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Validation Study of Experimental Insulating and Air-Sealing Technology for Enclosed Roof Cavities

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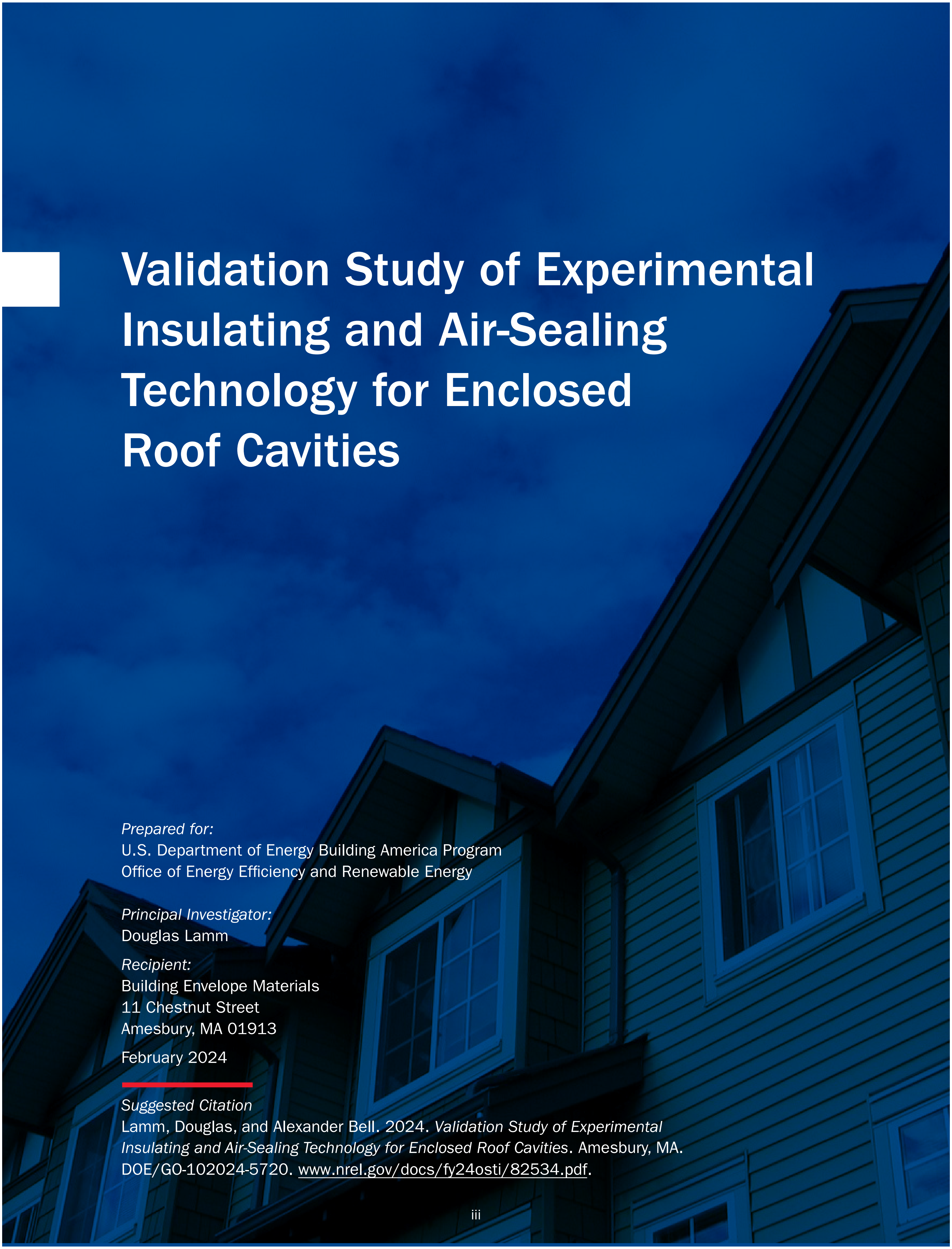

Validation Study of Experimental Insulating and Air-Sealing Technology for Enclosed Roof Cavities

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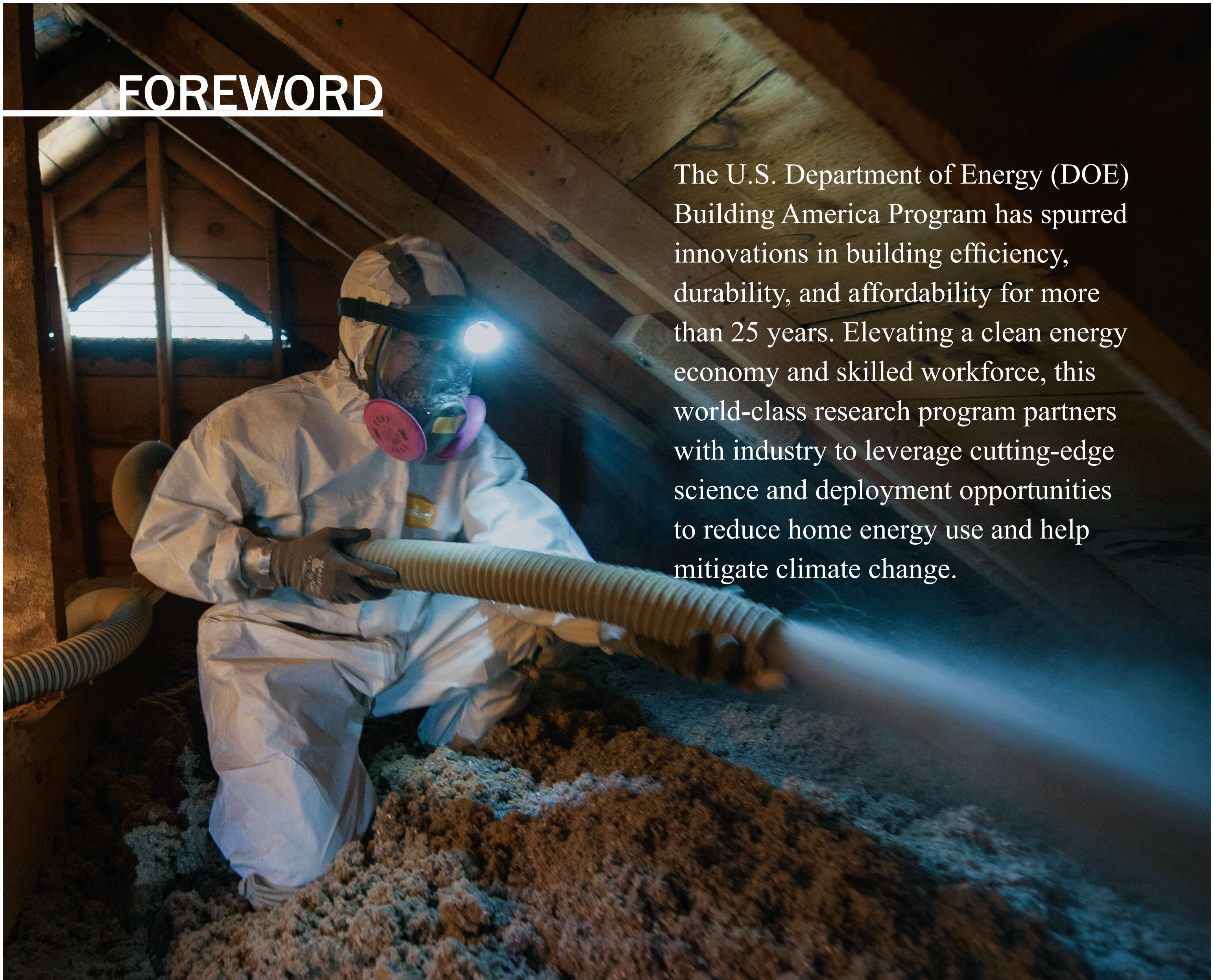
The work presented in this EERE Building America report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.



FOREWORD

The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, the Building Envelope Materials team is one of many Building America teams working to drive innovations that address the challenges identified in the program's Research-to-Market Plan.

This report, *Validation Study of Experimental Insulating and Air-Sealing Technology for Enclosed Roof Cavities*, explores a new minimally invasive procedure known as Pinhole Insulation® for retrofit insulation of cathedral ceilings, flat roofs, dormer roofs, and other enclosed roof cavities. It also explores the validation of the associated equipment, software, and materials used in this process.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

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LIST OF ACRONYMS

BEM	Building Envelope Materials
DOE	U.S. Department of Energy
ERC	enclosed roof cavity
GWP	global warming potential
IR	infrared
IPF	injected polyurethane foam
NREL	National Renewable Energy Laboratory

EXECUTIVE SUMMARY

PROBLEM STATEMENT

Enclosed roof cavities (ERCs) are common in many types of housing, e.g., cathedral ceilings in single-family homes, flat roofs in triple-deckers, and dormer roofs in homes with complex rooflines.

Based on the authors' experience retrofitting buildings in most U.S. climate zones, we estimate that approximately 80% of all ERCs are either uninsulated (contain no insulation) or are under-insulated (contain only fiberglass). As shown by the ice dam in Figure ES-1, even fiberglass-insulated ERCs can be a major source of air leakage, moisture damage, and heat loss. Similarly, ERCs insulated with dense pack cellulose are prone to moisture problems and do not satisfy building codes.

Figure ES-1. Ice dam in ERC
Photo from the authors

If the interior ceiling is removed, closed cell spray foam in combination with fibrous insulation can be installed from inside the building. However, removal and replacement of the ceiling is a highly invasive, time-consuming, messy, and expensive process, typically requiring furnishings to be removed, multiple trades, and extensive cleanup. Moreover, according to the U.S. Environmental Protection Agency, installation of spray foam requires residents and workers to leave the building for 24–48 hours to allow hazardous aerosolized particulates to clear from the air. Installing exterior rigid foam boards on the exterior of roof sheathing can be a highly effective approach. However, exterior foam is not used when only a portion of the roof needs retrofit insulation, as is commonly the case with cathedral ceilings and dormer roofs. Additionally, installation of exterior insulation requires careful fitting of foam boards and application of membranes, an expensive and time-consuming process even for flat roofs.

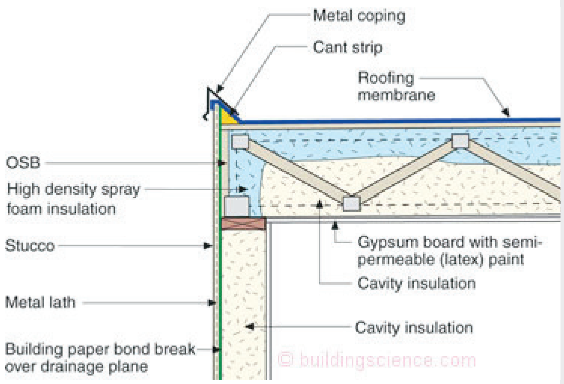

Figure ES-2. Retrofit insulation of ERC requiring ceiling removal
Graphic from the Building Sciences Corporation

Research Questions

In order to reduce the time, cost, and invasiveness of existing solutions to retrofit insulation and air sealing of enclosed roof cavities, we investigated the potential of injecting closed cell polyurethane foam through holes in the ceiling surface into a space between the exterior roof sheathing and the existing insulation. The key research questions addressed include:

- Does injecting thick foam present a fire hazard due to excessive exothermic heat buildup?
- How to eliminate void formation, particularly in cavities with 24” on center rafter spacing?
- How to minimize the number and size of holes drilled in the ceiling surface?
- How to inject foam in the presence of rafter vents?
- How to avoid foam drips through soffit vents?
- Is equipment reliable in a large-scale project? How best to modify?
- Can a software app simplify and/or improve the process and/or equipment?
- What are contractors’ concerns?
- How to best monitor fill quality and foam quality?
- How much improvement in R-value, perm rating, and air sealing can be achieved?

Methods

Building Envelope Materials (BEM) had previously developed a minimally invasive technology for injecting closed cell polyurethane insulation material into uninsulated and under-insulated wall cavities. The technology, Pinhole Insulation, uses a calibrated timing system in combination with an infrared (IR) camera and specially designed needles, tubes, and dispense equipment to ensure a cavity fill that is void free and that virtually eliminates risk of wall “blowout.”

The application of Pinhole Insulation to the ERC problem consisted of lab trials, field trials, equipment modifications, and market research with contractors, and two large validation projects encompassing a total of 35,000 square feet of insulated surface.

Results

Through the course of this project, BEM substantially modified the Pinhole Insulation process for use in ERCs, qualified a new low-global warming potential (GWP) foam, designed and validated a complementary smartphone app, and developed contractor training manuals and videos.

Answers to the questions posed above were as follows:

Thick injection foam does not present a fire hazard due to the exothermic reaction. The maximum temperature recorded in a 12” block of foam was 304°F. The self-ignition temperature of the foam is 550°F. To maximize safety and minimize potential for foam shrinkage due to exotherm, pilot projects were only conducted in rafters that were 6” in depth.

Voids in 24” on center rafter spacing are eliminated via injection next to the rafters. Material should be injected 3” inboard from each rafter when rafters are 24” on center. Injection in the center of cavity works well for 16” on center rafter spacing.

The number of holes drilled can be reduced by using a multiport tube dispense system. The use of tubes enables holes to be drilled at 8’ spacing. The multiport system uses a Y adapter on a tube to simultaneously dispense material on two sides of a rafter cavity.

Tape temporarily applied over soffit vents eliminates drips. We refer to the first shot of insulation at the bottom of an ERC as a “blocking shot” because it blocks the soffit from excessive pressure buildup from the expanding foam. Prior to injecting a blocking shot into the bottom of a cavity, tape is applied over soffit vents to eliminate potential for foam to drip through soffit vents. After the blocking shot has cured, the tape is removed.

Special needles eliminate challenges related to rafter vents. Many fiberglass-filled cavities contain rafter vents that are easily punctured by dispense tubes and needles. To avoid uncontrolled expansion of foam inside the rafter vent, we developed specially designed needles and tubes that eliminate the potential for foam to be dispensed within the vent.

The new Talking Rig addresses contractors' concerns. Contractors' main concern is the availability of skilled technicians. Contractors are also concerned about potential liability exposure due to improperly mixed materials, initial equipment investment required, ongoing maintenance costs, and access to ERCs in large buildings. We developed a new rig and smartphone app to address these concerns. The new system benefits include:

- *Doubled productivity.* The Talking Rig does not require a second technician in a trailer or truck to monitor equipment status. A two-person crew with two rigs can inject twice as fast as a traditional rig.
- *Minimal training.* The system "talks" to the technician, providing real-time information on quantity and quality of material dispensed. A technician can be trained in less than a day.
- *Mobile*. A Talking Rig full of materials weighs about 250 lbs and is less than 4' tall and 16" wide. In elevator service buildings, it is easily rolled through tight spaces. For stair access buildings, it can be separated into three components, and each component can be brought up the stairs with a hand truck. Virtually any space in any size building can be accessed.
- *Reliable*. Other than simple manual ball valves, the rig has no moving parts. Other than speech, the rig is silent.
- *Low cost.* When fully commercialized, the rig price is expected to be an order of magnitude less than traditional mobile rigs.
- *Reduced liability.* Rig components are designed to ensure on-ratio performance without operator intervention. Foam quality data is recorded and can be presented to building owners.

Injected ERCs achieved substantial improvement in energy measures. In uninsulated ERCs with 6" rafters, nominal R-value was improved from R6 to R35. In under-insulated fiberglass-filled ERCs with 6" rafters, R-value was improved from R19 to R31. In both cases, there were no voids and minimal variation in foam thickness (standard deviation of thickness less than 1"). Perm rating was also improved to less than 1.

Visual evidence of the effectiveness of injected foam insulation can be clearly seen in the infrared images in Figure ES-3. In this case study, we injected half of a cathedral ceiling, which was originally insulated with R19 batts. After injection, the R-value of the injected side was approximately R30. As can be seen in the IR image from a hot summer day (Figure ES-3, right IR image), the temperature difference between the injected side (purple) and the uninjected side (orange) was about 12 degrees. On a cold winter day (Figure ES-3, left IR image), the temperature difference between the injected side (orange) and the uninjected side (purple) was about 15 degrees. Moreover, the temperature difference is greatest at the bottom of the cathedral ceiling. This is the critical wall/roof transition where most of the air leakage often occurs in cathedral ceilings. Further visual evidence of the effectiveness of injected foam can be seen in the ice patterns on the roof of the house with the half-injected cathedral ceiling (Figure ES-4). The ice on the right has formed on the uninjected portion of the cathedral ceiling. There is no ice on the injected portion on the left.

Significance

The process, equipment, software, consumables, and materials developed through the course of this project will have many benefits:

- *Ice dam elimination.* As seen in Figure ES-4, injected foam is a quick, minimally invasive method for reducing or eliminating ice dams due to under-insulated ERCs.

- *Energy savings.* In houses that are entirely roofed with cathedral ceilings, energy modeling suggests that thermal energy savings of up to 30% could be achievable.

- *Improved comfort*. Because ERCs are such a significant source of heat loss, HVAC equipment is often unable to achieve desired set point temperatures during extreme cold or hot days. Building occupants will be more comfortable.

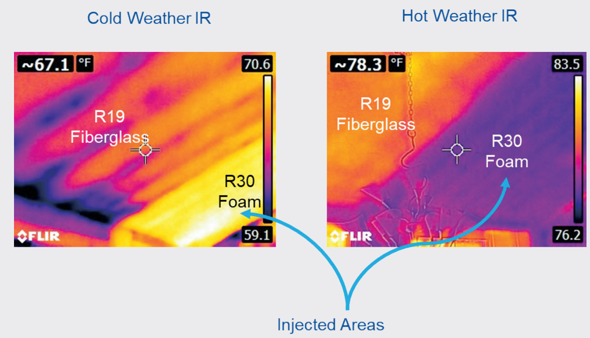

Figure ES-3. Infrared image showing the temperature difference between the injected side and the uninjected side

Figure ES-4. Ice formed on the uninjected (right) portion of the cathedral ceiling. No ice on the injected portion (left). *Photo from the authors*

- *Better worker retention*. The development of inexpensive, easy-to-learn injection foam equipment and software—which can be utilized for ERC, wall, and ultimately traditional attic insulation—will enable contractors to keep their technicians busy during the hot summer months from within comfortable conditioned spaces rather than requiring them to work in dangerous confined spaces in hot attics.

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1 Introduction

1.1 Problem Statement

Enclosed roof cavities (ERCs) are enclosed on four sides by rafters, on one side by roof sheathing, and on the other side by a ceiling surface. ERCs are common in many types of housing, e.g., cathedral ceilings in single-family homes, flat roofs in row houses and triple-deckers, and dormer roofs in homes with complex rooflines. We estimate that about 80% of all single-family homes contain at least one ERC. In addition, approximately 80% of all ERCs are either uninsulated (contain no insulation) or are under-insulated (contain only fiberglass). As shown by the ice dams in Figure 1, even fiberglass-insulated ERCs can be a major source of air leakage, moisture damage, and heat loss. Similarly, ERCs insulated with dense pack cellulose are prone to moisture problems and do not satisfy building codes.

Figure 1. Ice dam in ERC

All photos in report by the authors, unless otherwise noted

If the interior ceiling is removed, closed cell spray foam in combination with fibrous insulation can be installed from the inside of the building. However, removal and replacement of the ceiling is a highly invasive, time-consuming, messy, and expensive process that typically requires furnishings to be removed, multiple trades, and extensive cleanup. Moreover, installation of spray foam requires residents and workers to leave the building for 24–48 hours to allow hazardous aerosolized particles to clear. Installing exterior rigid foam boards on the exterior of roof sheathing can be a highly effective approach for flat roofs. However, exterior foam is not used when only a portion of the roof needs retrofit insulation, as is commonly the case with cathedral ceilings and dormer roofs. Additionally, installation of exterior insulation requires careful fitting of foam boards and application of membranes, an expensive and time-consuming process even for flat roofs.

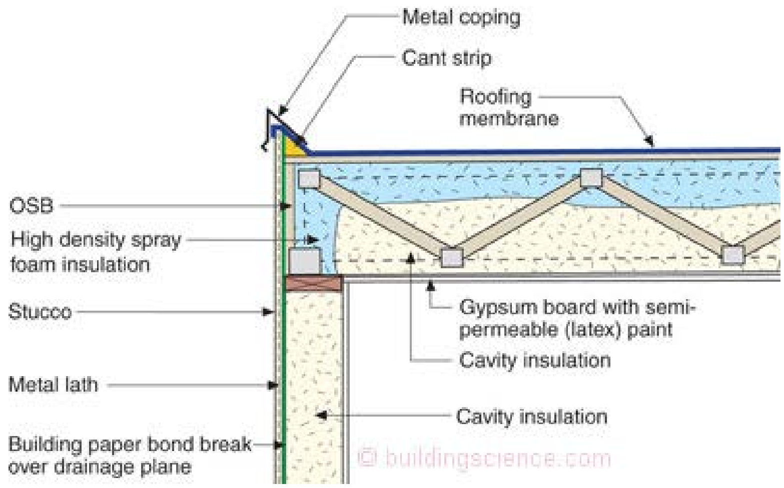

Figure 2. Retrofit insulation of ERC requiring ceiling removal

Graphic from the Building Sciences Corporation

1.2 Scope and Objectives of Study

The primary objective of the study has been to develop a minimally invasive system for retrofit insulation of enclosed roof cavities that will meet the following performance goals:

- Adds at least R12 to existing ERC insulation levels
- Achieves a perm rating of less than 1 in a 2” or greater thickness
- Contains no gaps in the air barrier.

The primary process challenge addressed in the study was development of a system of procedures, equipment, software, and materials that could reliably handle the challenges posed by the greater widths, wider cavity spacing, longer cavity lengths, and non-vertical angles of ERCs as compared to walls. The entire system was to be validated in two large-scale projects.

1.3 Research Questions

The key research questions and topics included:

- Does injecting thick foam present a fire hazard due to excessive exothermic heat buildup?
- How to eliminate void formation, particularly in cavities with 24” on center rafter spacing?
- How to minimize the number and size of holes drilled in the ceiling surface?
- How to inject foam in the presence of rafter vents?

- How to avoid foam drips through soffit vents?
- What kind of equipment modifications are required?
- What are contractors' concerns?
- How to best monitor fill quality and foam quality?
- How much improvement in R-value, perm rating, and air sealing can be achieved?

1.4 Background and Previous Work

Injection of polyurethane foam into enclosed cavities is a practice that dates back at least 60 years. Manufacturers use injected polyurethane foam (IPF) in a factory environment for refrigerators, water heaters, HVAC equipment, metal panels, and other insulated products. The use of IPF to insulate buildings is a newer and more unusual practice. Gaco Western and Icynene have both commercialized systems for injecting open cell polyurethane foam into uninsulated wall cavities using high-pressure spray foam equipment (see https://gaco.com/sprayfoam/retrofit-applications/).

Injection of closed cell polyurethane foam into building cavities has been much more limited. A firm known as Foam-Tech injected closed cell foam into empty cavities throughout the 1980s and 1990s (Foam-Tech is no longer in business). The authors are not aware of any other firms that practiced closed cell foam injection. The practice was limited by fear among contractors of "blowing out walls," difficulty in training technicians, and many other process issues. Applications were also limited. The majority of buildings in the United States are insulated with fiberglass insulation. While not uninsulated, many of these fiberglass-insulated cavities are under-insulated, i.e., they contain thin, low-density fiberglass with low R-value and/or significant air gaps. The authors are not aware of any previous process for injecting closed cell polyurethane foam into under-insulated wall cavities.

The previous use of high-pressure spray foam equipment to inject polyurethane foam is limited to buildings in which the hose from the spray foam rig can reach all walls in a building. Because most high-pressure spray foam hoses are 200 feet or less in length, the walls in many large buildings cannot be accessed. This is particularly problematic in urban areas with limited availability of parking for spray foam rigs. In addition, high-pressure rigs are generally installed in the back of box trucks or trailers and require large, noisy, high-power compressors. As such, they cannot be used in retrofit applications in occupied buildings without major disturbance to building residents.

Two-part closed cell polyurethane foam is also available in low-pressure "kits." However, kit foam suffers from many disadvantages including no way to measure or control ratio when injecting into an ERC, no way to accurately measure volume of foam dispensed in real time, exceedingly slow dispense rate, disposal of large numbers of used pressure vessels with unreacted residual material, and excessive cost.

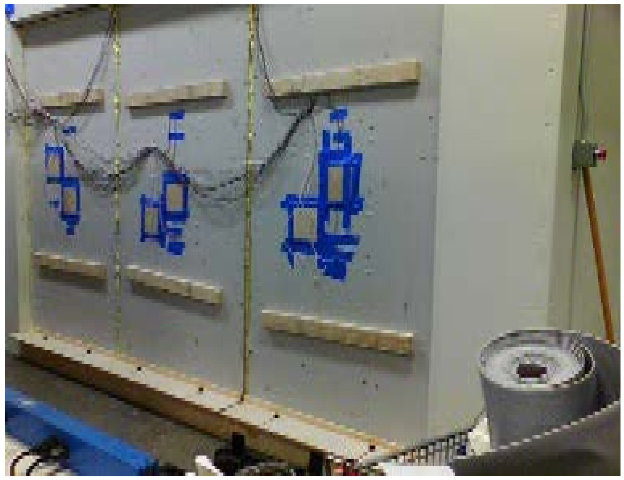

Figure 3. Testing R-value in full-scale test chamber

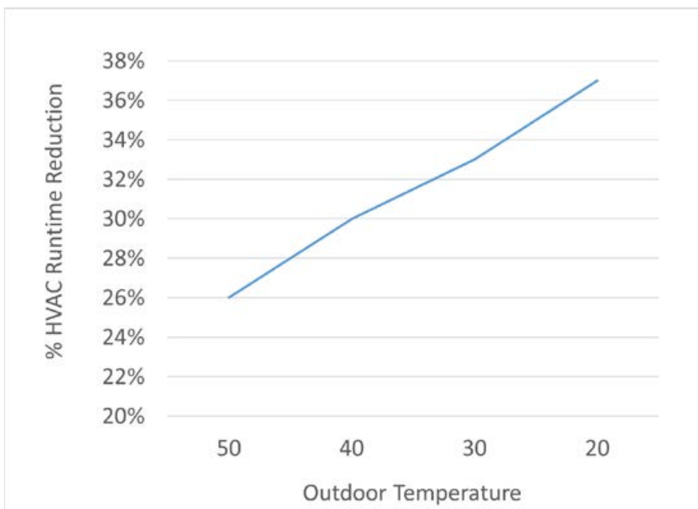

Figure 4. HVAC runtime reduction in injected apartments as compared to fiberglass-insulated apartment

Pinhole Insulation is a minimally invasive retrofit insulation system developed by Building Envelope Materials (BEM) to address the many shortcomings of the older IPF technologies. Doug Lamm founded BEM in 2013 to develop a comprehensive system for minimally invasive, cost-effective deep energy retrofits of residential, institutional, and commercial buildings. In addition, BEM developed Pinhole Insulation technology through a U.S. Department of Agriculture Technical Assistance grant and five grants from the Massachusetts Clean Energy Center (two Catalyst, one InnovateMass, one AmplifyMass, and one DeployMass). BEM has also partnered with CertainTeed/Saint Gobain in a consulting agreement, a joint development agreement, and a strategic partnership to assist with commercialization of the technology.

Energy modeling indicated that injection with closed cell polyurethane foam should result in an approximately 20%–25% reduction in thermal energy usage in buildings in climate zone 5. To validate this performance, Pinhole Insulation has been tested in full-scale test chambers and in pilot projects.[1] BEM demonstrated that the R-value of a typical "1950s wall" (i.e., plank sheathing, clapboard, 2" of fiberglass, drywall) in the test chamber (Figure 3 above) increases from approximately R10 before injection to R24 after injection. BEM also demonstrated a 25% HVAC runtime reduction in apartments injected with closed cell polyurethane foam as compared to apartments insulated only with fiberglass insulation (Figure 4 above).

Our first rig for dispensing foam was a trailer-mounted unit (Figure 5 below). The unit does a good job of proportioning materials in the proper ratio, but because the hose can only be extended 150', it cannot be used in larger single-family and multifamily residential buildings. Moreover, to avoid blowing out cavity walls when injecting, metering by volume is critical. The trailer-based unit is only capable of metering by shot time, not by shot volume. The trailer-based unit is also expensive (about $40,000) and complex to operate.

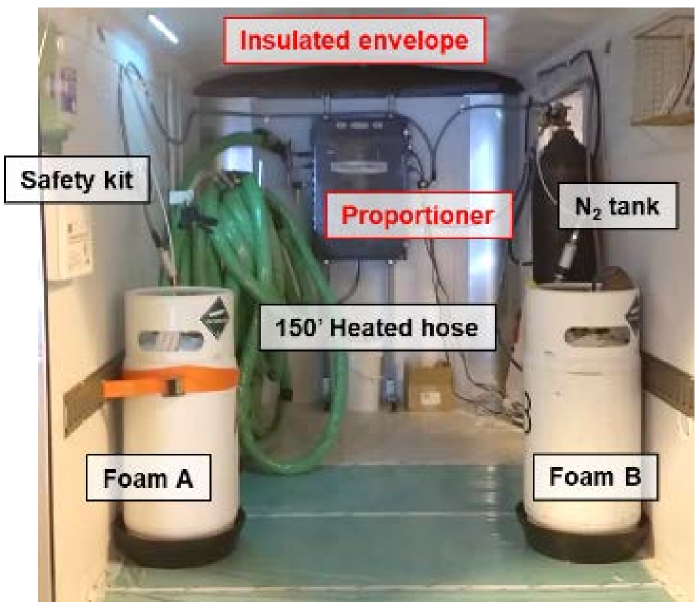

Figure 5. Trailer-mounted rig

[1] This refers to unpublished work by The Cadmus Group (Boston, MA) in 2016, produced for an "InnovateMass" grant from the Massachusetts Clean Energy Center.

2 Methodology

2.1 Research Design

We developed procedures for a minimally invasive ERC retrofit insulation process by first building test stands in the lab, and then iterating procedures, testing in the field, and repeating the cycle until we had perfected the process. We designed the sequence of our tests to first address the greatest expected challenges presented by ERCs and then, after field trials, address the greatest unexpected challenges that arose. Some of the more important expected challenges included:

- *Maximum safe thickness*. Before starting any lab tests, we needed to ensure that injecting polyurethane foam into ERCs was safe. We were particularly interested in whether there would be an excessive exothermic reaction when the foam is dispensed in a single pass in thick cross sections.

- *Rafter depth greater than 3.5"*. Wall cavities in older buildings are typically 3.5" deep. As a result, the interior and exterior wall surfaces serve as molding surfaces that constrain the thickness of injected foam to a maximum of 3.5". However, roof rafters in enclosed roof cavities are typically 6", 8", or 10" in depth. Dispensing closed cell foam in much greater thicknesses could be problematic due to excessive shrinkage and/or excessive cost.

- *Rafter spacing 24" on center*. Wall studs are typically spaced at 16" on center. Roof rafter cavities in older buildings are often 24" on center. Even dispersion of foam across the wider width of the rafter cavity could be challenging.

- *Variety of roof angles*. Because walls are vertical, foam fills voids via slumping. However, low-slope roofs might not allow material to fill voids through slumping.

- *Long roof rafter spans*. Wall studs are typically 8' long. Due to these short spans, foam can be injected either through a single ½" hole (using specially designed tubes) or through 4 ¼" holes using needles. Roof rafter spans are much longer. Techniques for minimizing the number and size of holes were not known.

The unexpected challenges included:

- *Soffit vents*. We discovered in field trials that injected foam spills into soffits and drips out of the soffit vents. In one pilot, we disassembled the soffit and inserted a liner on top of the vent to prevent the foam from dripping down through the vent. This liner process was labor and time intensive.

- *Rafter vents*. A properly constructed cathedral ceiling has a vent baffle running underneath the sheathing from soffit to ridge to promote ventilation and drying of the sheathing. These rafter vents are typically constructed of fragile polystyrene. During one of our pilots, we punctured the rafter vent with our dispense tubes. As a result, foam dispensed within the rafter vent flowed uncontrollably through the vent space and did not fill the rafter with sufficient thickness. We needed to develop a way to more consistently achieve desired foam thickness.

- *Scale-Up*. During the validation study, we needed to determine if the systems developed in the lab would hold up to the rigors of monthslong, large-scale projects in the field.

2.2 Test Stands

The following test stands were constructed to address each of the research questions listed in Section 1.3.

Maximum Safe Thickness. Before starting any lab tests, we needed to ensure that injecting polyurethane foam into ERCs was safe. We were particularly interested in whether there would be an excessive exothermic reaction when the foam is dispensed in a single pass in thick cross sections. We built five cavities representing the five most common rafter depths—3.5”, 5.5”, 7.5”, 9.25”, and 11.25”. Test cavity sides were approximately 22.5” apart. Cavities were covered with 6 mil polyethylene adhered to the cavity by spray adhesive. A spray foam release material was applied to the polyethylene. A thermometer was inserted through the top of the cavity to the center of the cavity, and the cavity was subsequently injected with a two-component polyurethane froth foam through a hole at the top. Temperature measurements were recorded every 30 seconds for 10 minutes after injection. After completing the tests with foam materials at ambient temps (70°F), we repeated the tests with foam materials at elevated temps (90°F) to simulate a “worst case” injection on a hot summer day.

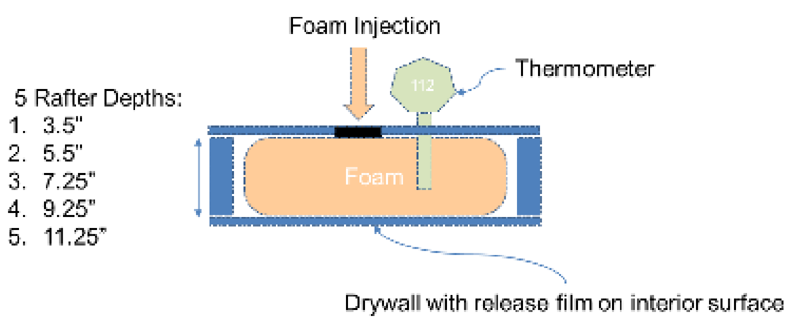

Figure 6. Maximum safe thickness test stand

Cross Cavity Dispense. Wall studs are typically spaced at 16” on center. Roof rafter cavities in older buildings are often 24” on center. Even dispersion of foam across the wider width of the rafter cavity could be challenging. We needed to determine the best method for achieving a consistent void-free filling across this much greater width.

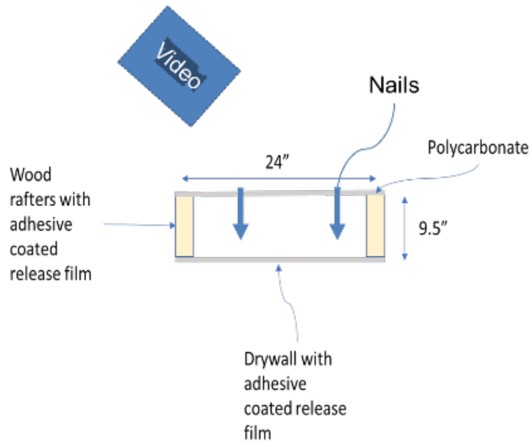

Figure 7. Cross cavity dispense test stand

A ¼"-thick clear plastic polycarbonate board with a clear adhesive-coated release film laminated to one side was mounted with removable screws to the open face of the constructed cavity. To facilitate observation, a 3 x 3" grid was superimposed on the release film. The cavity was mounted horizontally on a stand 4' above the floor. The polycarbonate served as the top surface. Nails were initially inserted through the polycarbonate to simulate roofing nails, but these were later removed because they were found to have no significant effect. Materials were dispensed either from below the cavity through needles or through the end of the cavity through tubes. Dispense patterns and coverage were observed and videotaped through the clear polycarbonate board on top.

A number of different dispense devices were tested. Dispense tubes were 3/8" OD x 4' straight high-density polyethylene tubes. For some tests, 2 3/16" holes were drilled in the end of the tubes to effect sideways shots. Needles were ¼" OD x 8" aluminum inserted into high-density polyethylene tubes and bonded with 3/8" adhesive-coated heat shrink tape. For some tests, the end of the needle was sealed with epoxy, and one or two 3/16" holes were drilled at various distances from the end.

Material was dispensed first into uninsulated cavities and subsequently into insulated cavities. Thickness and void measurements were obtained after each test.

Figure 8. Angle dispense test stand

Angle Dispense. Because walls are vertical, foam fills voids via slumping. However, low-slope roofs might not allow material to fill voids through slumping. To determine how best to control foam slumping at various angles, the angle dispense test stand (Figure 8) was designed to replicate the worst case cavity scenario. Because the greatest challenges were expected at steep roof angles, the test stand was set at 45 degrees. Rafter spacing was 24” on center. The top plate at the cavity bottom was 3.5” wide. We dispensed approximately 0.75 cubic feet of foam into the cavity with each shot. Each shot was spaced at 6” or 12” above the previous shot. We repeated these experiments in both empty uninsulated cavities and fiberglass-filled cavities (R13 batt). Average foam thickness was measured. The area of any void was also noted.

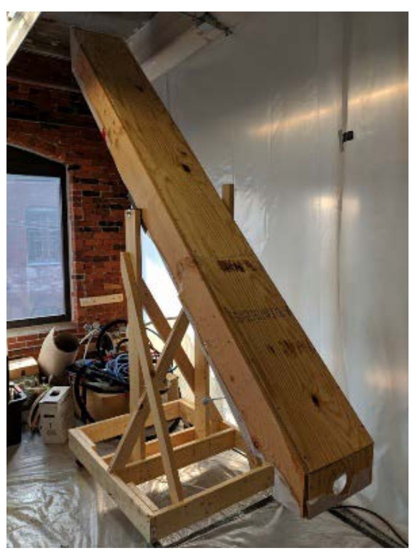

Figure 9. Length dispense test stand: angle iron pivot in center, soffit at bottom right, ridge at upper left

Length Dispense. Wall studs are typically 8' long. Due to these short spans, foam can be injected either through a single ½" hole (using specially designed tubes) or through 4 ¼" holes using needles. Roof rafter spans are much longer. Techniques for minimizing the number and size of holes were not known.

To determine optimal spacing, we constructed a 12' long ERC with 10" rafters. The cavity was mounted on a center angle iron. The angle iron allowed the ERC to be pivoted to replicate any angle from a low-slope roof to a gambrel roof. A typical soffit was constructed on one end, and a typical ridge was constructed on the other end.

Shot spacing at 4', 6', and 8' was tested using a needle dispenser. After noting that voids were formed at any spacing greater than 4', we injected through dispense tubes of 4', 6', and 8' in length to determine if shot spacing could be increased using tubes. We repeated these experiments with both empty uninsulated and fiberglass-filled under-insulated cavities.

Soffit and Rafter Vent Test Stand. During field trials, we discovered two problems that were not expected from our lab work. First, we discovered that injected foam spills into soffits and drips out of soffit vents. In one pilot, we disassembled the soffit and inserted a liner on top of the vent to prevent the foam from dripping down through the vent. This liner process was labor and time intensive.

The second problem was related to rafter vents. Cathedral ceilings often have a vent baffle running underneath the sheathing from soffit to ridge to promote ventilation and drying of the sheathing. When foam is dispensed into the cathedral ceiling, the vents are supposed to be crushed up against the sheathing, thereby converting the rafter space from vented to unvented. These rafter vents are typically constructed of fragile polystyrene. During one of our pilots, we punctured the rafter vent with our dispense tubes. As a result, foam dispensed within the rafter vent flowed uncontrollably through the vent space and did not fill the rafter with sufficient thickness. We needed to develop a way to more consistently achieve desired foam thickness.

We modified the angle dispense test stand to include two different types of soffit cavities. One cavity, typical of 1950s construction, had 6" rafters with 24" on center spacing. The other cavity, typical of more recent construction, had 10" rafters with 16" on center spacing.

Figure 10. Soffit test stand vent types

Soffit vent configurations (Figure 10) included simple vent holes in a bottom board, continuous vents, circular vents, and perforated vinyl vents. Rafter vents (Figure 11) included two commonly used polystyrene vents and one vinyl vent.

Figure 11. Rafter vent types

2.3 Measurement and Analysis

2.3.1 Methods

Thickness. The bottom surface of the cavity was removed, and foam was released. Paper with a 3" x 3" grid was applied to the flat surface of the foam. A ruled probe was then inserted at each intersection of grid lines through the foam to obtain thickness.

Infrared. A Flir E6 infrared (IR) camera was used to supplement direct thickness measurement and to identify voids when foam could not be removed from cavities during pilot projects. IR images of the curing foam were recorded approximately 5 minutes after injection. IR images were compared to direct thickness measurements to determine if thickness could be determined non-invasively with an IR camera. To determine if rafter vents have been punctured, IR images of both the interior ceiling surface and exterior roof surface were viewed (punctured rafters are easily visible as a hot spot at the roof surface).

Temperature. Foam temperature was logged using a thermocouple inserted into the center of the block of foam and connected to LabVIEW (Sensata 112CP series). Temperature measurements were logged approximately every 30 seconds for either 10 minutes or until the foam had reached maximum temperature.

Pressure. Fluid pressure was measured at the tank, at the proportioner, and at the gun using the Sensata 112CP sensors and LabVIEW.

Material volume. The volume of material dispensed into the cavities was determined by flow meters (Badger IOG, 1/4" fNPT, 0.067-2.2 g/min) in the Talking Rig, as described below.

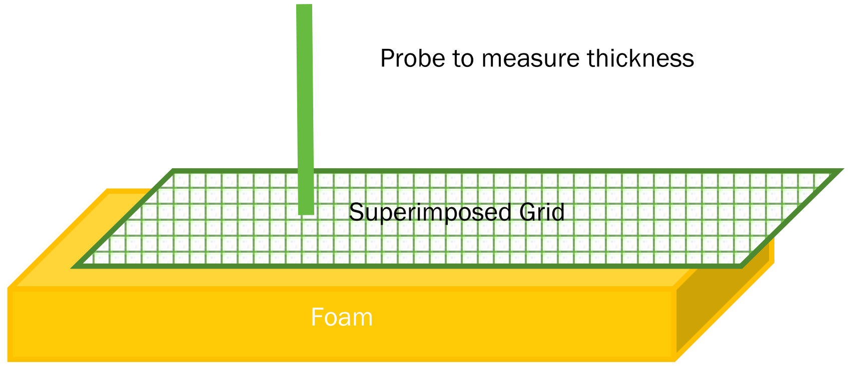

Figure 12. A grid was superimposed on the foam block. A probe was inserted at points on the grid to measure thickness

Figure 13. Cart-based Talking Rig

2.3.2 Software

During field trials in a 90,000-square foot building, we discovered significant reliability issues in the prototype Talking Rig due to jamming of flow meters and flow control valves. We further determined that these reliability issues would not be resolved through further modifications to our prototype rig.

To resolve these issues, we developed a Shot Timer app. The Shot Timer app is based on approximately 100 experiments that we conducted into the behavior of our foam under a wide range of temperature, moisture, pressure, and other conditions. By using data from these experiments, we were able to completely eliminate problematic flow meters and flow control valves in our fluid flow lines. In subsequent field trials, we encountered zero rig reliability issues.

The Shot Count app has been very popular with our installers and quickly grew to include other functions including scheduling, throughput logging, square feet until empty, and ratio logging.

2.3.3 Materials

During the period of the validation study, approximately 12 states implemented regulations banning the use of the high-global warming potential (GWP) blowing agents that had been used in our foams. To qualify a new material with a lower GWP, we had to conduct extensive additional processing tests to ensure that the new material behaved the same as our previous material. And, because our materials supplier was unable to create appropriate samples representing foam injected to the exterior of the fiberglass, we also prepared large numbers of samples for fire testing (Figure 14). The new foam passed as a Class A fire rated material when injected into fiberglass insulation. The new blowing agent has a GWP of 1. The previous blowing agent had a GWP of 1,200.

Figure 14. Foam blocks with fiberglass attached used for E84 fire testing

2.3.4 Analysis

Thickness. Foam thickness is by far the most important measure because it determines both R-value and perm rating. After each series of experiments, we measured coverage percent and calculated average thickness and standard deviation of thickness. To simplify visualization, data from our thickness measurements were compiled into a contour map of the foam surface in each cavity (Figure 15). Voids are indicated by the black areas in the contour map.

Temperature. Maximum safe thickness is defined as the maximum thickness of foam at which the foam exotherm remains below 350°F.

Voids. In addition to coverage percent, the number of voids, average void area and standard deviation of void area were calculated.

Video. Video and direct observation of foam expansion patterns were used to optimize shot intervals, shot direction, and tube or needle design.

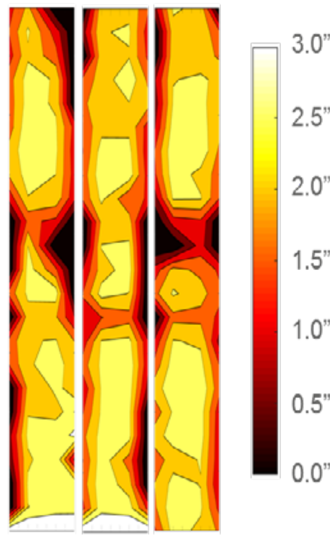

Figure 15. Contour map of foam thickness

3 Results

3.1 Maximum Safe Thickness Results

Foam exotherm does not present a fire hazard at ambient temperature. The goal of the maximum safe thickness test was to determine the maximum thickness of foam we could inject into an enclosed roof cavity without creating a fire hazard due to the foam's exotherm. We discovered that the internal temperature of the foam never came close to the self-ignition temperature of the foam material in any of the thicknesses tested. As shown in Figure 16, the maximum internal temperature reached by foam initially at ambient temperature (70°F) was 304°F. The flash ignition temperature of the foam is approximately 700°F. Based on these results, foam exotherm does not appear to present a fire risk even at maximum rafter depth. However, as a precaution, we did not inject any cavities with a depth of greater than 6". It should also be noted that the center of a block of standard spray foam often achieves temperatures in excess of 300°F and has not been known to degrade building materials in the cavities.

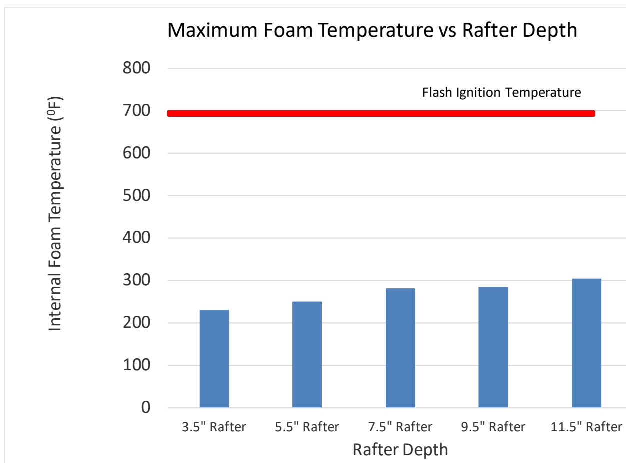

Figure 16. Maximum foam temperature versus rafter depth

Foam exotherm does not present a fire hazard at elevated ambient temperature. When the temperature of the foam materials prior to injection is 90°F, as might occur on a hot day in the field, the maximum temperature reached by the injected foam is 314°F and remains well below the flash ignition temperature of the foam (Figure 17).

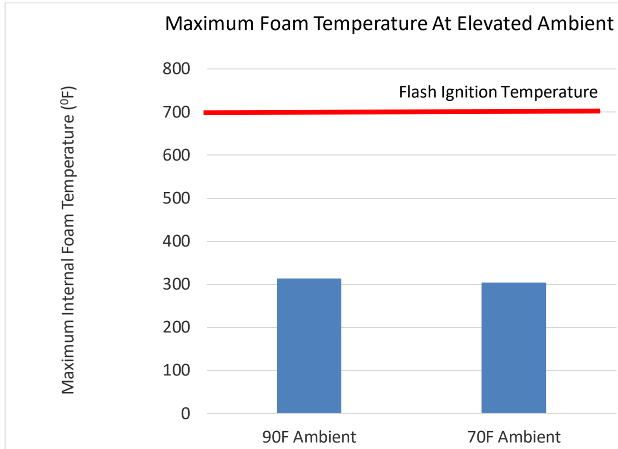

Figure 17. Maximum foam temperature at elevated ambient

Temperature inflection occurs at 4 minutes. Through this testing, we discovered many additional useful rules of thumb. For instance, after injection, there is a rapid rise in temperature followed by a slower rise or cooling. No matter the rafter depth, the transition between rapid temperature rise and slower rise or cooling occurs approximately 4 minutes after injection (Figure 18).

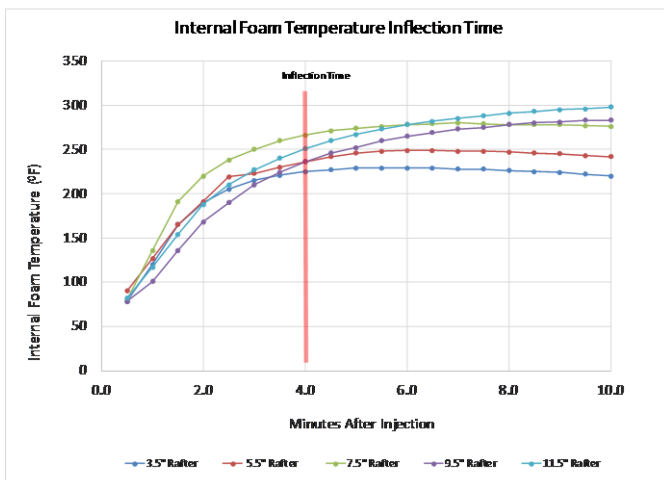

Figure 18. Internal foam temperature inflection time

Maximum temperature can be estimated. The following rule of thumb provides a good correlation to the observed maximum temperature of the foam:

Maximum foam temperature = 200 + 10*(rafter depth).

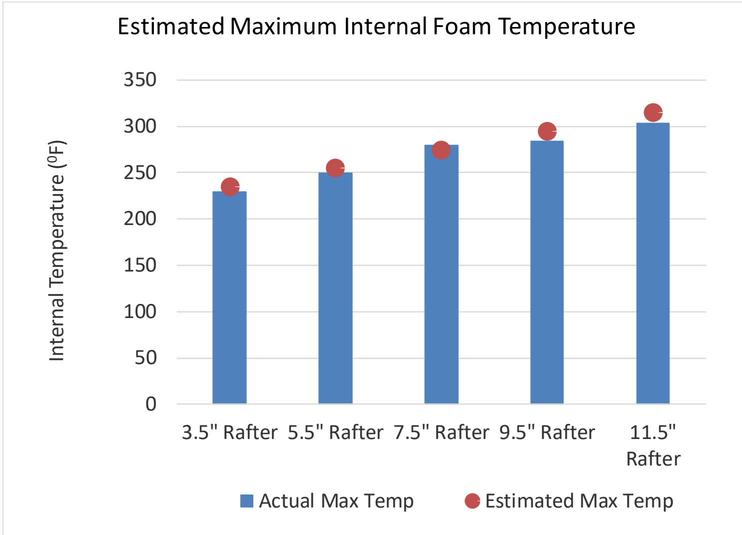

Figure 19. Estimated maximum temperature

Time to reach maximum temperature can be estimated. The rule of thumb for estimating time to max temp is:

Time (minutes) = Rafter depth (inches).

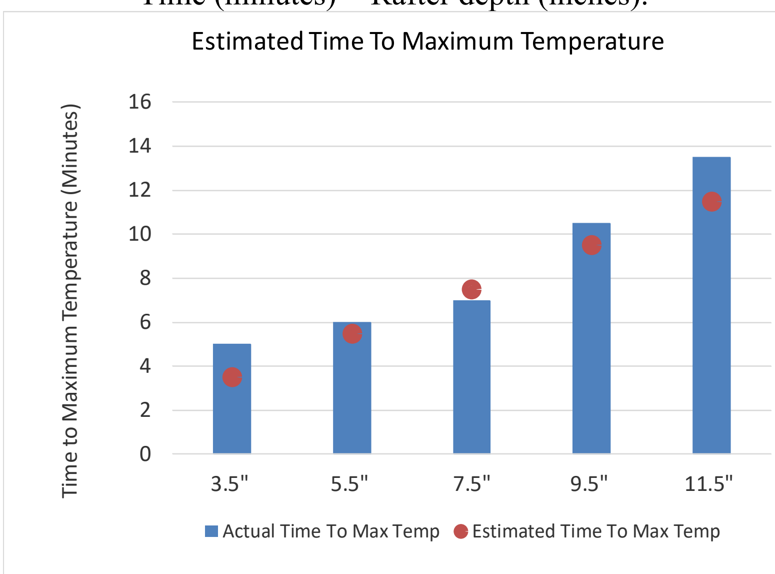

Figure 20. Estimated time to maximum temperature

3.2 Cross Cavity Dispense Results

We conducted experiments to determine how to optimally fill a 24”-wide horizontal ERC. As mentioned above, we anticipated that methods used on vertical cavities, such as walls, would not work well on horizontal or low-slope cavities because we could not rely on the foam to slump into place to fill voids. Results of these experiments are summarized below.

Straight tube shot into uninsulated cavity leaves voids at rafters. As shown in the before and after photos in Figure 21, shooting foam into an uninsulated ERC caused material to mound up in the middle and left voids at the rafters.

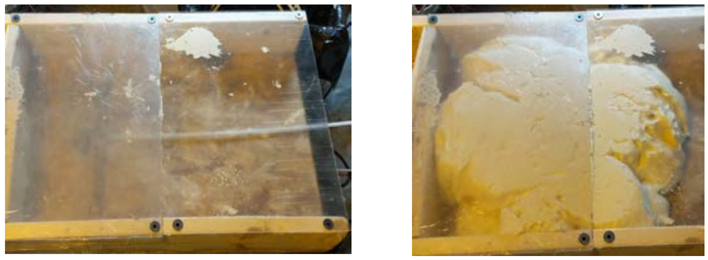

Figure 21. Straight tube shot into uninsulated cavity

Shooting material perpendicular to the tube into uninsulated cavity also leaves voids at rafters. To improve void filling at the rafters, we modified the dispense tube so that it would shoot perpendicular to the tube rather than straight out the end. Figure 22 shows foam material shooting sideways rather than straight out the end of the tube (left photo) and that the sideways shot did not significantly reduce voids at the rafters (right photo).

Figure 22. Perpendicular tube shot in uninsulated cavity

Shooting material through a needle next to rafter eliminates voids. Rather than shooting from the center of the cavity, we tried shooting from approximately 3” inboard of each rafter in the cavity. We drilled two holes from below the cavity and used a needle dispenser to shoot the material. Figure 23 shows a first mound of foam after dispensing but before complete expansion and a second mound of foam in the process of being dispensed (left photo), and both mounds of foam fully expanded (right photo). As can be seen, shooting material next to rafters completely eliminates voids at the rafter and creates a perfect fill in the center of the cavity.

Figure 23. Needle shots next to rafter

Shooting material through a dual sideways tube eliminated voids and would improve throughput. Although the dual needle process worked well, we wanted to find a way to improve throughput by developing a process that only required a single shot rather than dual shots. We also wanted to test a dual shot process on an under-insulated fiberglass-filled cavity. Figure 24 (left photo) shows a dual tube configuration using a Y connector for each tube; the middle photo shows material as it was dispensed next to rafters from each tube; and the right photo shows a perfect void-free fill of the under-insulated cavity after the foam had completely expanded.

Figure 24. Dual sideways tube next to rafter in under-insulated cavity

As noted above, single shot approaches, even when shooting across a cavity, left a mound in the middle of the cavity and voids at the rafter. Dual shot approaches, in which material was injected 2–3” inboard of the rafter and then spread toward the center, created a perfect fill across the entire width of the cavity. Dual shot approaches worked equally well in both uninsulated and under-insulated cavities. We could use two needle shots if holes are positioned appropriately inboard of the rafter. Or, for improved throughput, we could use a dual sideways tube shooter, as seen in the left-most image of Figure 24.

3.3 Angle and Length Dispense Experimental Results

The most difficult aspect of adapting our flat roof process to sloped roofs was that dispensed foam tends to slump down a sloped cavity as it cures. We were not concerned with the vast majority of cavity filling shots as they are all built up from the first shot, a shot we call the “blocking shot.” However, we were concerned about the potential for the blocking shot at the bottom of the cavity to spill into soffit spaces and, in particular, two aspects:

- How best to fill the complex geometry of the soffit space
- How to avoid foam spillage through the soffit vent.

Figure 25. Blocking shot foam slumping into soffit space and onto floor

We initially attempted to develop a process that minimized or eliminated blocking shot foam from slumping into soffits. We conducted most of our tests on an uninsulated cavity given that foam tends to slump into soffit spaces more readily in uninsulated cavities than in fiberglass-filled cavities. We tested six blocking shot processes. For each process, we ran multiple experiments to determine the optimal hole position, dispense quantity, dispense tubes, etc. As shown in Figure 25, we estimated the percentage of dispensed foam that slid off the top plate into and through the soffit space. Descriptions and results of each process are below. (Note: Black and gray indicate cavity cross sections; blue indicates tube geometry, and orange/yellow is foam dispense direction in cavity).

Dual Tube Process. In our initial attempt, we used the same process as developed for horizontal cavities, i.e., foam is dispensed from the nozzle through two tubes connected with a Y adapter. Holes in the end of the tube dispense material vertically in the cavity (Figure 26). Fill quality was excellent. A significant amount of dispensed foam (approximately 25%) slid off into the soffit space.

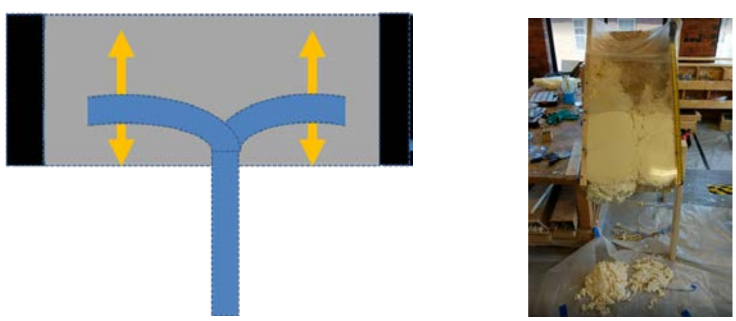

Figure 26. Dual tube soffit filling

Up-Cavity Shooters. To reduce material spillage into the soffit, we attempted a variety of approaches for directing material up into the cavity (Figure 27). These attempts resulted in only 4% spillage into the soffit space, but fill quality was not good, with approximately 20% voids in the filled area.

Figure 27. Up-cavity shooter

Top Plate Cross Cavity Dispense. The top plate cross cavity dispense provided the best combination of fill quality and minimum slump into soffits (Figure 28). In this process, a single hole is drilled into the cavity 3" up from the top plate and 3" in from the rafter. A 4' tube is inserted into the hole and fed across the top plate to the other side of the cavity. Dispense direction is vertical. The material is dispensed in four "puffs" as the tube is pulled across the top plate. This results in four small mounds of expanded material that sit directly on the top plate. Subsequent shots fill over the small mounds. There was zero spillage.

Figure 28. Top plate cross cavity dispense

Figure 29. Top plate cross cavity in under-insulated cavity

We then tested the same process on a fiberglass-filled cavity. The process again worked well, with only one small drip into the soffit space.

In sum, the dual sideways shooter provided the best fill quality, although it suffered somewhat from spillage into the soffit. The top plate cross draw provided good fill quality and minimal drips but would probably be difficult to implement consistently in the field. We decided to adopt the dual sideways shooter as our best practice method for injecting 24” on center cavities. We addressed the soffit spillage issue in a subsequent series of experiments.

3.4 Length Experiment Results

Inject soffit and ridge first, then fill in between. Length experiments were conducted to determine how best to extend the processes developed above to fill an entire full-length ERC. In our initial tests, we injected from a blocking shot in the soffit all the way up the cavity using both the tube and needle processes. These tests resulted in generally good consistent thickness throughout the body of the cavity, but we could not get consistently good fill at the ridge vent. We then changed to a new procedure in which we filled ridge and soffit first and then filled the rest of the body of the cavity. This procedure produced consistently excellent fill at the ridge vent (Figure 30).

Figure 30. Foam fill at ridge vent

There were no voids in the air barrier. After injecting a cavity in the test stand with a 2” x 6” rafter cavity, we removed the foam for inspection and measurement. Figure 30 shows the top of a block of injected foam removed from the test stand. As can be seen, the ridge vent area has been completely filled. Figure 31 shows the soffit end of the same block of foam. The foam conforms perfectly to the shape of the soffit. The maximum variation in foam thickness appeared to be around the middle of the foam near the point of injection. But, over the entire length of the foam, there were no voids or other discontinuities and foam quality appeared to be excellent.

Figure 31. Foam fill at soffit

Added R-value was greater than expected. We then measured the thickness of each block. Measurements were taken using a ruled wire probe at the face of each rafter and at 3” intervals across the width of the cavity. The measurements were repeated every 6” along the entire 12’ length of the test stand. Figure 32 shows a contour plot of the measurements.

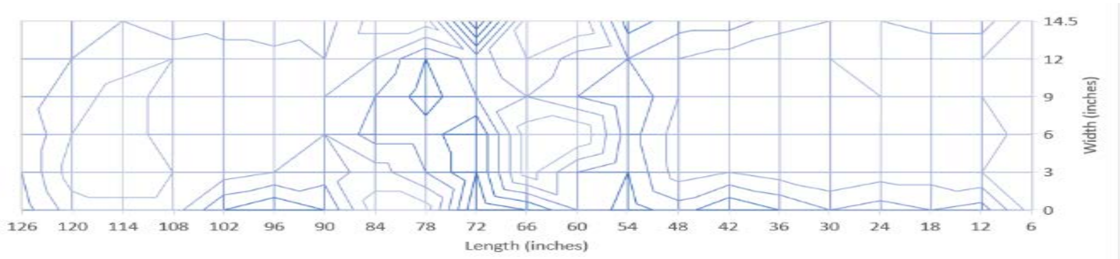

Figure 32. Contour plot of foam thickness

We had initially estimated that foam thickness in an under-insulated R19 fiberglass-filled cavity would be 2”. However, actual measurements of foam thickness significantly exceeded our estimates. Summary thickness measurements of the block of foam shown in the contour map were:

- Average thickness = 3.9” (R27.3)*
- Median thickness = 4” (R28)*
- Standard deviation of thickness = 0.7”
- Minimum thickness = 2.5” (R17.5)*
- Maximum thickness = 5” (R35)*.

* RHH class 1 fire rated slow-rise foam has a nominal aged R-value of 7 per inch.

3.5 Equipment Development Results

To address the complexity, cost, size, and other issues associated with truck- or trailer-mounted rigs, we developed a much simpler Talking Rig mounted on a cart. Because the unit can be easily rolled into any building with large hallways and/or elevator service, building size is not a limitation. More importantly, the unit meters material flow by volume and audibly communicates volume information to the injection technician during injection, greatly reducing blowout risk. It also provides audible information not only about foam quality, but also solutions to foam quality problems. This enables the technician to fix quality problems before injecting bad foam into an entire building.

Figure 33. Cart-based Talking Rig

We further developed a system that reinforces the audible feedback with a visual display. The display stores all data related to foam quality for later output in a quality report. The quality report provides building owners and occupants assurance that the material in their building is of good quality. All data is transmitted wirelessly to off-site managers who can monitor job productivity in real time.

Figure 34. Display for Talking Rig

Though our cart-based Talking Rig was a major advance, we found that it was too big for many cramped urban buildings. It was especially difficult to move up and down stairs. To address these issues, we developed the Talking Rig pictured in Figure 35. This unit provides the same functionality as the cart-based system in a more compact package. The unit is mounted on a hand truck with stair glides that allow it to be moved up and down crowded stairwells.

Figure 35. Stair-climbing Talking Rig

3.6 First Pilot Project Results

Injecting from the top of the ERC with 8' tubes achieved a perfect fill. We were fortunate to find a relatively simple first pilot project—a cathedral ceiling with 15 uninsulated cavities that could be injected from the top with 8' tubes. Each cavity was approximately 12' in length. Figure 36 shows Alex Bell injecting one of the cavities. Figure 37shows all cavities completely injected.

Figure 36. Injecting uninsulated cavity from the top

We injected each cavity with four shots of 3' feet each. Rather than attempting to fill an entire cavity at once, we did an initial shot in each cavity and then allowed the initial shot to fully rise and expand (Figure 38). We then did a second, third, and final shot in a similar fashion. Although we initially used a sideways shooting tube (as described above), we discovered that we could adequately fill the cavity with a simple 8' tube with material shot out the end of the tube rather than sideways. For the final shot, we did not need to use a tube.

Figure 37. All cavities filled

This project validated that empty ERCs could be successfully injected using a straight tube without sideways shooting. All cavities were filled without any voids. There were no blowouts or other structural issues. The only major issue was the heat inside the attic. When we started early in the morning, the attic was about 75°F. By the time we were done in the mid-afternoon, the attic was an estimated 115°F. Excessive attic heat is a major issue for all weatherization contractors. We are considering installation of radiant foil under the roof rafters prior to our next attic job to reduce the severity of the problem.

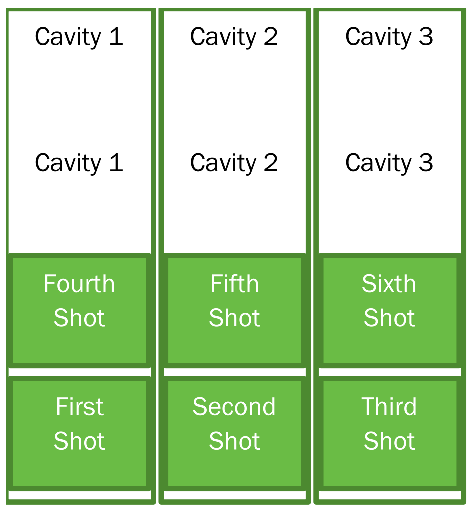

Figure 38. Shot sequence

3.7 Second Pilot Project Results

In our second pilot project, we tested our injection process on a cathedral ceiling that was significantly more challenging than the first pilot project. The increased challenges of the second pilot project are summarized in Table 1.

Table 1. Challenges of Second Pilot Project Versus First Pilot Project

	First Pilot Project	Second Pilot Project
Rafter depth	6”	10”
Cavity fill	Uninsulated	Under-insulated
Rafter vents	None	Polystyrene
Hips and valleys	No	Yes
Soffit	Blocked	Open and vented
Access	From top	Through ceiling

Results of our various approaches to the challenges are described below.

10” rafter depth required shorter lifts. While our calibration process works equally well in cavities of any depth, we found more fill variability with the greater cavity depth in the second pilot project. For example, while a 30-second shot might fill a normal 6” cavity about 30” +/-1”, a 30-second shot in the 10” cavity might fill the cavity 20” +/-2”. Because we were concerned that these errors would accumulate, and possibly result in voids or excess pressure build, we decided to try short lifts of approximately 2’ rather than long lifts of 8’. This approach worked quite well. As shown in Figure 39 , there were no voids and there was no excess pressure buildup. (Note: The darker grid shaped areas are rafters and strapping).

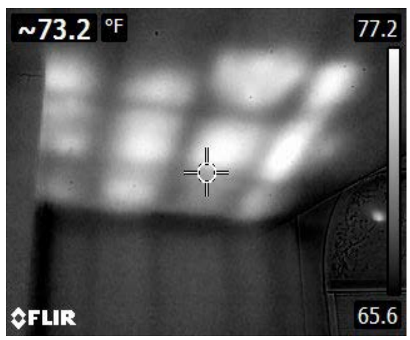

Figure 39. IR image of injected ERC

Thick fiberglass required pointed tubes. In uninsulated cavities, as in the first pilot project, we can simply drill a hole and inject foam. In fiberglass-filled cavities, we need to inject foam to the exterior of any existing fiberglass insulation (this avoids any moisture issues in the fiberglass). We normally drill a hole through the ceiling surface, drill through the fiberglass, and then insert our tube or needle through the holes in the fiberglass and ceiling surface. However, the fiberglass was so thick and dense in these cavities that the hole in the fiberglass would often close before we could insert our tube. We solved this problem by creating a sharp point on the end of our tubes and then driving the pointed tubes through the fiberglass (our tubes are made from semi-rigid high-density polyethylene and do not easily bend when pushed). This approach was effective in achieving our ideal placement of the foam just at the outer edge of the existing fiberglass, although it did create other issues as described below.

We punctured old rafter vents. After imaging the roof above the injected cavities with an IR camera, we discovered that the roof was hotter above one of the cavities than the others. We also noticed that the aged polystyrene rafter vents were flimsy compared to new rafter vents. We concluded that we must have punctured one of the flimsy rafter vents and injected foam inside of the vent directly against the roof sheathing (Figure 40). This led to an uncontrolled spread of the foam through the rafter vent. The thickness of the foam was probably also only about the same thickness as the gap in the rafter vent, i.e., about 1.5”. In filling cavities with rafter vents, we did not expect to be able to maintain ventilation from soffit to ridge vent. In other words, we expected to create an unvented ERC. However, the uncontrolled spread of foam through the rafter vent was unacceptable because voids would form at the sides of the cavity and because the thickness of the foam would be insufficient.

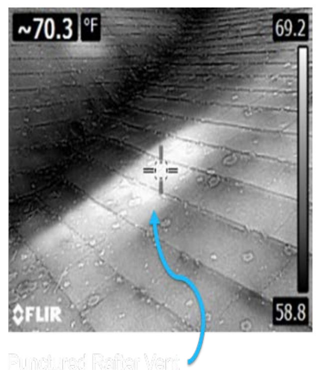

Figure 40. Hot spot on roof from punctured rafter vent

Shoot hips and valleys from the vertex, and half as long as a standard cavity. The bottom of many of the cavities were angled due to a dormer that created a hip/valley structure in the cathedral ceiling. We have encountered similar angled injection issues when injecting walls with diagonal bracing. As a rule of thumb, we assume that our shot time to fill the triangle will be approximately half the shot time of a standard rectangular-shaped cavity of the same length. We have also found that voids tend to form in the bottom vertex of the angle. To eliminate this issue, we position our first shot in the bottom vertex of the angle. These two modifications worked well in the hip/valley section of the cathedral ceiling (Figure 41).

Figure 41. Hips and valleys in ERC

Paper liners could be used to block soffit vents. We spent a significant amount of our lab time experimenting with various approaches for solving issues related to material slumping into open soffits. However, once in the field, we discovered that both the top plate cross draw and dual tube methods were difficult to implement. The dual tube approach required careful placement of tube ends at precisely the right location over the top plate. The top plate cross draw method required similarly precise positioning of the tube. In the pilot project, we instead lined the bottom of the soffit with a paper liner to avoid having foam leak through soffit vents (Figure 42). We applied the paper by first removing a section of the soffit vent and then sliding the paper underneath the rafter tails. Standard kraft paper was used. Though somewhat time-consuming, the process worked exceedingly well, allowing us to entirely fill the soffit without any foam drips.

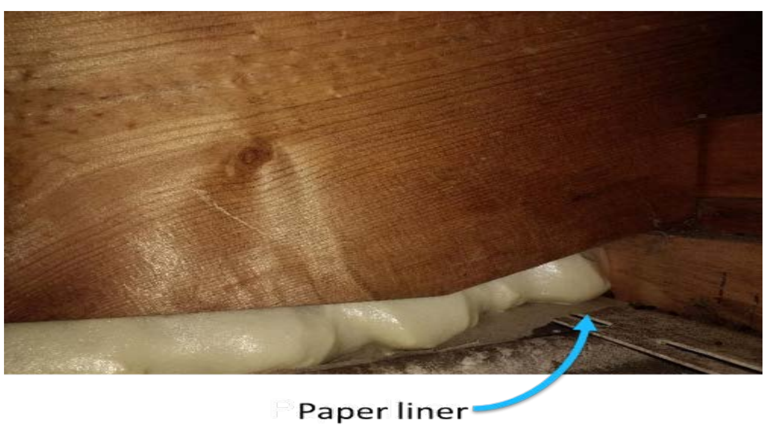

Figure 42. Paper liner in soffit

Baker staging would reduce repetitive motion issues. Holding drills and injection guns overhead for 8 hours was quite tiring (Figure 43). Baker staging, as used by painters and drywall contractors (Figure 44), would bring the work level down to shoulder height.

Figure 43. Injecting through the ceiling

Figure 44. Baker staging

3.8 Improved Soffit Filling Process Results

The goal of the new soffit filling process was to replace the paper liner that we had used inside the soffit space with a less time-consuming method of reducing drips through the soffit vents.

Foam bulges through round and continuous soffit vents do not drip. To better understand how material flows through vents, we injected soffits with both round and continuous vents. To our surprise, foam does not typically drip out of the vents. Rather it clogs the vents and creates a bulge of foam below (Figure 45 and Figure 46). The foam contains no UV inhibitors. Over time, the bulge of foam would turn a dark orange color and would become highly visible against the typically white paint of the soffit bottom board.

Figure 45. Foam bulging out of round soffit vents

Figure 46. Foam bulging out of continuous soffit vents

Thick duct tape pre-applied to vents stops foam bulge in round and continuous vents. To eliminate the foam bulge, we applied tape to the soffit bottom board and vents prior to injection (Figure 47). We initially used masking tape but found that masking tape was too thin and still allowed foam to form a bulge under the vent. We then applied 17-mil thick duct tape. The thick duct tape worked well and completely eliminated the bulge. In the field, tape would be applied prior to injection and would then be removed after injection.

Figure 47. Pre-taped continuous soffit vent

Thick duct tape pre-applied to vents stops foam drips in vinyl soffit vents. In vinyl soffit vents, we have found that material drips out of the many holes in the vent. To illustrate the effect of taping on vinyl soffit vents, we injected with a vent that was half taped and half open. As can be seen in Figure 48, material dripped out of the open vents but was completely controlled by the taped side on the right.

Figure 48. Pre-taped vinyl soffit vent

Shot count for complete soffit filling can be easily calculated. To determine the proper amount of material to inject into the soffit, we determine an approximate volume of the soffit. From this, we can easily determine the proper shot count. For example, a 24” on center soffit with a 6” wide bottom board and 10” fascia board has a volume of approximately 1,440 cubic inches. Because each count from the Talking Rig produces approximately 100 cubic inches of expanded foam, the technician would need to shoot for a 14 or 15 count to fill the volume.

3.9 New Rafter Vent Baffle Filling Process Results

The goal of the new rafter vent baffle filling process was to develop a better way to avoid puncturing old flimsy roof rafter vents when injecting cathedral ceilings. Foam injected into fiberglass-filled cathedral ceiling cavities typically expands in a space between the rafter vent and fiberglass. Occasionally, our dispense needles or tubes puncture the rafter vent. When this happens, foam expands uncontrollably between the sheathing and rafter vent, causing a significant loss in insulating value. When the foam expands in the space between the rafter vent and fiberglass, the thickness of the foam is 4–5” or more (>R24). When the foam expands within the rafter vent, the thickness of the foam is only about 1.5” (R9).

We developed two solutions to the rafter puncture problem. The first approach employs a sideways shooting needle dispenser (Figure 49). Two holes are drilled through a ¼” diameter x 12” long needle dispenser, 2” from the tip. The distance from the tip of the needle to the holes is approximately the depth of a typical rafter vent (1.5”). The needle is sharpened at the tip, and the sharp end is blocked with epoxy or solder. The needle is then inserted into the rafter space until it punctures the rafter vent and rests against the roof sheathing. When foam is injected through the needle, it sprays out sideways through the two holes into a space between the fiberglass and the rafter vent.

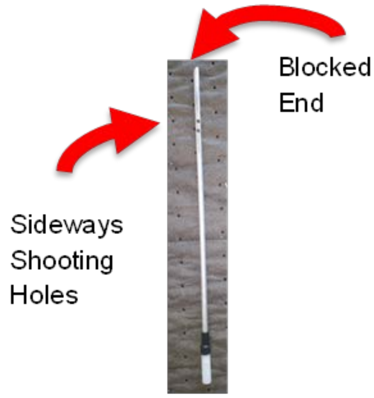

Figure 49. Rafter vent dispense needle

The second approach employs a 4' tube dispenser with angled end and "top of tube" mark (Figure 50). The angled end causes the end of the tube to be almost parallel to the angle of the rafter vent. Due to the shallow angle with which the tube intersects the rafter vent, the tube has much less tendency to puncture the vent. Because the angle of the tip of the tube is hidden once the tube has been inserted into the rafter space, we put a "top of tube" mark on the tube so that the technician can maintain proper tube alignment.

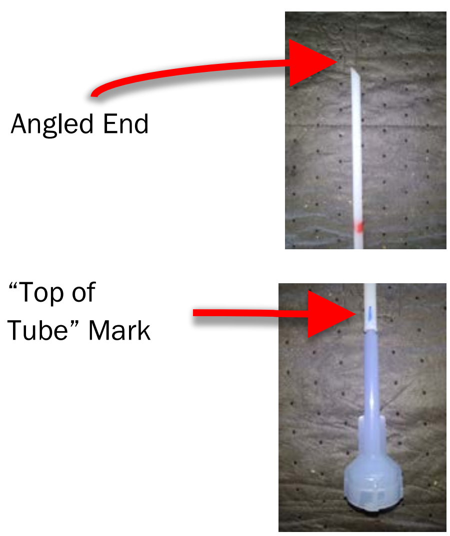

Figure 50. Rafter vent dispense tube

The primary advantage of the tube over the needle is that the tube only requires one ½" hole to cover an 8' span (we inject both up and down the rafter vent from the same hole). The primary advantage of the needle over the tube is simplicity—the needle is simply inserted into the hole and the appropriate amount of material is injected.

The first shot surrounds the rafter vent. As for performance, both the sideways shooting needle and angled tube produce identical results. First a blocking shot is injected into the soffit. After the blocking shot has been injected, there is usually a gap between the foam in the soffit and the bottom end of the rafter vent. Whether we use the needle or the tube, foam expanding into that space flows both into the bottom of the rafter vent and around the outside of the rafter vent. We call this first shot a "surrounding fill" (Figure 51). The foam typically surrounds about 1' of the rafter vent.

Figure 51. Surrounding shot

Subsequent shots do not fill the rafter vent. However, once the foam has expanded into the rafter vent about 1', it stops and then only flows around the outside of the vent. We call these subsequent shots "outside fills". Figure 52 shows the point at which foam stops expanding inside the vent and only expands around the outside of the vent.

Figure 52. The outside shot

The needle process is simple and foolproof. Although it produces more holes than the tube process, the holes are tiny (1/4") and easily patched. In our field trials, we were able to inject the cathedral ceiling with holes spaced approximately every 4'. We are confident the needle will work well in field trials. Whether the tube process works in the field remains to be determined. While the tube never punctured a vent in the lab, the rafter vents in our lab were new. We suspect that rafter vents become increasingly flimsy and easily punctured over time. If the rafter vents are too flimsy, the tube may still cause a puncture.

3.10 Validation Study Results

To provide graphic evidence of the effectiveness of the cathedral ceiling injection process we developed during the first phase of this project, we injected two-thirds of a large cathedral ceiling and then monitored performance using an infrared camera. The cathedral ceiling had 2 x 6 rafters and had previously been insulated with R19 fiberglass batts. Figure 53 shows the cathedral ceiling, and Figure 54 shows the temperature difference between the section of the cathedral ceiling insulated with R19 fiberglass batts versus the injected section on a hot summer day. The 10-degree temperature difference is impressive evidence of the effectiveness of Pinhole Insulation in ERCs. The injected side would require minimal air conditioning compared to the uninjected side.

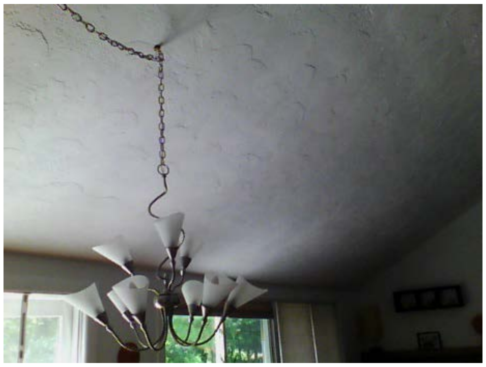

Figure 53. Cathedral ceiling

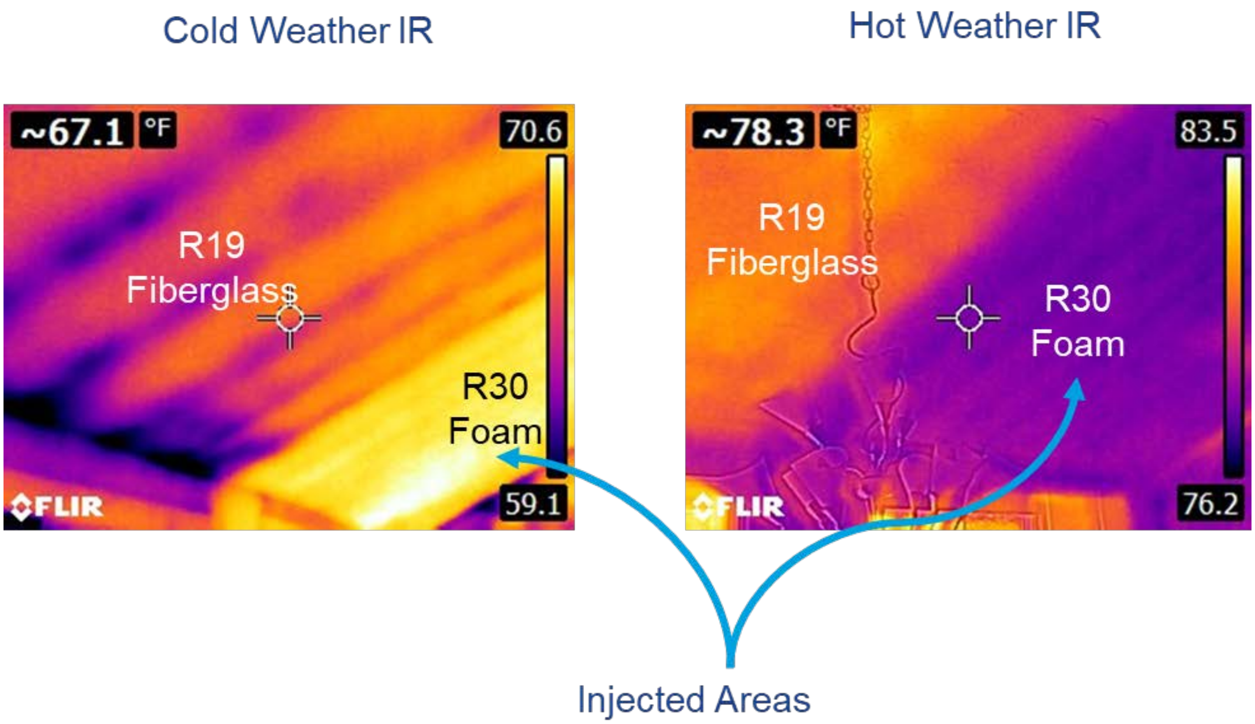

Figure 54. Temperature of cathedral ceiling section insulated with R19 fiberglass batts versus injected section

Monitoring conducted over the winter was even more impressive. On a cold winter day, the temperature difference between the injected side (orange) and the uninjected side (purple) was about 15 degrees. Moreover, the temperature difference is greatest at the bottom of the cathedral ceiling, which is the critical wall/roof transition where most of the air leakage often occurs in cathedral ceilings. The 15-degree difference is the difference between having the heat on or off.

Further visual evidence of the effectiveness of injected foam can be seen in frost and ice patterns. In Figure 55, the ice on the right formed on the uninjected portion of the cathedral ceiling. There is no ice on the injected portion on the left. The lack of ice on the injected portion of the roof demonstrates the potential for injection foam to eliminate ice dams. Similarly, in Figure 56, frost can be seen on the injected (colder) side of the roof while no frost is seen on the uninjected (warmer) side of the roof.

Figure 55. Ice formed on the uninjected (right) portion of the cathedral ceiling

Figure 56. Frost formation on the injected (colder) side of the roof

3.11 Relevance to Research Questions

The original research questions and topics we hoped to address through this study are:

- Does injecting thick foam present a fire hazard due to excessive exothermic heat buildup?
- How to eliminate void formation, particularly in cavities with 24” on center rafter spacing?

- How to minimize the number and size of holes drilled in the ceiling surface?
- How to inject foam in the presence of rafter vents?
- How to avoid foam drips through soffit vents?
- What kind of equipment modifications are required?
- What are contractor's concerns?
- How best to monitor fill quality and foam quality?
- How much improvement in R-value, perm rating, and air sealing can be achieved?

Answers to these questions are discussed below.

Thick injection foam does not present a fire hazard due to the exothermic reaction. The maximum temperature recorded in a 12" block of foam was 304°F. The self-ignition temperature of the foam is 550°F.

Voids in 24" on center rafter spacing are eliminated via injection next to the rafters. Material should be injected 3" inboard from each rafter when rafters are 24" on center. Injection in the center of the cavity works well for 16" on center rafter spacing.

The number of holes drilled can be reduced by using a multiport tube dispense system. The use of tubes enables holes to be drilled at 8' spacing. The multiport system uses a Y adapter on a tube to simultaneously dispense material on two sides of a rafter cavity.

Tape temporarily applied over soffit vents eliminates drips. We refer to the first shot of insulation at the bottom of an ERC as a "blocking shot" because it blocks the soffit from excessive pressure buildup from the expanding foam. Prior to injecting a blocking shot into the bottom of a cavity, tape is applied over soffit vents to eliminate potential for foam to drip through soffit vents. After the blocking shot has cured, the tape is removed.

Special needles eliminate challenges related to rafter vents. Many fiberglass-filled cavities contain rafter vents that are easily punctured by dispense tubes and needles. To avoid uncontrolled expansion of foam inside the rafter vent, we developed specially designed needles and tubes that eliminate potential for foam to be dispensed within the vent.

The new Talking Rig addresses contractors' concerns. Contractors' main concern is availability of skilled technicians. Contractors are also concerned about potential liability exposure due to improperly mixed materials, initial equipment investment required, ongoing maintenance costs, and access to ERCs in large buildings. We developed a new rig and smartphone app to address these concerns; benefits include:

- *Doubled productivity.* The Talking Rig does not require a second technician in a trailer or truck to monitor equipment status. A two-person crew with two rigs can inject twice as fast as a traditional rig.
- *Minimal training.* The system "talks" to the technician, providing real-time information on quantity and quality of material dispensed. A technician can be trained in less than a day.
- *Mobile*. A rig full of materials weighs about 250 lbs, is less than 4' tall, and 16" wide. In elevator service buildings, it is easily rolled through tight spaces. For stair access buildings, it can be separated into three components, and each component can be brought up the stairs with a hand truck. Virtually any space in any size building can be accessed.
- *Reliable*. Other than simple manual ball valves, the rig has no moving parts. Other than speech, the rig is silent.
- *Low-cost*. When fully commercialized, the rig is expected to cost an order of magnitude less than traditional mobile rigs.
- *Reduced liability*. Rig components are designed to ensure on-ratio performance without operator intervention. Foam quality data is recorded and can be presented to building owners.

Injected ERCs achieved substantial improvement in energy measures. In uninsulated ERCs with 6" rafters, nominal R-value was improved from R6 to R35. In under-insulated fiberglass-filled ERCs with 6" rafters, R-value was improved from R19 to R31. In both cases, there were no voids and minimal variation in foam thickness (standard deviation of thickness less than 1"). Perm rating was also improved to less than 1.

4 Discussion

4.1 Significance and Applicability of Results

Significance. The minimally invasive retrofit ERC insulation system developed through this project would be easy for spray foam contractors to adopt and would likely cost about 90% less than the conventional approach, an approach that requires the highly invasive and expensive removal and reconstruction of the ceiling surface. Lack of insulation and/or under-insulation not only leads to significant heat loss but can also contribute to ice damming and other significant moisture problems. We estimate that 60%–80% of single-family homes have an uninsulated or under-insulated ERC.

Applicability. Climate zones 3 through 7 are the main targets for this new process because buildings in these climate zones suffer the greatest heat loss and moisture damage through ERCs.

Sloped cathedral ceilings are the primary application. However, ERCs are also common in the following building applications:

- Dormer roofs
- Upper sections of gambrel roofs
- Enclosed roofs over kneewalls, especially in older capes and similar buildings
- Older commercial buildings with flat roofs
- Flat roofs in the “deck houses” and international style houses popular in the 1950s through 1980s
- Flat roofs under upper-level porches.

Both spray foam and weatherization contractors could make use of this process. Spray foam contractors are already familiar with procedures for dispensing closed cell polyurethane foam. Once trained, we believe that spray foam contractors would find IPF simpler than sprayed polyurethane foam. Weatherization contractors would generally need to purchase equipment and have a significant need for a solution for the ERC above kneewall application.

4.2 Potential Limitations of Experimental Design

Our lab testing covered a wide range of potential ERC configurations, including typical cavity spacing, depths, lengths, and angles; uninsulated and under-insulated cavities, and various commonly used soffit and vent configurations. However, our pilot projects were only able to test two configurations—one uninsulated ERC and one fiberglass-filled ERC. In future testing, we expect to conduct pilot projects in a much wider range of ERC types in the field. We would also intend to more thoroughly evaluate any changes in air flow and potential moisture issues.

4.3 Future Work

The processes previously described in this report have all been optimized for horizontal and sloped enclosed roof cavities. However, open roof cavities present a related and equally important need. In houses, the ability to air seal attic floors by injecting foam from within occupied spaces would enable contractors to avoid working in dangerous, exceedingly hot confined spaces, particularly during the summer months. Triple-deckers, as described below, present an even more urgent application. Although a fully developed solution to open roof cavity insulation was outside the scope of this project, we were able to conduct initial experiments and develop a clear path toward a solution.

The triple-decker problem. Triple-deckers, as pictured in Figure 57, are one of the dominant building types in older cities in the Northeast and Upper Midwest. When originally constructed in the early 20th century, most triple-deckers were uninsulated. Thanks to various weatherization programs, the walls of many triple-deckers have been retrofit insulated with dense pack cellulose. However, the low-slope "flat roof" on the top of the triple-decker, the area of greatest thermal energy loss, is usually not effectively insulated or air sealed.

Figure 57. Typical triple-decker

Triple-decker attics cannot be accessed. In most triple-deckers, there is an inaccessible attic between the roof rafters and ceiling rafters (Figure 58). Because attic spacing typically ranges from 24" at the height of the cavity to 10" or less at the bottom of the cavity, most weatherization technicians are understandably unwilling to crawl into these highly confined hot spaces.

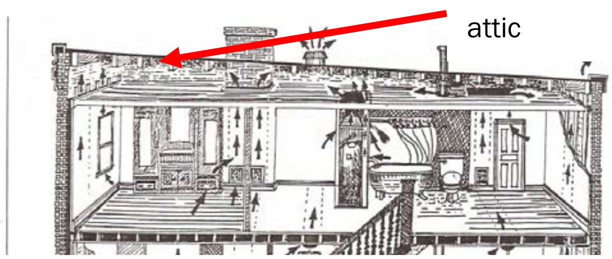

Figure 58. Triple-decker attic

Figure **59** (left photo) shows what a typical attic space looks like (max height about 18”), the feet of air sealer Jason Taylor accessing a flat roof attic (middle photo), and the difficulty of air sealing a flat roof with plaster and lathe construction (right photo). The unwillingness of most air sealers to undertake this type of extremely uncomfortable and dangerous work is entirely understandable.

Figure 59. Air sealing triple-decker attics

Toward an open roof cavity solution. Because it would not be cost-effective (or probably even possible) to fill the entire space between the triple-decker ceiling rafters and roof rafters with foam, we attempted to develop a process to inject closed cell polyurethane foam fill just to the top of the ceiling rafters. We envisioned the following benefits:

- Adds approximately R35 to the attic
- Air seals the attic
- Could be completed from the interior living space of the building; would not require attic access
- Would be minimally invasive, with easily patched holes in the top floor ceiling.

We attempted two approaches. In the first approach, we used the same “froth foam,” the same Talking Rig, and the same dispense needles that we had developed for ERCs. In the second approach, we attempted to use a different kind of closed cell polyurethane material called “pour foam.” We also attempted to inject foam into both an uninsulated open cavity and an open cavity with a fiberglass batt.

The ERC system worked reasonably well in open uninsulated roof cavities but exhibited poor thickness control. For rafter spacing less than 16” on center, we could use the single needle approach (Figure 60). For wider cavities, we used the dual needle approach.

Figure 60. Single needle shooting sideways in narrow open cavity

Figure 61. Dual needle shooting next to rafter in wide open cavity

Figure 62 shows a flat roof open cavity with multiple width cavities filled with froth foam using these processes. As can be clearly seen, the biggest issue in using standard ERC systems in open cavity applications is thickness variability.

Figure 62. Open roof cavity with multiple rafter spacings

The ERC system in under-insulated open roof cavities exhibited somewhat better thickness control. Because some triple-deckers have a small amount of fiberglass in the ceiling rafters, we attempted to inject under the fiberglass using the procedures developed for uninsulated cavities. As can be seen in Figure 63, the foam essentially lifted the fiberglass up over the top of the rafter. When we peeled the fiberglass off the foam, we noticed the fiberglass had reduced the variability in the thickness of the foam somewhat—a desirable outcome but not a situation that will apply to the majority of flat roof cavities.

Figure 63. Injecting into fibrous insulation in open roof cavity

A pour foam provides better thickness control in open roof cavities. As a result of the variability in thickness of the froth foam, we attempted to use a somewhat different material called pour foam. Closed cell pour foams have the same exceptional air sealing, vapor retardance, and R-value as closed cell froth foams. But, because they use a blowing agent that expands more slowly than the blowing agent used in froth foams, they tend to self-level, i.e., they flow to a more even thickness before beginning expansion. Figure 64 compares open cavity injection of a froth foam (left photo) with open cavity casting of a pour foam (right photo).

Figure 64. Pour foam compared to froth foam

To better quantify variability in thickness between a pour foam and froth foam, we measured thickness variation of the two types of materials. While the standard deviation of thickness of the froth foam was 25% of the overall thickness, the standard deviation of thickness of the pour foam was only 15% of the overall thickness. In Figure 65, these differences can be clearly seen in the surface topographies of the two materials as dispensed into open cavities.

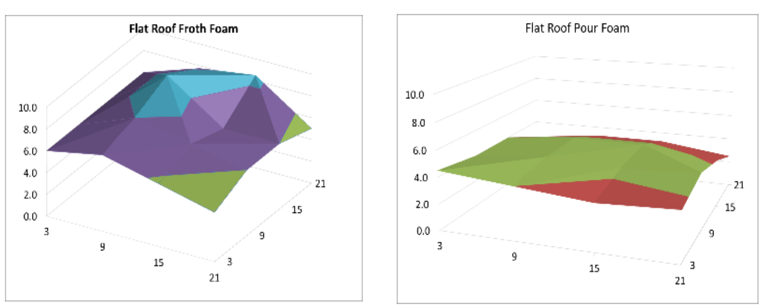

Figure 65. Surface contours of pour foam versus froth foam

Unfortunately, we were unable to dispense the pour foam through the same mobile rig or with the same mixers and dispense needles we had developed for the froth foam. Due to the slower expansion of the pour foam, there is less initial mixing energy in the portion of our system that mixes the two components of the foam. The static mixer in our system does not mix the two components of the foam sufficiently. The resulting foam has a candy-striped appearance, with some regions too rich with one component, and some regions too rich with the other component. While we strongly believe that pour foams will be the ideal solution in this application, the use of pour foams will require either modifications of our existing equipment or high-pressure spray foam equipment.

Open roof cavity plan outline. While development of a perfected flat roof process was beyond the scope of this project, the experiments we conducted have provided a clear outline of how to arrive at a perfected process. The steps would be as follows:

1) Test pour foams in modified Talking Rig. Preliminary experiments in our lab have indicated that we might be able to achieve sufficient mixing energy with our current equipment with a few small modifications. For instance, we could introduce compressed air to the area between the end of the gun and the static mixers, and/or we could introduce aerator screens into the same area.

2) Use high-pressure spray foam equipment. Though high-pressure equipment does not provide many of the advantages of the Talking Rig, pour foams are routinely mixed successfully in high-pressure equipment. If the modifications to our existing equipment do not work, we can use high-pressure equipment instead to dispense pour foam into flat roofs.

3) Perfect thickness control. Because foam thickness cannot be seen or measured from inside a building, we would need to develop a procedure for controlling not only the XY spread of the material but also the Z dimension. There are many potential approaches—for instance, we could vary foam dispense temperatures (higher temperatures will cause faster reactions and greater thickness), optimize hole spacing, and/or use longer dispense tubes.

4) Develop process for large gaps inaccessible from ceiling surface. A major source of heat loss in older triple-deckers are the large openings in the attic floor at the top of demising walls and plumbing walls. Because these areas are inaccessible from the ceiling surface, we would inject from the top of the interior wall. If we injected with a pour foam or our standard slow-rise froth foam, the foam would slump to the bottom of the cavity. We would instead inject with a standard fast-rise froth foam to seal just the top part of the wall.

5) Reduce cost. Foam is expensive. We envision that a cost-optimized process would be a mix of foam and less expensive insulation materials, such as cellulose or blown-in fiberglass. This hybrid system would be analogous to the hybrid construction used in walls, a system called “flash and batt.” Our experiments with fiberglass batts suggest that we should be able to first blow cellulose or fiberglass into the flat roof area from below the ceiling surface. We

could then inject a thin layer of foam underneath the blown-in loose fill material. We would expect the blown-in cellulose or fiberglass to rise up and float on top of the foam, just as the fiberglass batts in our experiments floated over the foam.

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