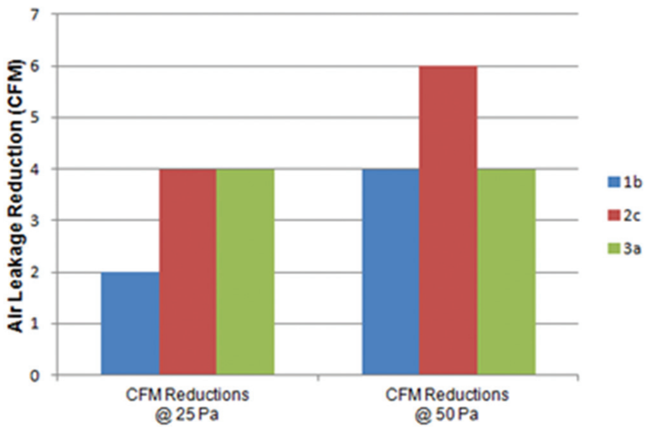


***Figure 13** Reduction in air infiltration in cubic feet per minute (cfm) obtained by sealing the top plate using techniques 1b, 2c, and 3a.*

## DISCUSSION

### Practicality and Effectiveness of Air Sealing Methods Explored in Phase II

Generally, the installer could not physically reach closer than within about 14 in. of the interior edge of the top plate; however, it was possible to apply air sealing materials to most of the perimeter of a 3/12 slope roof using various reach extension tools and techniques. With the 3/12 hip roof, the installer was generally able to *apply* air sealing materials within 6 ft of the corner.

Various techniques were explored during the early phases of this research program; however, they were eventually refined and narrowed to three techniques that were quantitatively tested in phase II, yielding similar performance results. Since these three techniques were deemed most suitable for use in low-slope attics relative to the other techniques explored, only phase II air sealing techniques are discussed at greater length in this paper.

With three significantly different techniques for air sealing the top plate yielding similar quantitative air infiltration reductions in a laboratory setting during phase II, it is easy to understand why home performance retrofitters consistently stated that a "one size fits all" approach does not exist. Each installation technique employed in phase II was equal in terms of air infiltration reduction; however, the practicality and feasibility study in phase I revealed pluses and minuses of the techniques that would need to be considered for an in-field attic retrofit.

First, while the one-component foam applied using the long, curved dispensing gun was physically the easiest technique to execute and gave the installer the longest reach, the quality of the air seal was not as good at extended distances as it was using other techniques. The dispensing gun was designed for pinpointed application of the foam sealant. The installer, though, could not see if he was applying the foam along the gaps. The installer had to rely on intuition or, in the case of a larger, well-defined gap, feeling the dispensing gun setting into the gap and then moving along the gap.

Further, the one-component foam sealant technique was also plagued by limited maneuverability of the can and long, curved dispensing gun. The can must be in the vertical position to apply the product. The long, curved dispensing gun could not be adequately rotated in the confined space to enable applying one long, continuous bead of foam sealant in a given cavity. Rather, the installer had to stop short of the full cavity width, reposition the dispensing gun, and finish applying the foam sealant the remainder of the cavity width.

The second technique of applying one-component foam to the top plate area and then installing a pre-sized foam sheet extending over the top plate area and slightly into the main attic floor space also faced maneuverability issues. The foam sheet was cumbersome to maneuver around rafters and objects penetrating through the attic. While not completely resolved, some of these issues were reduced when the pre-attached baffle used in phase I was removed in phase II. Logistics aside, one significant disadvantage of this method was the need to pre-cut the foam sheets to size. For in-field applications, depending on the attic layout, this could be tedious.

Despite its in-field limitations, this technique was still considered after phase I largely since it presented a viable method to improve the thermal insulation levels around the perimeter of an attic. Assuming a 3 in. thick R-6.5 foam insulation and a generic R-3.5 insulation installed over the foam, Figure 14 illustrates the shrinking distance of the underinsulated area for R-30 and R-49 targets using this technique with a 3/12 roof. Overall, for a $32 \times 40$ ft attic, the technique enables ~10% more of the attic area to be insulated to the target value.

The third and final technique explored, using a two-component foam to seal the top plate area, seemed to offer the best balance between reach and air seal quality. While the reach was not as far as the long, curved dispensing gun used with the one-component foam, the two-component foam technique was able to effectively air seal cavities further out than the one-component technique. The reach of the two-component foam might be improved if an extension wand was available to attach to the end of the dispensing hose. The disadvantage of using a two-component polyurethane foam sealant in field is that it requires a specially trained installer who must wear a respirator during the installation.

For all three techniques, the dispensing equipment in-field cleaning factor was a disadvantage. The one-component gun had to be cleaned after application to approximately every fifth cavity, otherwise the nozzle would have a large glob of foam build-up on its end. The tip on the two-component foam dispensing equipment had to be replaced every time the installer had to reposition and relocate himself on the OSB boards laid over the ceiling joists. Otherwise, the foam would harden in the tip and block dispensing. This worked out to be approximately every third cavity. Overall, in-field cleaning

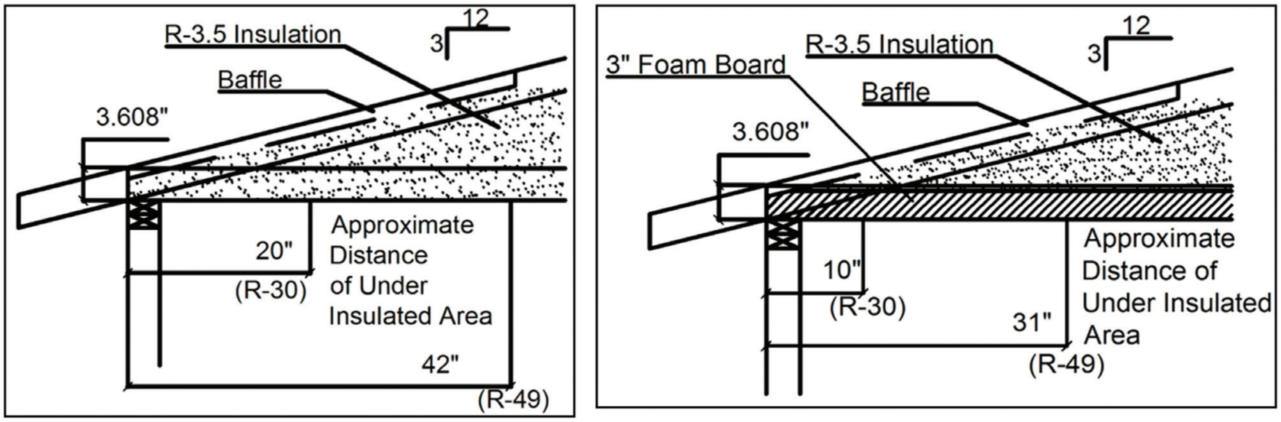


***Figure 14*** *Shrinking distance of underinsulated area using technique 2c in a 3/12 roof.*

requirements were cumbersome to execute in the confined attic space and slowed the installation work.

Unfortunately, all three air sealing techniques shared a quantitative performance gap. None were able to address sealing between the top plate and exterior sheathing when the exterior sheathing was not flush with the top plate. While few sources specifically recommended sealing this gap and several home performance contractors voiced consciously not working to seal this gap, this gap does offer significant potential for air leakage in a home. Assuming a 1/32 in. gap on each side of the top plate, an unsealed gap between the top plate and the exterior sheathing represents slightly more than 50% of the 107 $in.^2$ of open space around the top plate in a 32 × 40 ft attic space.

### Air Sealing and Insulating Limitations for 3/12 Slope Hip Roof

Most home performance retrofit contractors commented that they deem air sealing to be more important than insulating. Some of their emphasis on air sealing may be due to the inability to insulate low-slope attics due to a lack of materials with R-values high enough to insulate height-constrained attic spaces of attics to the targeted values. Blown-in cellulose (R-3.8/in.) generally offers a higher R-value than blown-in fiberglass (typically ~R-3/in.) and is most commonly used (CIMA 2012; CertainTeed 2011; GBP 2008a, 2008b; Greenfiber 2012; JM 2012; Owens Corning 2012). If a 3/12 slope roof attic has a targeted R-49 insulation level, though, blown-in cellulose can only insulate approximately 66% of a 32 × 40 ft attic area to this target level.

Foam insulation board products can offer a higher R/in. (e.g., up to R-6.5/in.). However, they are cumbersome to install in an attic and their impact on achieving targeted R-values in attics is minimal unless relatively thick boards are used. For a 32 × 40 ft home with a 3/12 roof, adding a 1 in. thick R-6.5 foam sheet under blown-in cellulose only enables ~68% of the attic area to be insulated to a R-49 target. Adding a 3 in. thick R-6.5 foam sheet under blown-in cellulose enables ~73% of the attic area to be insulated to an R-49 target.

Two-component spray polyurethane high pressurized drum foams can offer R-values comparable to foam boards (e.g., R-6.5). In a 32 × 40 ft attic with a 3/12 slope, it can be installed at heights that would result in the R-49 target being realized in ~86% of the attic area.

### Cost Considerations

Recognizing every attic space is different and costs fluctuate (i.e., over time, by geographic regions, between manufacturers, etc.), some basic considerations of cost are appropriate.

First, a 24 oz can of one-component polyurethane foam sealant can typically be purchased for less than $20 per can. By contrast, a ~100 board foot two-component spray foam sealant costs between $200 to 300, and a 55 gal drum set of high-pressure drum foam runs around $2000 (Diamond Tool 2012; FarmTeck 2012a, 2012b; Home Depot 2012; Industrial Products 2012a, 2012b; Lowe’s 2012; Menards 2012a; SD 2012; SoyThane 2013). Accordingly, the initial sticker price of both the two-component foams can be an immediate deterrent to an individual inexperienced with the relative effectiveness of attic air sealing and insulating of various materials. Of course, the 24 oz can will not cover as much area as the 100 board foot kit or 55 gal drum set, but its functionality is limited to air sealing whereas many two-component foams offer insulation.

On a board foot (BDF) basis, the material cost of the two-component low-pressure foam can be five times the cost of the two-component high-pressure drum foam. At the low end of the material cost for two-component low-pressure foam, the cost is typically 40% higher than the cost of the two-component high-pressure drum foam on a BDF basis.

Next, moving beyond the sticker shock, the labor costs for each technique might vary. It has been reported that labor costs often outweigh material cost considerations (Keefe 1995). While this research indicated that it was physically easier to install the one-component foam in the laboratory attic than the low-pressure two-component foam, the two-component foam was less tedious, which may equate to less time on the job. On the other hand, a trained installer is required for both the low-pressure and high-pressure two-component foam as well as a supplied-air or air-purifying respirator. These measures are aimed at protecting workers from potential health risks; however, it should be noted that health risks are under continuous evaluation (Yost 2011). The need for trained installers and additional personal protective equipment may increase labor costs for two-component foams.

Although each of these products can be used to achieve the desired air sealing result, a more important consideration than cost is the pairing of the product to work-space access, equipment availability, and installer expertise. All can cost-effectively air seal in the situation appropriate to the product.

## CONCLUSIONS

The following conclusions pertaining to air sealing and insulating an existing low-slope attic were drawn from the work documented in this report.

- **The tools are as important as the product.** Phase II results showed that both one-component and two-component foam sealants can effectively seal the gaps surrounding the top plate; however, the tools to reach and apply the products ultimately impact the quality of the air seal. When using the one-component foam sealant, more confined attic space areas were accessible and effectively air sealed using the long, curved dispensing gun than the standard dispensing gun. Yet, the long, curved gun still had some maneuvering challenges and could not seal a gap in a continuous bead. Further, it often did not achieve an air seal in many areas, as it was difficult for the installer to tell where the product was being applied with the gun. Similarly, the two-component foam could have reached even more areas if it had an extension wand.
- **Keep it simple in the attic.** Using foam boards with baffles pre-attached to foam sheets was cumbersome and resulted in damage to the baffles during installation. It was easier and more successful installing the two items independently. That said, maneuvering 24 × 20 in. foam boards around rafters and other obstructions was not trivial either. Accordingly, assembling smaller pieces as they are installed in the attic is preferred over pre-assembly and large pieces.
- **High-pressure two-component spray polyurethane foam offers the highest thermal insulating potential.** Existing thermal materials, independent of cost, do not have the R-value/inch to meet the targets along the perimeter of the attic. When strictly insulation value is considered, high-pressurized two-component spray polyurethane foams offer the best potential to meet target R-values in low-slope attics. Yet, they still cannot meet higher (e.g., R-49, R-60) R-value targets at the perimeter of the lower-sloped attics. While not tested for air sealing during research, they are assumed to have capabilities similar to their low-pressure, small-kit versions.
- **Insulating the exterior gap is very difficult from the interior.** Air sealing the joint between the exterior sheathing and top plate when the exterior sheathing was not flush with the top of the top plate was problematic with the approaches investigated. It is highly probable that this gap is best addressed from the exterior of a low-slope attic home.
- **Two-component foam sealants have the best air sealing capacity.** While it is possible to achieve a good air seal over the top plate area with all three of the air sealing methods explored in this paper, the air sealing achieved with the two-component foam is superior as it is able to adequately air seal more confined-spaced areas than either of the one-component foam techniques investigated.

## RECOMMENDATIONS

Overall, the work presented in this paper lays a foundation to begin work on developing better methods and materials to address air sealing and insulating space-constrained areas of low-slope attics. The following recommendations are drawn from the work documented in this report.

- Manufacturers of one-component foam sealants should continue to refine the design of their extended dispensing guns to maximize the ability to efficiently and effectively apply these products in space-constrained, non-visible areas.
- Manufacturers of two-component foam sealants should explore developing extended-reach dispensing wands to increase the accessibility to more confined attic areas.
- Manufacturers of both one- and two-component foam sealants should consider extension dispensing guns to address accessing the joint between the exterior sheathing and top plate when the exterior sheathing is not flush with the top of the plate.
- Manufacturers of one-component foam sealants should consider enabling product dispensing from cans oriented in more directions to improve the ability to effectively apply these products.
- Further research should be conducted to better understand the cost and practicality of using high-pressure two-component spray polyurethane foams in low-slope attics, since they currently offer the greatest insulating potential for such attics.
- Research should be conducted to explore the cost-effectiveness of attic air sealing approaches from the exterior of the home.
- Research should be conducted to understand the ability of various blind wall cavity fill insulations to simultane-

ously insulate the wall cavities and air seal the top plate area.

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