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TRANSFORMATIVE BUILDING ENVELOPE RETROFIT USING INSULATION-INFLATABLE WALLS ASSISTED BY AUTOMATION

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OAK RIDGE National Laboratory

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Buildings and Transportation Science Division

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ABSTRACT

This work highlights the effort to develop a low-cost envelope retrofit for homes built prior to the implementation of energy conservation measures established by the Department of Energy. Inflatable structures were constructed to conform to the exterior envelope (a corner wall construction with a fenestration was used as a prototype). The structures were then filled with spray polyurethane foam insulation. The flexibility in construction and the ability to fill with spray polyurethane foam insulation were demonstrated. In addition, hygrothermal simulations showed that the installation of these systems does not compromise the moisture durability of uninsulated and insulated building envelopes across eight climate zones from hot humid to subarctic. Preliminary cost estimates, based on retail pricing, of the inflatable retrofit including 3 inches of spray foam insulation (insulation value of approximately R 20) is $4.25 per square foot uninstalled. The installed cost was calculated using two labor rates, the labor rate for the installation of a weather resistive barrier and the installation of spray foam insulation. Aggregating those values into one labor rate results in an installed cost between $11 and $28 per square foot. The low end includes the installation of vinyl siding as the exterior cladding. The higher value includes an exterior stucco finish.

1. INTRODUCTION

1.1 PROJECT OVERVIEW

The goal of this project is to develop a low-cost envelope retrofit solution for vintage homes built prior to the implementation of the energy conservation measures established by the Department of Energy. The retrofit is suitable for older residences, old or new manufactured housing, low-income residential housing, and small, medium, or large commercial buildings. The concept is relatively simple and leverages existing technologies. A flexible package is custom built to accommodate any structure, installed and then filled with a polymer foam insulation on site. The installation is then completed by the application of a surface finish, e.g., stucco or cladding material such as vinyl or wood siding.

1.2 PROCESS STEPS

The installation process is highlighted in the Figure 1 and described by the following steps:

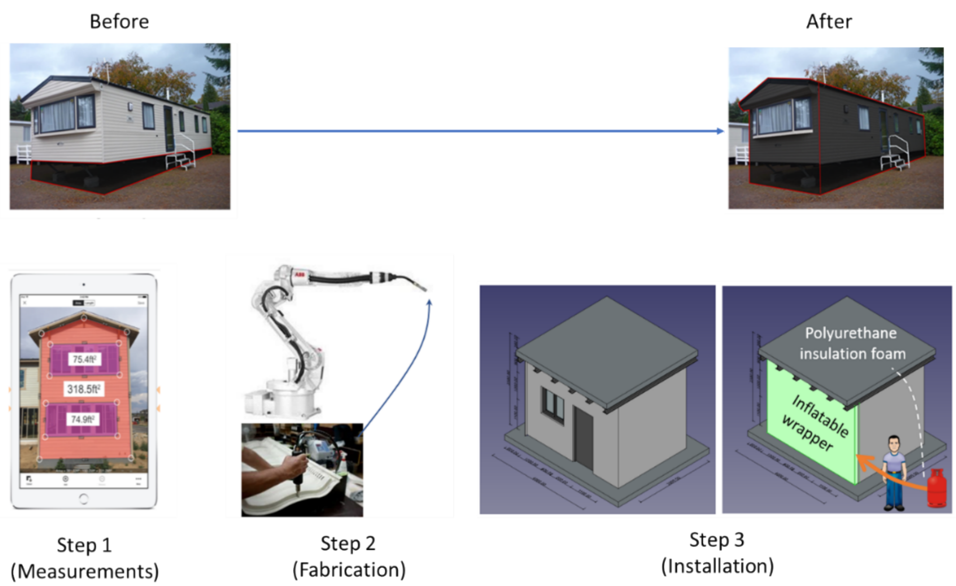


Figure 1. The retrofit installation process. Step 1 is the field measurement. Step 2 is the automated fabrication process. Step 3 is the installation process.

Step 1 (day one): The process starts with a site visit by the contractor to measure the dimensions of the building including the location and size of fenestrations and service penetrations. This can be done conventionally or by using a measurement application together with digital images. The solution is flexible enough to tolerate small differences in measurement. The flexibility also can accommodate simple corrections for large differences.

Step 2 (day 2): The measurements are converted to CAD files that can be used by fabrication machines to cut the fabrics and construct the flexible packages off site. The construction method depends on the fabric selection (sewn, adhered, and/or welded). These processes are amenable to semi and full automation and are standard manufacturing processes used in the textile and packaging industries. The manufacturing method and materials enable customization on site if required.

Step 3 (days 3 and 4): The flexible package elements are transported to the site and installed similar to the application of weather resistive barriers using mechanical fasteners or adhesives. Similar to weather resistive barriers, the joints may require some detailing. Tapes, caulks, and backer rod can be used to address joints similar to the installation of conventional wall panel systems. Mechanical fastening of joints is also possible but adds more manufacturing and material cost. The former certainly provides the installer more flexibility to accommodate small structural differences. Once the elements are installed, they are filled with a polymer foam insulation. Depending on the type of polymer foam (open or closed cell), an insulation value between 3.5 to 6 per inch is possible.

Step 4: The final step is the application of exterior cladding. The system can accommodate finishes such as stucco. In fact, the materials to receive stucco (plastic and or glass reinforced mesh or lathe) can be integrated into the system effectively reducing the installed cost. The application of cladding materials such as vinyl and wood siding, in theory, are possible with further modifications.

The objective is to reduce cost along all elements of the retrofit value chain, e.g., raw materials, manufacturing, freight, and installation. The goal is to complete the project within 3 to 4 days using only two laborers with minimal disruption to building occupants. The installed cost target for the systems is approximately $10/ft^2$ with an insulation value of R 20.

2. MATERIALS SELECTION

2.1 INFLATABLES

Several factors were considered when selecting construction materials for the inflatable structure: manufacturability, durability, availability, and cost. Four materials were reviewed: spun bonded polyolefin, vinyl coated polyester, architectural fabric and drop stitch cloth (non-baffled). A description of each is provided below.

2.1.1 Spun bonded polyolefin

Spun bonded polyolefin sheets are made from high-density spun bound polyethylene fibers. The material is lightweight, durable, and breathable. It has good water and abrasion resistance, does not support mold growth, and has good aging properties. Spun bonded polyolefin has a long history as a weather resistive barrier in residential and commercial construction. The material is manufactured by Dupont and sold under the trade name Tyvek (DuPont de Nemours, Inc., 2021). Tyvek comes in two forms, a flat sheet referred to as House Wrap and a wrinkled sheet designed to be installed before the application of stucco finishes. The advantage of this material is that it's application, together with joining details, is well established in residential and commercial construction.

2.1.2 Vinyl Coated Polyester

Vinyl-coated polyesters are most commonly used in outdoor soft structures of all types that includes awnings, commercial tents, outdoor signage, truck tarps, field covers, geo-membranes, air-domes, etc. They have good UV resistance, with an exposure period of 5 to 7 years. High end products can be exposed up to 10 years. This level of UV resistance is more than sufficient since the material will be covered by the cladding material well before the exposure period has passed. These materials have a higher density than spun bonded polyolefins and tend to be more expensive.

2.1.3 Drop-Stitch Fabric

Drop-Stitch fabric is a special construction that consists of two layers of cloth, usually made from polyester, which are coated with vinyl or polyurethane and stitched together enabling a space to be created when inflated. The width of the space is determined by length of the stiches that joins the two layers of fabric together. These materials are almost exclusively manufactured in China. This fabric enables inflatable structures to be manufactured without baffles creating a flatter surface. Baffles are the unit cells used to construct most inflatable structures. Similar to Vinyl Coated Polyester, these materials have a higher density than spun bonded polyolefin.

Table 1 shows the material properties together with unit cost. The polyvinyl chloride and polyester composites are materials normally used to manufacture inflatable structures. New to the mix is spun bonded polyolefin. Spun bonded polyolefin, for commercial inflatables has not been used. Several factors made spun bonded polyolefin attractive, performance and cost. Spun bonded polyolefin has a long history as a weather resistive barrier in residential and commercial construction. More importantly, it is the lowest cost option compared to the other materials, $0.20/ft^2 compared to more than $1/ft^2 for the other materials.

Table 1. Material properties and cost of fabric materials.

Materials	Tyvek Homewrap (*spun bonded polyolefin)*	Tyvek Stuccowrap (*spun bonded polyolefin)*	10 oz vinyl coated polyester	Shelter-Rite (*vinyl coated polyester)*	Ferrari Soltis 502 (*vinyl coated polyester)*
Manufacturer	DuPont	Dupont	TVF	Shelter-Rite	Serge Ferrari
Weight (oz/yd^2)	1.8	2.1	16.7	18	16.7
UV life	< 4 mos	< 4 mos	10 yrs	10 yrs	10 yrs
Flame spread (ASTM E84)	Class A 5/25	Class A 5/25	Class A	FMVSS 302*	Class A
Cost ($/ft2)	0.20	0.20	1.25	1.25	1.27

2.2 INSULATION

Several factors were considered for the insulation material: insulation value, flame spread, and cost. For this work, closed cell foams were used, in large part because it was easier to acquire kits for prototyping. In addition, the compressive strength of the closed cell foam is higher making it more suitable to apply an exterior cladding material. For those reasons, an open cell foam for exterior retrofit applications was not considered further. Table 2 compares the properties of the insulation materials including cost. All the insulation materials are comparable with respect to cost and performance. This is no surprise since all the materials are closed cell polyurethane foams. In this case, since the material was going to be introduced into a confined space, the inflatable retrofit package, a slow rate of expansion was desired to better control the application. There is equipment available that meters the application of polymer foam, however, to facilitate prototyping a slow rise or expansion rate foam was selected.

Table 2. Material properties and cost of insulation materials.

Product	Touch N' Seal	Foam it Green Fire Retardant	Versi-Foam Slow rise foam
Density, pcf	1.75	1.75	1.75
R value per inch	7.12	7	6.7
Flame spread (ASTM E84)	Class A (15)	Class A (25)	Class A (20)
Cost, $/bd-ft	0.91	0.90	0.65

3. DOWN SELECT

3.1 INSULATION AND INFLATABLE MATERIALS

When comparing the physical properties and cost, spun bonded polyolefin and Versi Foam Slow rise polyurethane insulation were the obvious choices. Spun bonded polyolefin was selected because its cost is significantly lower than the other materials, approximately $0.20 per square foot compared to over a $1 per square foot for the other options. Versi Foam, Slow-Rise, was selected because it had the lowest cost position and was an insulating foam with slow expansion properties making it suitable for prototype development. For large scale kits that supplied greater than 600 board foot of insulation, the cost was \$0.65 per board foot. The other insulating materials were \$0.90 per board foot. A board foot is a unit volume that is has a surface area of 1 ft^2 and 1 inch thick.

The material cost will depend on the insulation value, R. Figure 2 shows the total insulation cost per square foot as a function of R value.

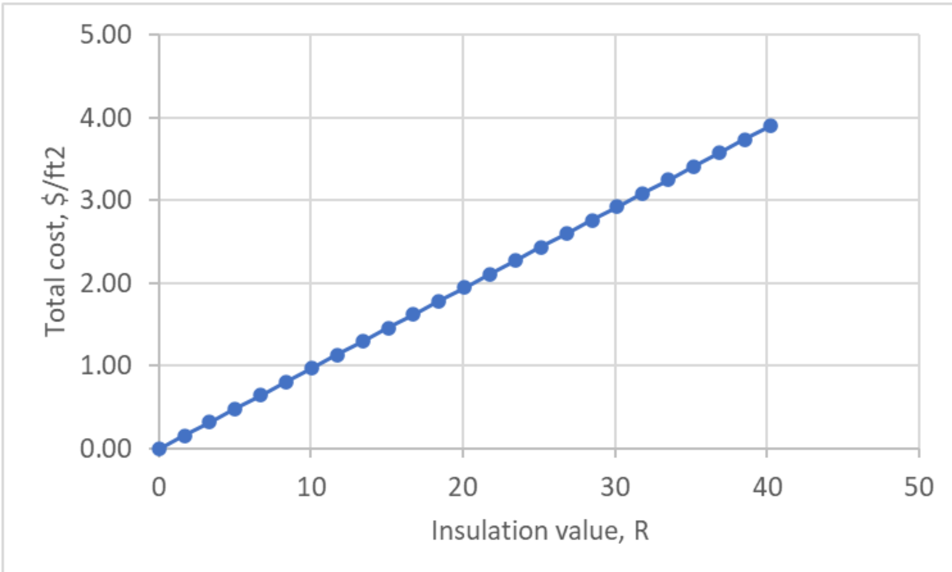


Figure 2. The cost of the insulation in $\$/ft^2$ as a function of R value.

For example, if the target retrofit insulation value is R 20, the insulation cost will be approximately \$2 per square foot. As a result, the difference between the $\$10/ft^2$ target value and the insulation cost is what remains for materials and manufacturing cost for the inflatable structure and the installation, or $\$8/ft^2$.

3.2 PROCESS VISUALIZATION

To evaluate the filling process, rigid transparent structures were used, e.g., fish tanks or aquariums. At the start of this study aquariums were filled with polymer foam to observe how the foam expands and to measure temperature changes. Spray polyurethane foams are two component systems that are comprised of a polyether polyol and diisocyanate (Rao, et al., 2017). When the two are mixed and react, an exothermic reaction occurs producing polyurethane foam. This reaction is accompanied by a significant increase in temperature, the magnitude depends on the volume of foam as well as the application rate or build up. It’s recommended that the temperature not exceed 180 degrees F during application in residential and commercial structures.

Figure 3 shows the surface temperature as a function of time for a polymer foam after filling a confined volume. The confined volume was a 20-gallon aquarium.

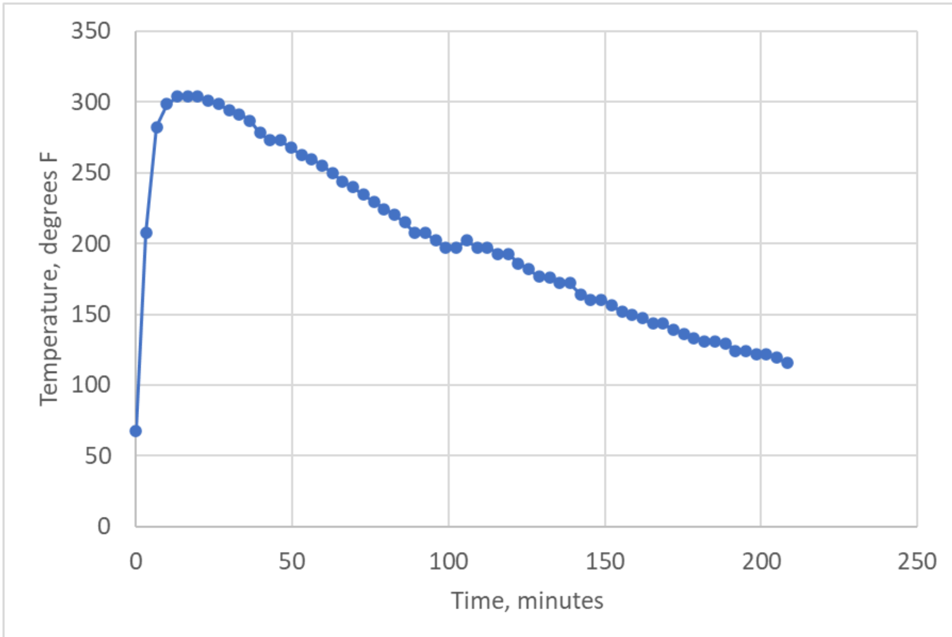


Figure 3. Surface temperature of glass aquarium after filling with closed cell polyurethane foam.

When the aquarium was filled, the surface temperature measured approximately 300 degrees Fahrenheit and decreased to less than 200 degrees Fahrenheit in just over one hour. The range of stability for spun bonded polyolefin is approximately 240 degrees Fahrenheit (Yan, 2016). The problem with the 20-gallon aquarium is the volume to surface area was approximately 20% therefore there was little opportunity to allow for convective cooling. Prototype samples, 4 inches thick and 4 ft. by 4 ft. were fabricated and filled and the measured surface temperature was less than 180 degrees Fahrenheit. Going forward, all the prototype testing or testing of the application of polymeric foam was carried out on retrofit prototypes. The samples were very easy to construct, so the use of large, rigid containers was no longer required. In addition, these containers were not representative of geometries used in the field.

With the help of the team at VersiFoam, samples were filled, and the temperature measured. Because the inflatables were so easy to construct, to expedite the development work the inflatables were filled and then autopsied to determine the extent of filling. In all cases, the samples were filled with polymer foam insulation. There were no voids or cavities in the small sections that were filled, approximately 2 ft^2 in area by 4 inches thick.

4. INFLATABLE DESIGN

4.1 INFLATABLE STRUCTURE DESIGN USING HOOP STRESS ANALYSIS

The following construction methods were considered: baffles and drop stitch method. These methods were selected because they result in a relatively flat surface on the exterior once the inflatable is filled. The pros and cons of each method are listed below:

Baffles is a technique used to control the rounding expansion caused by inflating a structure and are used in structures like air mattresses and jump houses. Variations in the design include spacing, materials, and direction (horizontal, vertical, etc.).

- Pros: A wide range of materials can be used. Easy to construct.
- Cons: Results in some bulging between baffles. Requires more manufacturing time compared to other options.

Drop stitch is a technique that joins two surfaces by using regularly spaced threads between them. The thickness of the inflatable is governed by the length of the thread array. Variations in the design include, materials, thread frequency and pattern.

- Pros: Quick to manufacture and construction offers little bulging.
- Cons: Expensive with limited manufacturers supplying the drop stich fabric. The empty space is filled with fabric array that could inhibit insulation filling.

Based on the differences, coupled with the selection of the fabric material, spun bonded polyolefin and a baffle construction were selected. Below is the cross section of a baffle geometry shown inflated and uninflated.

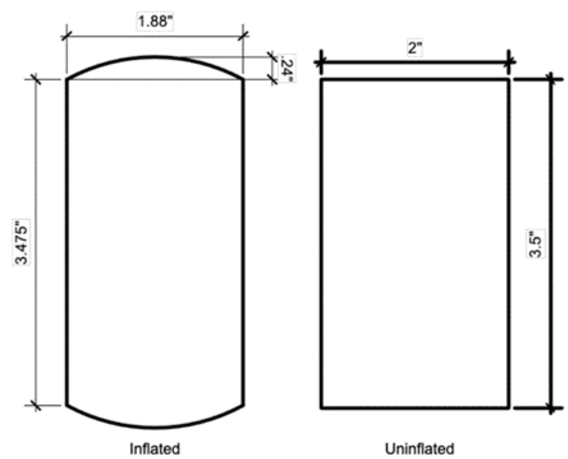


Figure 4. Cross section of a baffle construction inflated and uninflated. The uninflated baffle has a baffle spacing of 2 inches and width of 3.5 inches.

LTA Projects developed a geometrical model based on the hoop stress of a cylindrical body to calculate how the baffle dimensions, spacing and width, affect billowing (Trenchlesspedia, 2021). Billowing can be explained in the following figure (Figure 5):

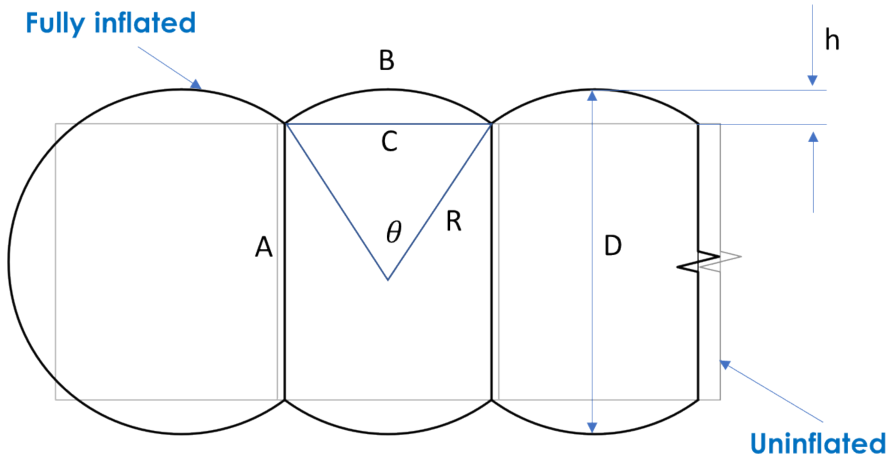


Figure 5. The geometry of the inflatable retrofit element using the method of baffles. A is the baffle width, B is the baffle spacing, theta is the central angle, C is the cord length between the baffles when fully inflated and D is the diameter of the circle formed when the baffle is fully inflated. The difference in height between a fully inflated and uninflated baffle is defined as h.

The figure shows the geometry or shape of the inflatable panel uninflated and fully inflated. The billowing is defined by the height or the difference in height, h, between the uninflated and fully inflated geometries. The objective is to keep the height, h, below one inch.

The central angle for the baffle can be determined or calculated when the baffle is fully inflated. When the baffle is fully inflated, the spacing becomes the arc of a circle. Since a gas or liquid exerts pressure equally in all directions in a confined space, the shape of the baffle when fully inflated assumes a spherical or cylindrical shape as shown in Figure 5. Using the relationship between the arc length, radius, and central angle of a circle and the spacing and width of the baffle, Equation 2 is derived.

$$\theta = \frac{B}{2} cos^{-1}\left(\frac{A\theta}{2B}\right)$$

Equation 1. Relationship between the central angle of a circle created when a baffle with spacing B and width A is fully inflated. The central angle is determined by using a simple iterative process.

To calculate the central angle, an iterative process is carried out by varying the central angle given in radians until the right- and left-hand sides of the equations are equal. This is easily accomplished using the Goal Seek function in Excel.

Once the central angle is calculated, the following Equations 2, 3, and 4 can be used to calculate the radius, R, chord length, C, diameter, D, and finally, the difference in height between the uninflated and inflated baffles or what is referred to as the billowing, h.

$$B = \frac{\theta \times R \times \pi}{180} \qquad R = \frac{B \times 180}{\pi \times \theta}$$

(a) (b)

Equation 2. (a) is the equation for the arc length, B. (b) is the same equation rearranging terms to solve for the radius, R, as a function of the arc length, B, and central angle, θ.

$$C = 2 \times R \times \sin\left(\frac{\theta}{2}\right)$$

Equation 3. Chord length, C, as a function of the radius, R, and central angle, θ.

$$D = 2 \times R = \sqrt{A^2 + C^2} \qquad h = \frac{D - A}{2}$$

(a) (b)

Equation 4. The diameter of the circle as a function of the radius, and as a function of the baffle width, A, and chord length, C (a). (b) is the height of the billowing as a function of the circle diameter, D, and baffle spacing, A.

To understand the effect of baffle width and spacing on the height, or billowing, a series of calculations were carried out varying both. Using the equation or model, the baffle spacing, and width were varied to understand the effect on height, h. The baffle spacing was varied between 4 and 6 inches and the width between 3 and 5 inches. Figure 6 shows the variation at fixed widths as a function of the baffle spacing. Note, that in all cases, the calculated height was always less than one inch.

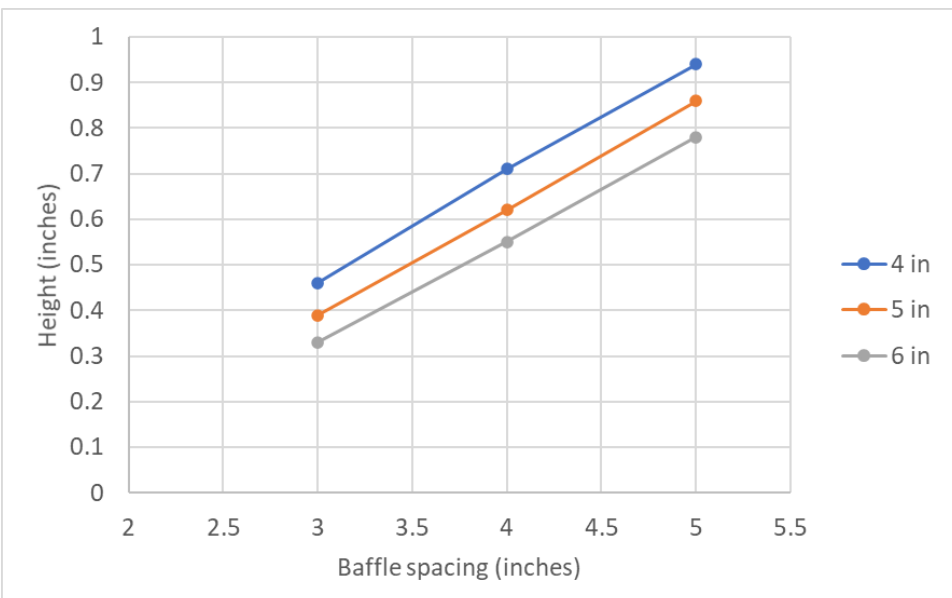
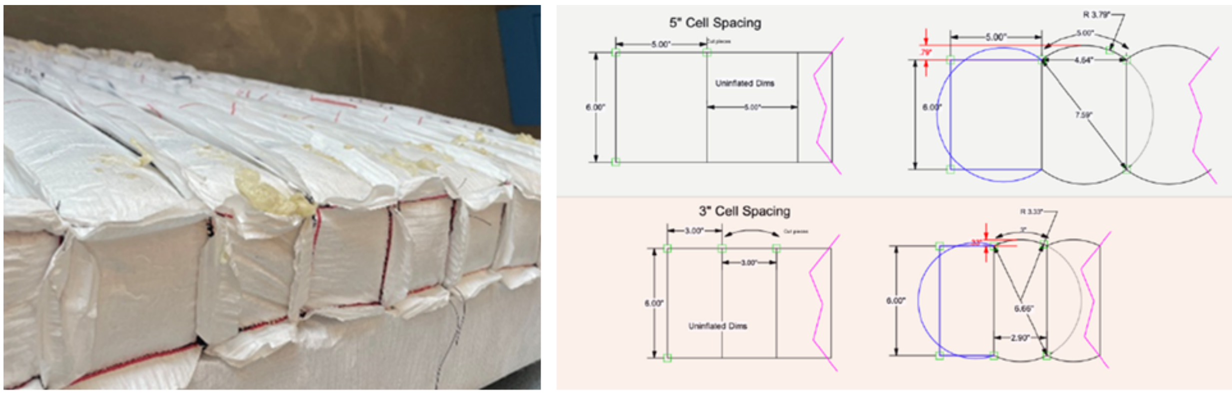


Figure 6. The effect of baffle spacing on the height between an uninflated and fully inflated structure for different baffle widths, 4, 5, and 6 inches.

Billowing, also referred to as drawing up, is a tendency of the spacing between the baffles to decrease as the rounding effect causes the material to 'draw up'. The chart shows that as the width of the baffle increases and spacing is reduced, the effect on a single section is small. However, the decrease in spacing between baffles increases as the number of baffles increase up to a limit. To understand the difference, two samples with different baffle spacings were constructed using multiple baffles. The samples were fully inflated and the calculated values for heights were compared to measured values. This was also done to validate the model.



(a) (b)

Figure 7. Two geometries of a baffle with a width of 6 inches and a spacing of 3 and 5 inches. A is showing the construction that is filled with foam note the variation in surface height moving left to right (a). (b) are the geometries showing the theoretical or model calculations for surface height.

Two geometries were selected, and the dimensions are given in the Figure 7 above. Using *Equation 1*, 3- and 5-inch baffles would result in displacements from the flat geometry of 0.33 and 0.79 inches respectively.

Inflatable structures were constructed with the geometries in Figure 7 and fully inflated. The displacements were measured and compared to the predicted or calculated values based on the geometry of the baffles. Table 3 compares the measured values to the calculated values together with the percent difference.

Table 3. The measured and calculated height for baffles with a width of 6 inches and spacing of 3 and 5 inches.

Baffle geometry, inches		Height, inches		
Width	Spacing	Calculated	Measured	% Difference
6	3	0.33	0.30	9.1
6	5	0.79	0.71	10.1

The results show a difference between measured and calculated values of approximately 10%. The measured values are less than the calculated values which basically makes the model based on hoop stress analysis conservative with respect to billowing. In this case, the billowing behavior will be determined by how well the inflatable is filled with insulation. If the insulation delivered does not completely fill the inflatable structure, the billowing will be small relative to the theoretical value. Too much insulation could result in material expanding beyond the boundaries of the inflatable package, e.g., entry ports and seams. The filling process, currently, is controlled by visual inspection during filling, and dividing the filling into sections to prevent overfilling. This will be discussed further in the installation section.

5. CONSTRUCTION

5.1 DESIGN AND CONSTRUCTION OF INFLATABLE RETROFIT

Based on the hoop stress analysis and a target insulation value of R20, the following baffle geometry was selected (Figure 8).

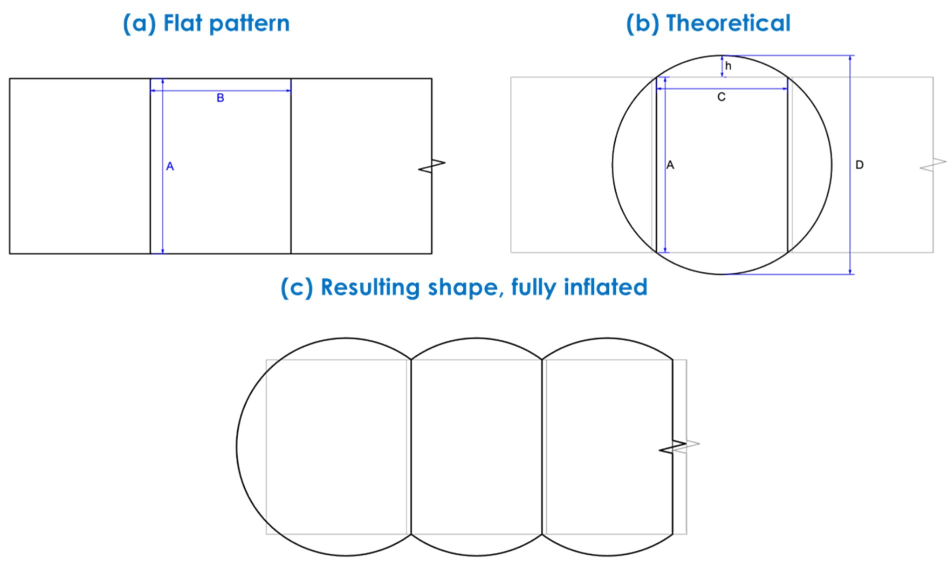


Figure 8. The figure shows the baffle dimensions used in the construction of the prototypes.

The baffle spacing B was 4 inches and the baffle width, A, was 3 inches. Using an R value of 6.7 and a baffle width of 3 inches, the insulation value at the spacing which represents the smallest width along the cross section would be 20.1.

Based on the materials selection and design, elements were constructed using standard practice for the construction of these types of structures. Figure 9 shows the unit cell construction.

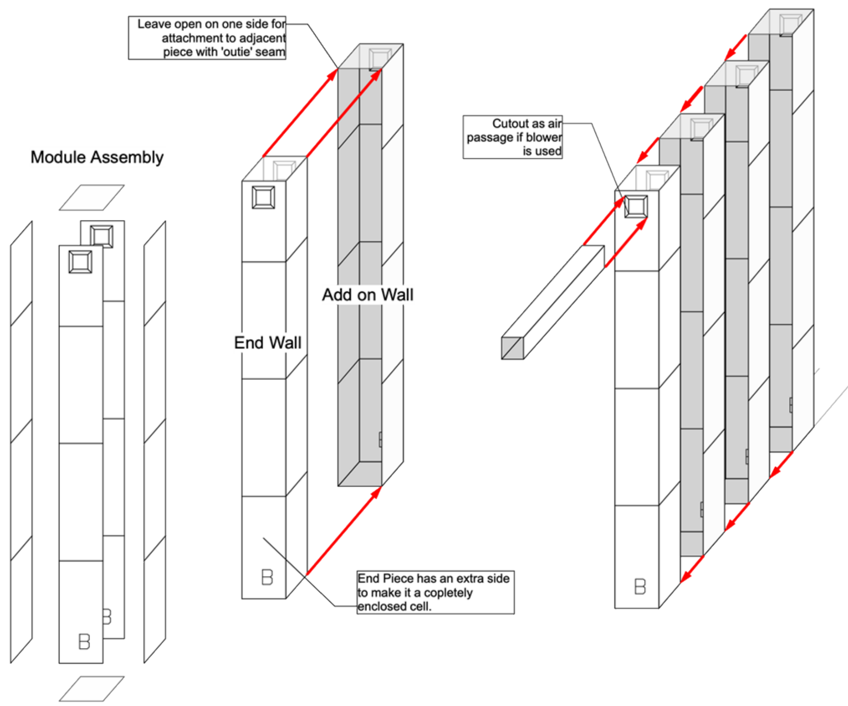
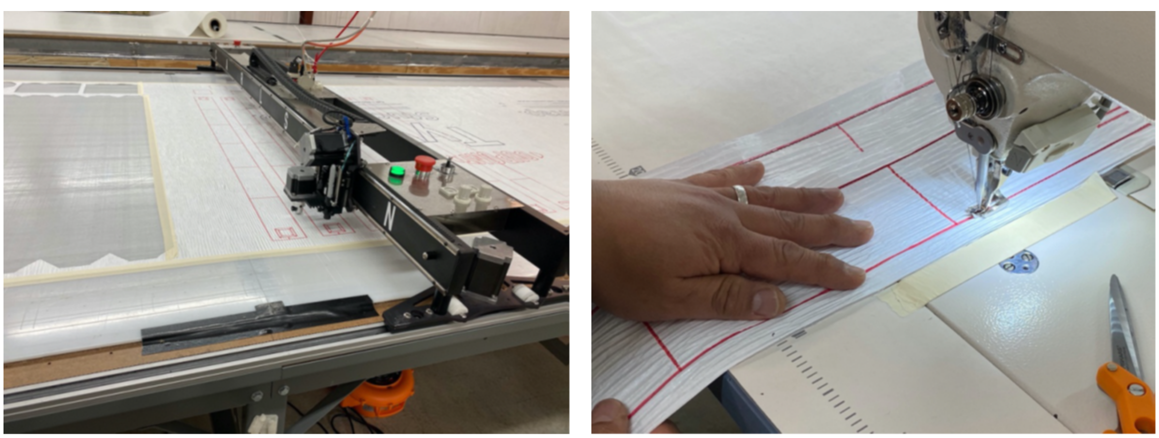


Figure 9. Unit cell for inflatable.

The fabric is cut to size, and then assembled by stitching the pieces together to form a unit cell. Figure 10 below shows the material being cut and then assembled or stitched in this case to create one unit cell. At scale, these processes would be semi or fully automated depending on the level of customization. The cutting will certainly be fully automated. The construction or fabrication may require some level of customization that would be simpler and faster to do using some level of manual construction. This step has yet to be determined since this project did not implement automation processes to build or fabricate the inflatables.



(a) (b)

Figure 10. The cutting and fabrication of unit cells for the inflatable retrofit. The cutting shown in (a) is automated and the construction of the unit cells were manual (b).

In this case prototypes were constructed as large as 4 ft. by 8ft. with a baffle spacing of 3 inches. When fully inflated the thickness along the cross section varied from 3 inches to 4.6 inches because of the baffles shown in Figure 9 assuming the cylindrical shape from the hoop stresses generated by the foam. In this work, all the prototypes were assembled or constructed by hand but are amenable to automated cutting and fabricating methods. To facilitate integration or combination of multiple elements a slot is constructed to accommodate a channel that ensures all the segments are aligned as seen in Figure 11. Each unit cell is isolated from its neighbors. This provides flexibility with respect to onsite modifications and makes filling the structures or elements easier. The unit cells can be cut to any size and put together or assembled to accommodate a variety of shapes and sizes.

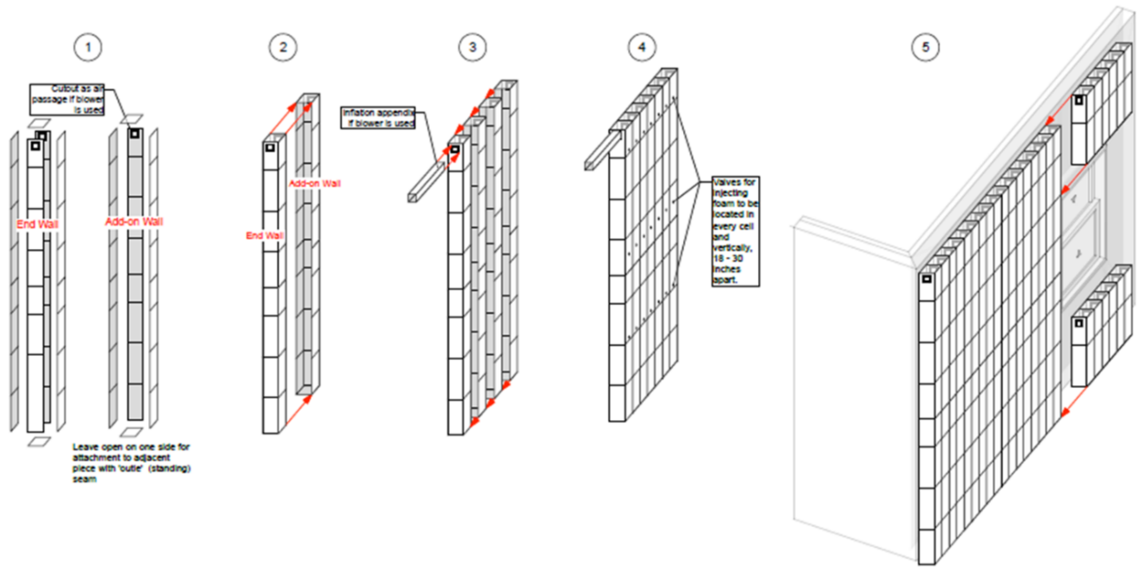


Figure 11. Shows the flexibility in construction and the accommodation around a wall. Unit cells can be constructed in a variety of lengths and preassembled and delivered to the job site fit to size or can be pieced together at the job site.

6. INSTALLATION

6.1 DEMONSTRATION OF INSTALLATION AND FILLING OF PROTOTYPES

As with any retrofit process, a pre assessment was carried out. To help, the Building America Solution Center has resources available to assess the materials and conditions of the structure prior to starting a retrofit (Energy, 2021). After the site measurements are made and the inflatable retrofits constructed, the inflatable retrofits are installed on the wall. The elements are installed like a weather resistive barrier using mechanical fasteners. Figure 12 shows the beginning of the installation. To facilitate the installation of prototypes a corner wall was constructed 8 ft in height. The wall was used to install and fill inflatable retrofit elements. The installation method describes installation on exterior sheathing. No work has been done to fasten these systems to exterior claddings such as vinyl or wood siding.

The inflatable retrofit has standing seams on the back side of every other unit cell. These seams allow the inflatable to be fastened to the sheathing using half inch staples. Working from right to left or left to right, and starting at the top of the wall, staples are inserted every 8-12 inches down the full length of the standing seam. One vertical seam is completed before moving on to the next. Shifting unattached material in the opposite direction of the installation reveals the standing seams to be stapled. Once the entire seam has been stapled, the installer will skip to the next seam, so that the inflatable will be attached at every other vertical seam, approximately 6 inches apart horizontally. Note that the cells are pulled out flat with slight tension in the horizontal and vertical directions. Always staple the first and the last standing side seam in place, even if a cell is not skipped. Notice that the completed module shows a natural tendency to keep itself open after stapling is complete, Figure 12(c). This is due to the rigidity of the materials the square seam structure formed by the top and bottom piece. This coupled with fastening from behind causes the structure to naturally open. The benefit of this behavior, which was unexpected, facilitated the filling step. Initially, the plan was to use air to open the inflatable to facilitate filling with foam. The structures natural tendency to open once installed eliminated that step making it easier to fill with insulation.

As the process continues, additional modules are stapled to the structure until the installation is complete. The flexibility in construction provides options to have multiple pieces constructed or a single section covering the entire wall. Ultimately, the size and shape will be determined by installers with respect to the facility in handling and installation including filling with polymer foam insulation.

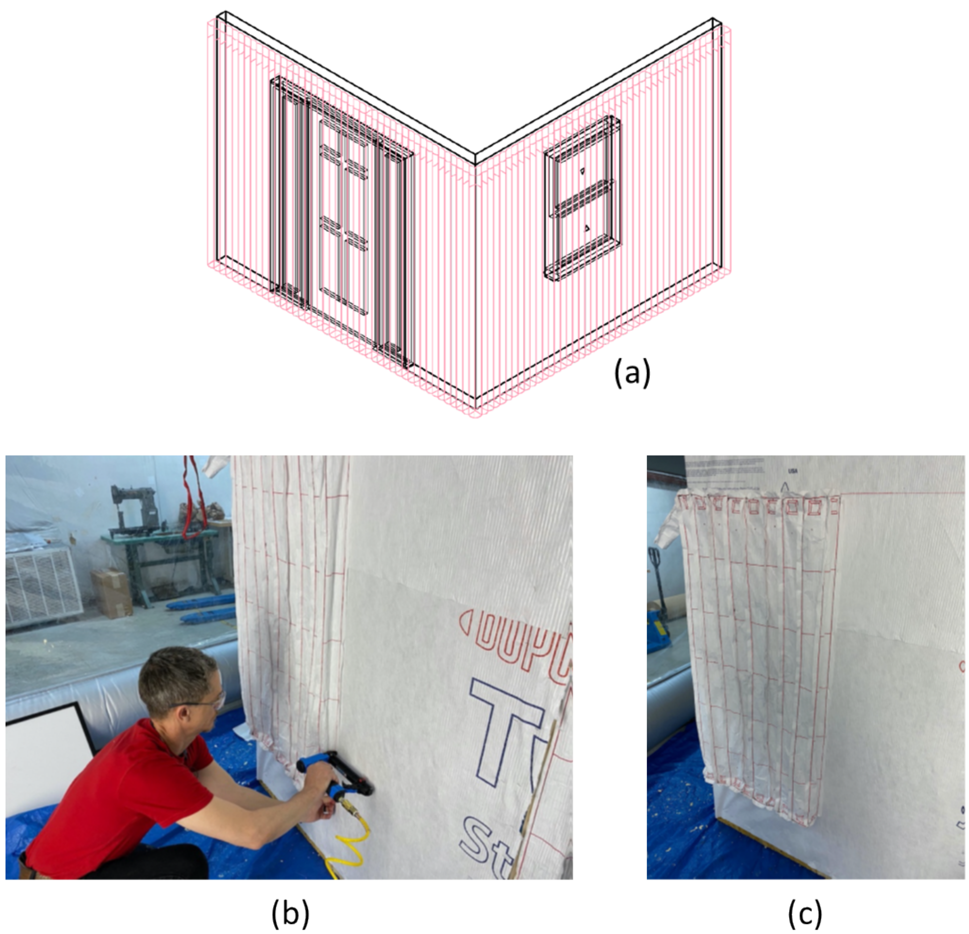
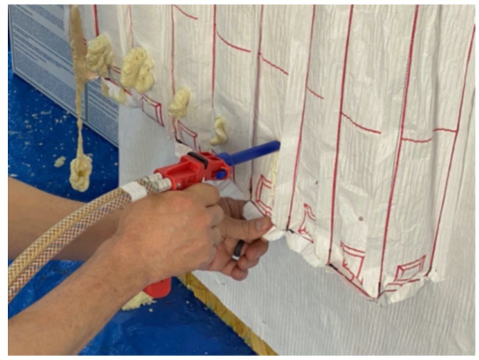


Figure 12. The figure shows the beginning of an installation of a corner section. (a) is a schematic of the mockup. (b) shows the installation of the inflatable retrofit and (c) shows the inflatable structure opened after the installation is complete but before spray foam insulation is introduced.

After the inflatable retrofit is fastened to the exterior sheathing, the next step is to fill the inflatable structure with foam insulation. Figure 13 shows the sequence of steps involved in filling the retrofit structure with foam insulation. In this case, small openings are cut to accommodate a small spray gun. The retrofit structure being filled is approximately 5 ft tall. Filling starts at the bottom, and the section is filled in thirds terminating at the top of the structure. Since each unit cell is independent from its neighbor, filling is required for every unit cell.

(a)



(b)

(c)

(d)

Figure 13. Shows the filling sequence of the inflatable section. The filling starts from bottom of the unit cell (b) and works its way up to the middle section (c) and finally the top section (d).

The benefit or advantage of this system relative to rigid panelized systems is in the flexibility of construction. Figure 14 shows a corner detail and the installation of retrofit section adjacent to a window. Because the fabric material is light, approximately 2 oz per square yard, very large sections can be constructed and installed without the need for lifting equipment. All that would be required is scaffolding for larger or taller structures. The retrofit system also offers contractors the ability to install the retrofit system over an entire wall and then cut out sections for openings such as doors, windows and service penetrations as illustrated in Figure 15. The possible benefits are labor savings at the expense of material cost in the form of wasted material. If windows are going to be replaced and labor rates are high, installation over the entire envelope is an option if it results in labor savings. Again, this is something that will be determined or confirmed by installers working on actual structures.

(a) (b)

Figure 14. Inflatable retrofit system showing the formation of a corner element (a) and the installation and filling with foam integrated with a window (b).

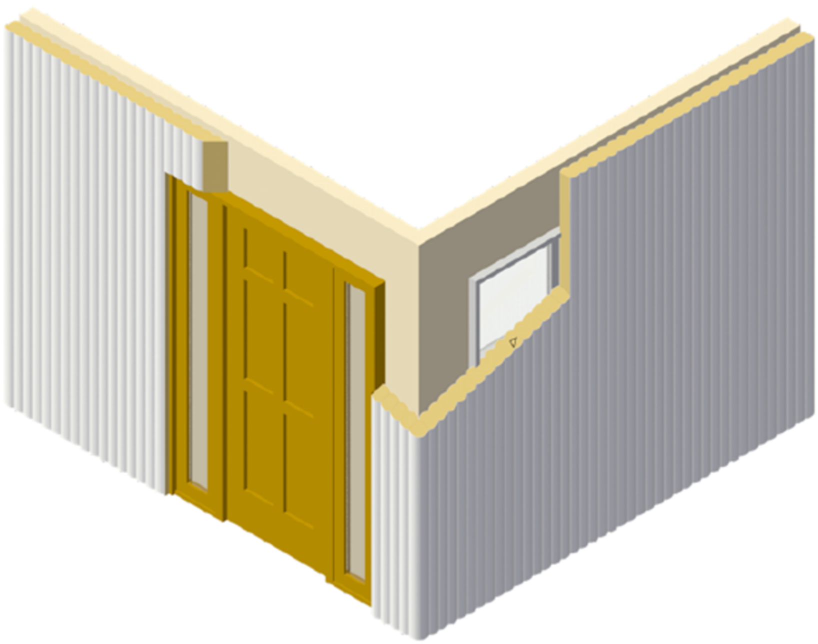


Figure 15. Depending on the application and details around fenestrations, the materials are very easy to customize, and openings can be cut after the installation. This may be a cost savings opportunity in very high labor markets.

Another added benefit is the self-sealing behavior inherent or as consequence of the hoop stresses generated when the system is filled with foam and shown in Figure 16. When two ends are joined as in Figure 16, depending on the installation you may have a gap. However, depending on the spacing, the gap can be sealed by the expanding baffles coming into contact because of the hoop stresses generated during filling causing the baffles to billow. The height that was minimized earlier now offers a benefit in that joints can “self-seal”.

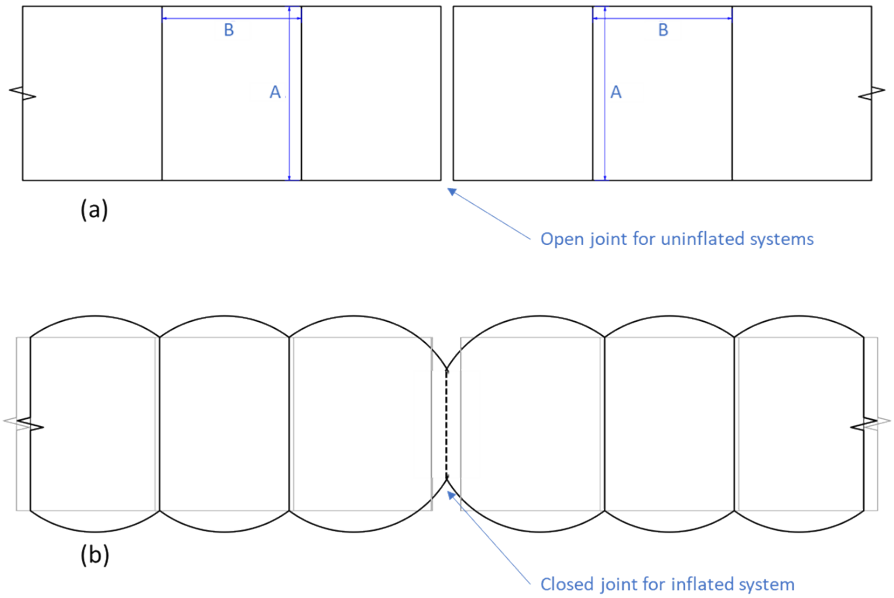


Figure 16. Installation detail between two separate panels or sections. (a) shows the joint or space between two panels that are uninflated. (b) shows how the joint is sealed once the panels are filled with insulation.

6.2 FINISHED SYSTEMS

After the installation of the retrofit system, cladding needs to be applied to complete the retrofit. In this case, several cladding options were considered but only one was demonstrated, in part, because elements of the cladding system could be integrated into the inflatable retrofit. The cladding or façade material is stucco. Figure 17 shows an inflatable retrofit system with a polymer mesh reinforcement used for the application of stucco in exterior insulation finish systems, EIFS. In this prototype, the reinforcing mesh was integrated into the retrofit system so that the retrofit, after it's installed, would be ready to accept the base and finish coats required to complete the application of stucco. The advantage of using stucco is that the differences in height could be easily masked by the stucco finish as shown in Figure 17.

Figure 17. The application of a stucco finish to the inflatable retrofit. (a) shows the inflatable retrofit with mesh reinforcement preinstalled on the inflatable retrofit panel ready to accept the stucco base and finish coats. (b) shows the finished or completed stucco installation

7. PERFORMANCE TESTING AND HYGROTHERMAL SIMULATIONS

7.1 AIR PERMEANCE

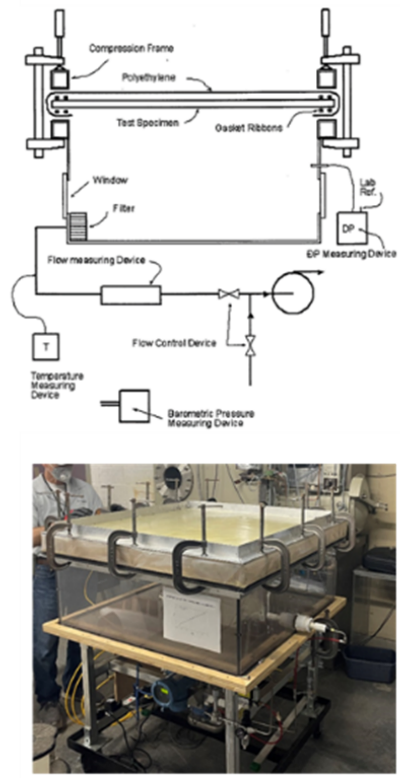
To measure the air permeance of the system, testing of a one square yard assembly in accordance with ASTM E2178, Standard Test Method for Air Permeance of Building Materials was carried out. The table in Figure 18 shows the extraneous, full and specimen air permeance values. A baseline measurement is carried out with the assembly sealed using polyethylene sheet. The purpose is to measure any extraneous leakage not associated with the specimen or attributed to the test apparatus. The measurement is then carried out again with the polyethylene sheet removed. The results are subtracted to get the air permeance of the test specimen. The air permeance at a pressure of 50 pascals is represented in bold in the table in Figure 18 and is normalized to the area of the test specimen. The size of the test specimen is approximately one square yard and the measured air permeance at 50 pascals is 0.00365 cubic feet per minute. To put this value into context, ASHRAE 90.1-2010 specifies that for materials, the air permeance shall not exceed 0.004 cfm at a pressure of 75 Pa. Based on these measurements, the air permeance at 75 Pa is 0.0055 cfm, about 20% higher than what's specified for a material. In addition, ASHRAE 90.1-2010 also specifies that the leakage for an assembly shall not exceed an air permeance of 0.04 cfm at 75 Pa measured in accordance with ASTM E 2357. In this case, a hybrid system was tested in accordance with ASTM E2178. Additional work is required to get a measure of the impact of joints and penetrations on the air permeance of an assembly system, i.e., measurements need to be carried out in accordance with ASTM E 2357.

	ΔP (Pa)	Flow (LPM)	Flow (cfm)
Extraneous	24.66	0.415	0.015
	51.11	0.719	0.025
	157.62	1.9384	0.068
	308.97	3.3928	0.120

	ΔP (Pa)	Flow (LPM)	Flow (cfm)
Full	24.3	0.432	0.015
	49.8	0.817	0.029
	74.4	1.219	0.043
	100.9	1.569	0.055
	150.8	2.158	0.076
	305.0	3.856	0.136
	149.3	2.103	0.074
	49.6	0.772	0.027

	ΔP (Pa)	Flow (LPM)	Flow (cfm)
Specimen only	25.0	0.04247	0.001
(removing	50.0	0.10332	**0.00365**
extraneous	100.0	0.21377	0.008
using	150.0	0.30922	0.011
trendlines)	300.0	0.50557	0.018

(a)



(b)

Figure 18. The results from air permeance test in accordance with ASTM E2178.

7.2 THERMAL CONDUCTIVITY

The thermal conductivity of a finished section was carried out in accordance with ASTM C518 - Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. Data in Table 4 are the results from the thermal conductivity measurements. Because of the variation in surface height of the inflatable system, flexible/compressive foam pads had to be used to ensure contact between the heat flux transducers and the sample surface. The pads are inserted on the top and bottom surfaces and the composite system is measured. The thermal conductivity of the flexible/compressive pads are then measured independently from the sample. The insulation values for the pads and composite are then calculated. The difference between the two are calculated to determine the insulation value of the test sample. The insulation value, R/inch, for the inflatable insulation system with an EIFS finish measured using this approach is 4. The total insulation value of the system is 14.8, sample thickness is 3.7 inches. The target value was R 20. The difference between the measured and calculated value is approximately 26%. It’s not clear what’s giving rise to the difference in performance with respect to the calculated value. One possible explanation is that the fill was poor and/or there was insufficient blowing agent resulting in an air-filled foam which would give rise to a lower insulation value or higher thermal conductivity consistent with these measurements. Another possibility is increased foam density as a consequence of package confinement. Unlike an open wall cavity where the foam can freely expand, the delivery of excess foam to a closed package could result in increased density since the expanding foam is constrained. This could lead to an increase in thermal conductivity. Unfortunately, measuremens of foam density after filling were not carried out. In aggregate, the increase in thermal conductivity could be attributed to both a reduction in blowing agent and increased density. Additional work is required to understand the cause.

Table 4. Result from thermal conductivity measurement of inflatable retrofit system with stucco finish in accordance with ASTM C518, Standard Test Method for Steady State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus.

EIFS Sample								
	thickness		k		insulation value			
	mm	in	W/mK	Btu in/hr ft^2 ^{o}F	RSI, m^2 K/W	R, hr ft^2 ^{o}F/Btu		R/inch
Black foam pads	15	0.598	0.049	0.337	0.313	1.778		2.972
EIFS sample plus foam pads	109	4.309	0.037	0.259	2.927	16.619		3.857
EIFS sample	**94**	**3.710**			**2.614**	**14.841**		**4.000**

In addition to thermal conductivity measurements, the effect on the insulation value of wall assemblies was investigated. In this case, simulations were carried out using THERM to determine what impact the inflatable retrofit would have on the total R value of an uninsulated and poorly insulated wall (Lawrence Berkeley National Laboratory, 2019). Figure 19 shows the calculated R values for four wall constructions: an uninsulated wall, 2 in x 4 in framing with empty wall cavity, the same wall with the inflatable retrofit measured in Table 4. In addition to the uninsulated wall, the same wall was simulated with cavity insulation, a fiber glass batt, and the inflatable retrofit using the thermal properties measured in Table 4. The results are between R value of 2.8 for the uninsulated wall and as high as 25.8 for the wall with the retrofit and cavity insulation. These wall constructions and insulation values will be used for the hygrothermal simulations.

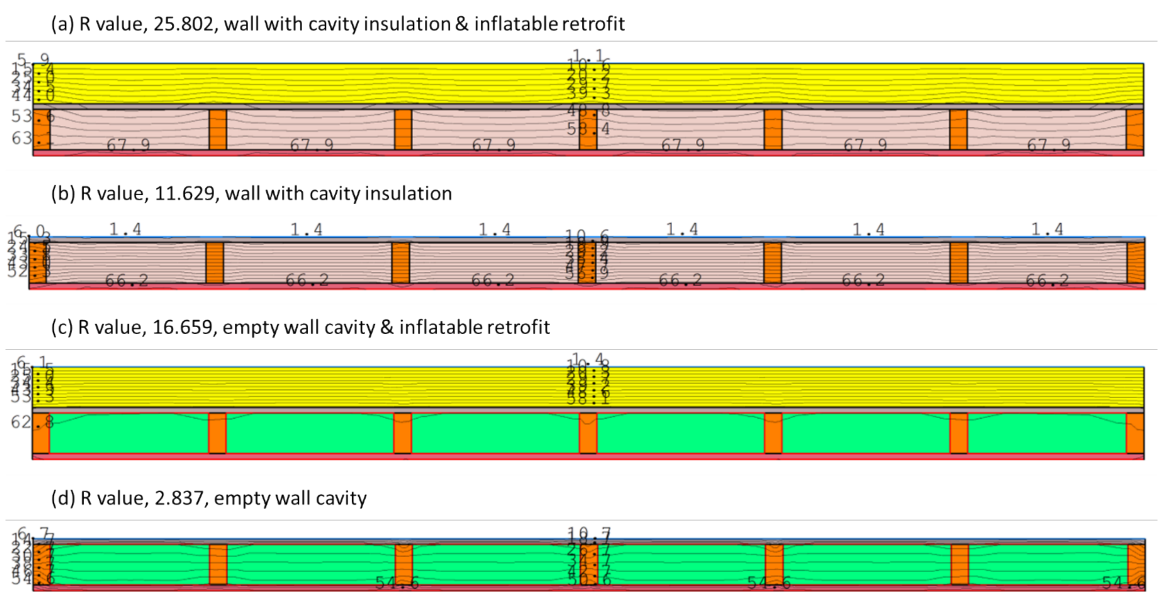


Figure 19. Insulation values for wall constructions, 2 in x 4 in framing, 16 inches on center. (a) wall with cavity insulation and inflatable retrofit, (b) wall with cavity insulation, (c) wall with no cavity insulation and inflatable retrofit, and (d) wall with no cavity insulation.

7.3 PHYSICAL TESTING

The tensile strength of a small section of the inflatable insulation system with EIFS finish was measured using static loads. The system was secured to oriented strand board (OSB) exterior sheathing by staples using the schedule described in the installation section. The sample size was 17.5 inches by 24 inches (surface area of 2.917 ft^2). Figure 20 represents a schematic of the test setup.

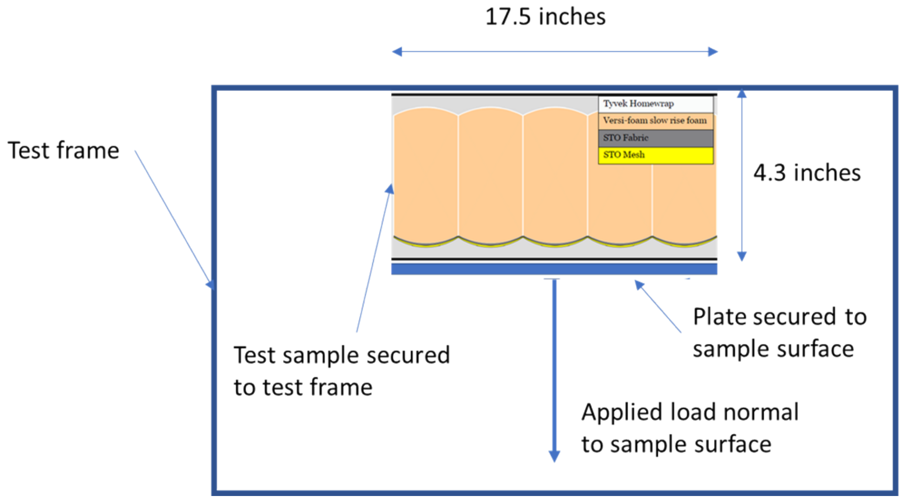


Figure 20. Test frame and sample used to measure applied load to sample secured to OSB sheathing.

A fixture was attached to the sample surface to uniformly distribute the load and the entire sample secured in a rig that facilitated the application of a static load. The static load was applied according to the chart in Figure 21. Failure occurred at a maximum load of 465 pounds.

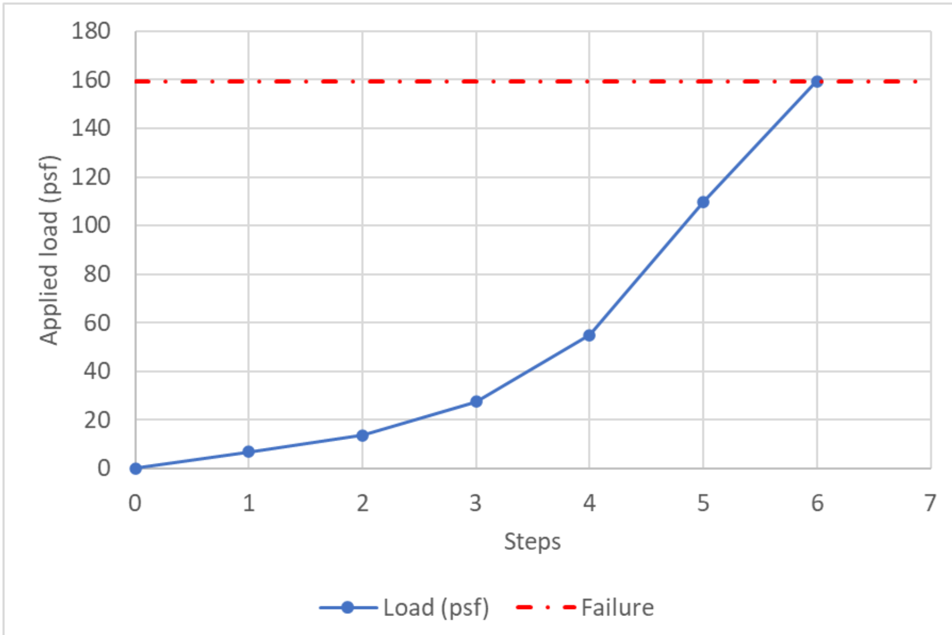


Figure 21. The applied load normal to the sample surface measured in pounds per square foot (psf). The sample separated from the surface at an applied load of approximately 160 psf.

The failure mode was an "adhesive" failure in the sense that failure occurred at the point where staples were fastened into the OSB sheathing. Based on the load and surface area, the tensile strength of the system was approximately 160 psf (pounds per square foot). To put this value into context, the uplift force on roof shingles exposed to a 90-mph wind is approximately 20 psf. Considering this retrofit is not structural, a tensile strength of 160 psf should be sufficient to resist normal service loads. This will need to be verified in large scale assemblies.

7.4 HYGROTHERMAL SIMULATIONS

Hygrothermal modeling is used to evaluate the condensation potential, moisture content, drying capacity of the assembly, potential for mold growth, and freeze-thaw damage. During the last two decades, several computer simulation tools have been developed to predict thermal and moisture conditions in buildings and the building envelope. In addition, these types of simulation have been used as tools in forensic investigation of building failures. Architects and Engineers are increasingly using these hygrothermal simulations of building envelope systems to make design recommendations for buildings as a function of location or climate.

WUFI® is one of the most used hygrothermal simulation tools in the building industry (Fraunhofer IBP, 2021). WUFI® a German acronym that stands for Wärme Und Feuchte Instationär which, when translated in English, means heat and moisture transiency. Fundamentally, WUFI is built on the physics of material properties such as sorption, suction isotherms, vapor diffusion, liquid transport, and phase changes. The model is well documented, and field validated.

The objective of carrying out these simulations is to determine if these types of retrofits will create moisture or durability problems after they are installed. The use of transient hygrothermal models for moisture control is well established in the building industry in its codes, standards, and building insulation design principles. Building envelopes are designed to naturally shed liquid water and minimize its entry. Building envelopes should also be constructed to facilitate vapor transport so that moisture doesn't accumulate within the envelope leading to subsequent durability failure.

Hygrothermal simulations were carried out using WUFI Pro (Version 6.4). Simulations were carried out on two constructions typical of uninsulated and poorly insulated homes. The wall constructions were 2 in x 4 in framing spaced 16 inches on center. In one case, the wall was uninsulated. In the second case, the wall was insulated with fiber glass batt insulation. The interior sheathing was gypsum board and the exterior sheathing plywood. The cladding material was vinyl siding. A moisture sink was used to simulate moisture getting behind the cladding due to wind driven rain. In addition, air change behind the cladding was also simulated.

The climate zones selected are the reference cities used by the Department of Energy for whole building energy simulations (Office of Energy Efficiency & Renewable Energy, 2021). Only cities in humid climates (designated by the letter A in the Department of Energy's climate zone map) were simulated, a total of eight and listed in Table 5 (Pacific Northwest National Laboratory, 2015).

Table 5. Cities selected for the hygrothemal simulation the cover all 8 climate zones in the moist humid regions (A).

Cities	Climate Zone
Miami, Florida	1A
Houston, Texas	2A
Atlanta, Georgia	3A
Baltimore, Maryland	4A
Chicago, Illinois	5A
Minneapolis, Minnesota	6A
Duluth, Minnesota	7
Fairbanks, Alaska	8

Simulations were carried out for prevalent driving rain direction in accordance with standard ANSI/ASRHAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings (ANSI/ASHRAE, 2016). Simulations were run for three years. The equilibrium moisture content at 80 percent relative humidity (EMC80) was used for all the wall elements representing a worse case condition.

Figure 22 shows the results from the hygrothermal simulation for the uninsulated wall with no retrofit. What's important to note in this case is that total moisture accumulation for the analysis or simulation period of three years is negative. The number of consecutive days over 80% relative humidity and time of wetness are high, but that is because the initial moisture content is high. The total simulation time is 26,295 hours, so the consecutive days over 80% and time of wetness represent drying of the wall assembly during the first year. Similar behavior was observed for the other wall assemblies and the results are given in Figure 22, Figure 23, Figure 24, and Figure 25. The conclusion from these simulations is that the introduction of the inflatable retrofit system does not compromise the moisture durability of the existing wall.

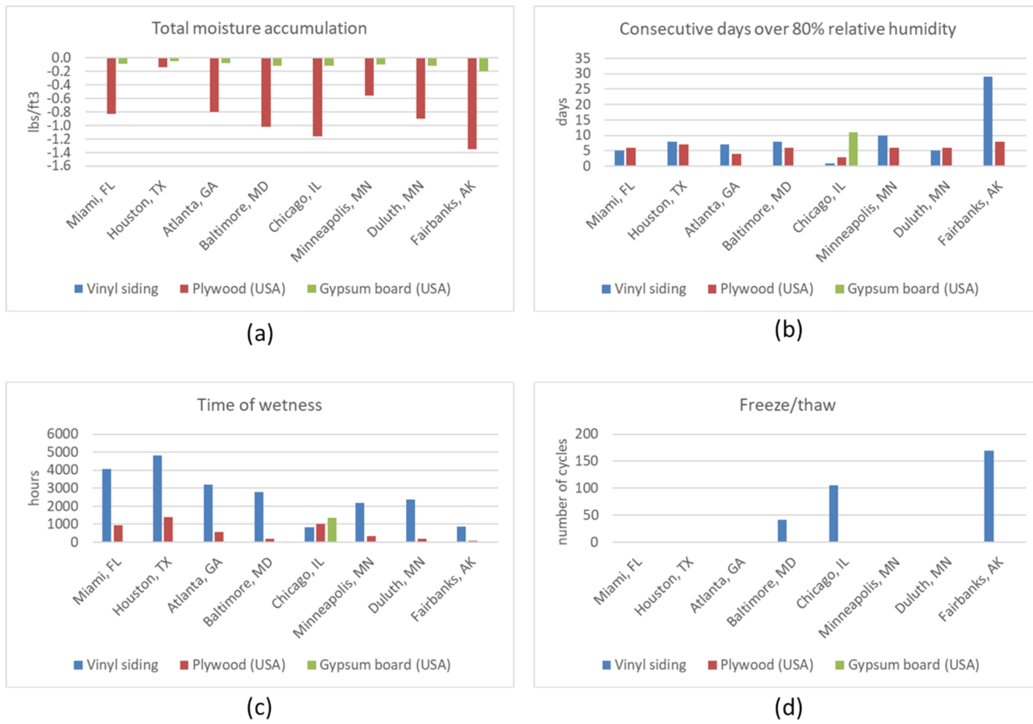


Figure 22. Hygrothermal performance of uninsulated wall assembly. (a) total moisture content in lbs/ft³, (b) consecutive days over 80% relative humidity in days, (c) time of wetness in hours, and (d) freeze/thaw measured in cycles.

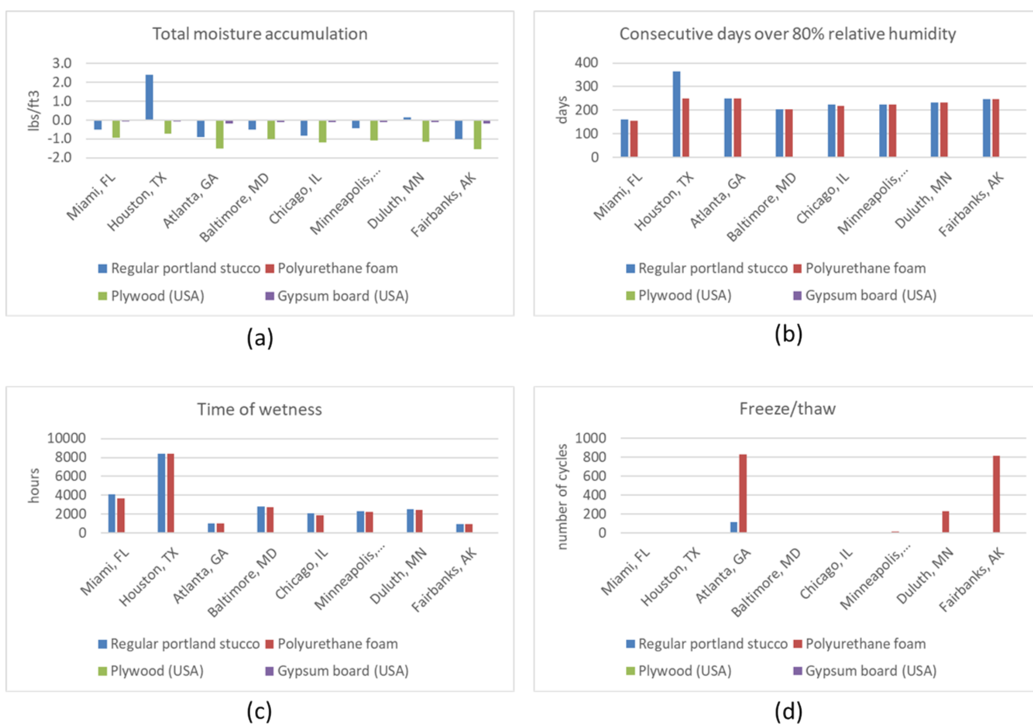


Figure 23. Hygrothermal performance of uninsulated wall assembly with inflatable retrofit installed. (a) total moisture content in lbs/ft³, (b) consecutive days over 80% relative humidity in days, (c) time of wetness in hours, and (d) freeze/thaw measured in cycles.

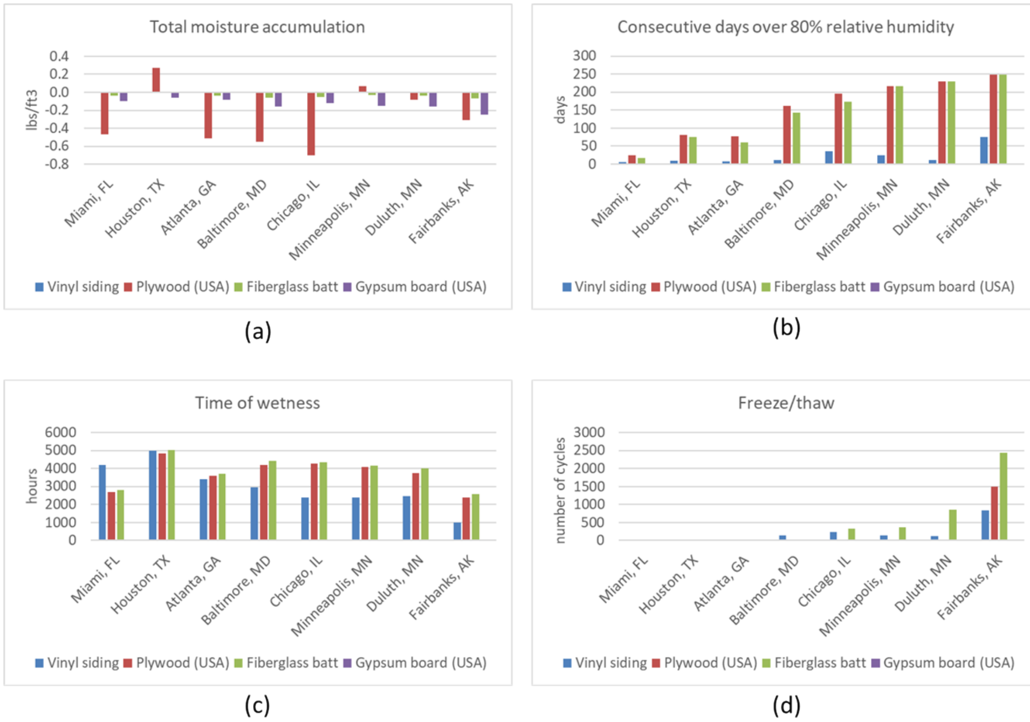


Figure 24. Hygrothermal performance of insulated wall assembly. (a) total moisture content in lbs/ft³, (b) consecutive days over 80% relative humidity in days, (c) time of wetness in hours, and (d) freeze/thaw measured in cycles.

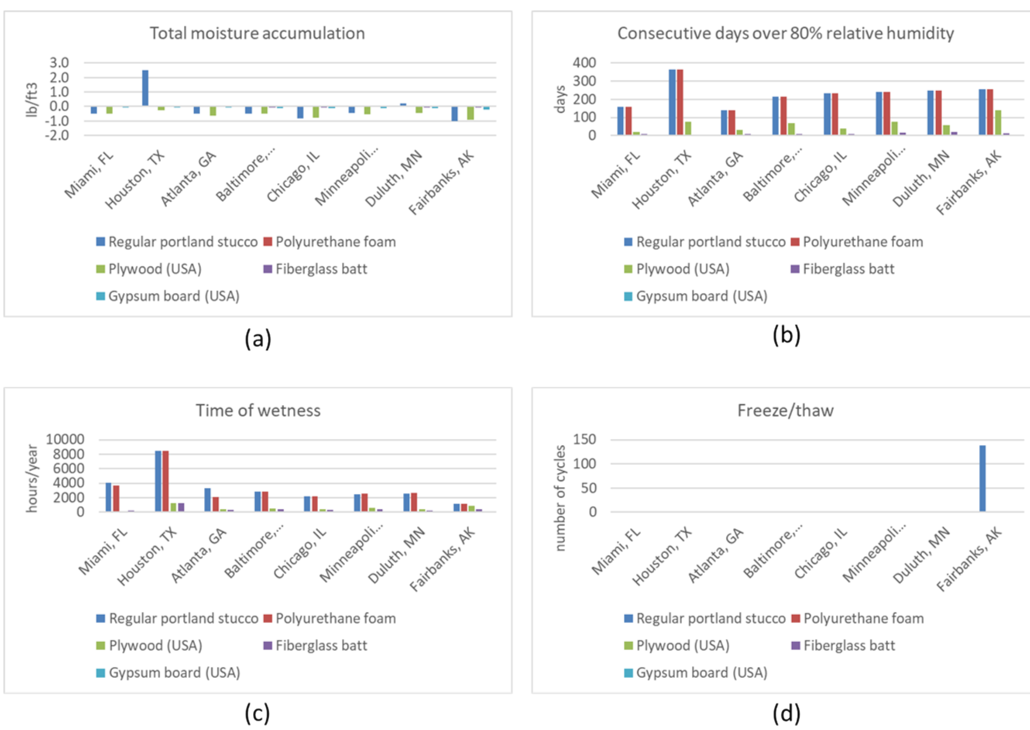
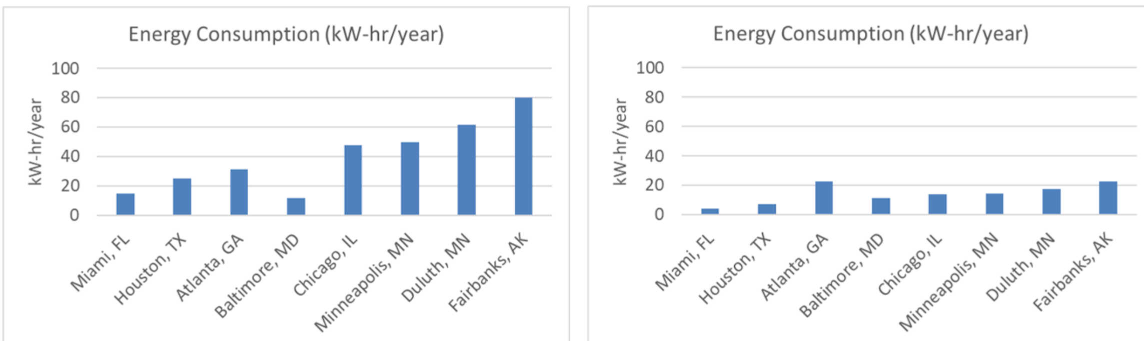


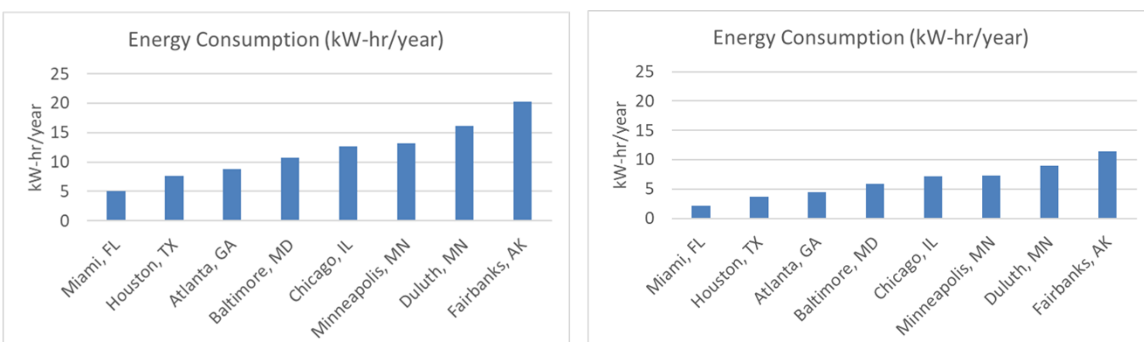
Figure 25. Hygrothermal performance of insulated wall assembly with inflatable retrofit installed. (a) total moisture content in lbs/ft³, (b) consecutive days over 80% relative humidity in days, (c) time of wetness in hours, and (d) freeze/thaw measured in cycles.

The hygrothermal simulations also calculate energy consumption based on the difference between the interior and exterior boundary conditions. The energy consumption calculated in kW-hr/year for the uninsulated wall with without an inflatable retrofit is shown in Figure 26. From the results it’s clear that the biggest improvement in thermal performance from the retrofit will be in cities where the climate is colder. In this case, the cities would be in climate zones 5, 6, 7, and 8. The same is true for the case of the poorly insulated wall with and without an inflatable retrofit as shown in Figure 27. To accurately determine the reduction in energy or energy use intensity, a whole building assessment needs to be carried out. But in this case, the results provide some direction as to where the most significant improvements will be realized.



(a) (b)

Figure 26. Energy consumption from hygrothermal simulations for an uninsulated wall (a) and uninsulated wall with a 4-inch inflatable retrofit system (b).



(a) (b)

Figure 27. Energy consumption from hygrothermal simulations for an insulated wall (a) and insulated wall with a 4-inch inflatable retrofit system (b). The insulated wall is 4 inches of fiberglass batt insulation.

8. PRELIMINARY COST ANALYSIS

8.1 COST OF INFLATABLE

The last exercise was to carry out a simple cost analysis for the inflatable retrofit system. For direct comparisons, the Department of Energy's reference cities used for whole building energy simulations were selected. The labor and material costs were then obtained from the website homewyse.com. The approach used was simple. The first step was to calculate the cost of the inflatable retrofit system as designed and tested in this study, i.e., with a baffle spacing of 4 inches and a baffle width of 3 inches. The cost includes the insulation material and is given in Table 6.

Table 6. The cost of the inflatable retrofit insulation system including the polyurethane foam insulation required to achieve an insulation value of R20.

	$\$/ft^2$
material	$ 0.60
manufacturing	$ 1.70
insulation	$ 1.95
total	**$ 4.25**

8.2 INSTALLED COST

The labor rate required to install the retrofit was obtained for each city, a high and low value, from homewyse (homewyse, 2021). Since there isn't a labor rate for this type of system, the sum of the labor rates for the installation of housewrap and spray polyurethane foam was substituted. Using this labor rate an installed cost for the inflatable retrofit was calculated. Then the installed cost for two cladding systems was obtained, stucco and vinyl siding. Taking the sum of the two, the installed cost for the retrofit system including the cladding was calculated and the results are shown in Figure 28 and Figure 29, for stucco and vinyl siding respectively. The estimated installed cost for the stucco system, Figure 28, ranges from a low of $\$15/ft^2$ to over $\$28/ft^2$. For the case of vinyl siding, Figure 29, the cost is between \$11 and \$21 a square foot. Note that the cost of the inflatable retrofit is less than half of the total cost based on the lowest installed cost, $\$11/ft^2$. The installed cost for the retrofit alone is represented by the red bars in Figure 28 and Figure 29. This difference could be considered the available cost to integrate a cladding system into the inflatable retrofit to develop a complete system. This is certainly a path or opportunity for further cost reduction by converting labor to materials. Also, one could argue that these costs are conservative since they treat the installation of the retrofit as two separate steps and do not leverage synergies or possible savings between the application of the two systems as part of a single installation. Again, this is a preliminary cost assessment. A complete list of the data used in these calculations is presented in Table 7 and Table 8. Note, the coverages used to calculate the cost for the cladding, house wrap and spray foam insulation are 10,000, 1,000 and 4,000 square feet respectively. The coverages used for house wrap and spray foam insulation were the maximum values allowed by the calculator, homewyse, for those systems.

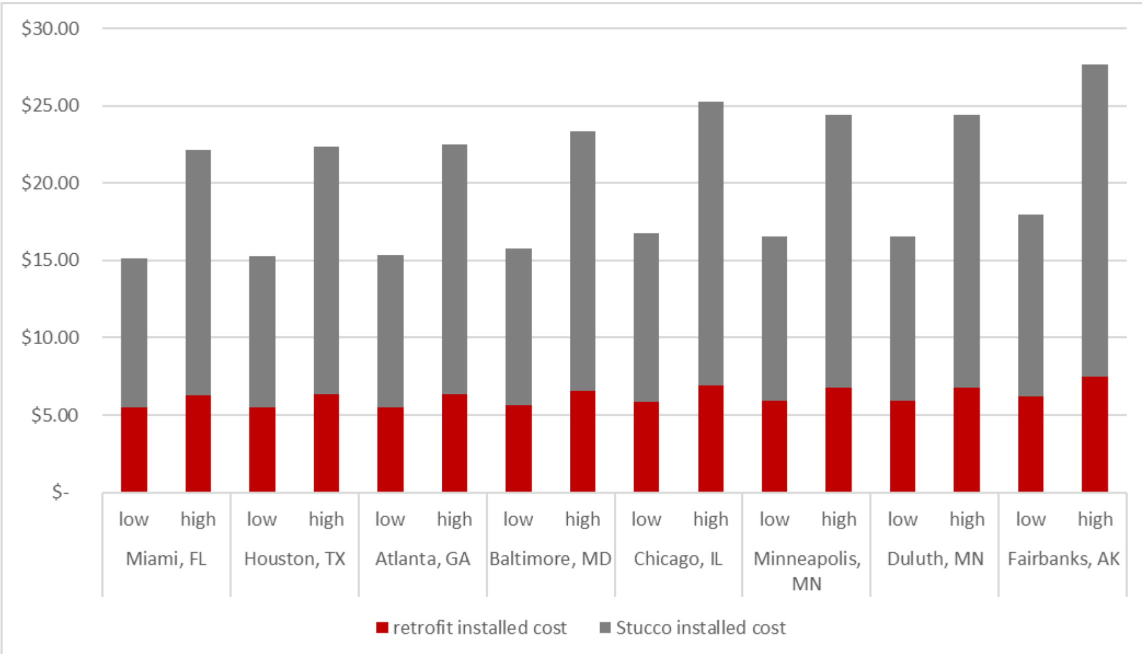


Figure 28. Estimated cost in $\$/ft^2$ of the inflatable retrofit system with stucco finish applied coverage is equal to 10,000 sq.ft.

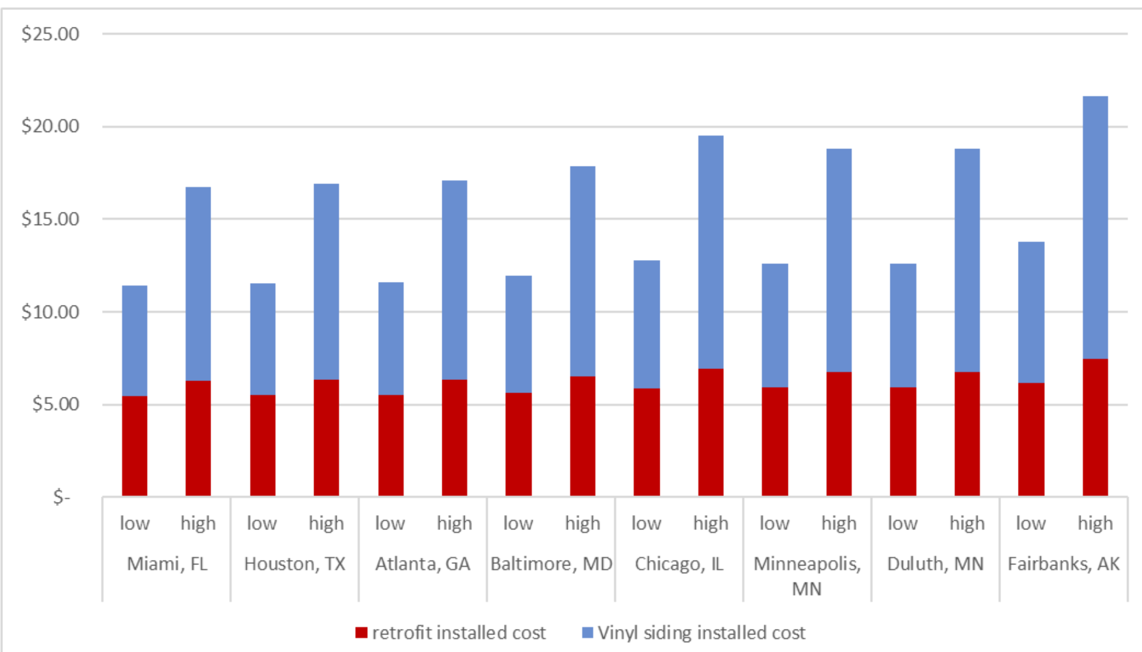


Figure 29. Estimated cost in $\$/ft^2$ of the inflatable retrofit system with vinyl siding applied coverage is equal to 10,000 sq.ft.

Table 7. Cost assessment of the installation of an inflatable retrofit system with a stucco cladding applied as separate step.

	33101		77001		30301		21201		60601		55401		55801		99701	
	Miami, FL		Houston, TX		Atlanta, GA		Baltimore, MD		Chicago, IL		Minneapolis, MN		Duluth, MN		Fairbanks, AK	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
retrofit material	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60
retrofit manufacturing	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70
retrofit insulation	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95
retrofit on site assembly	$ 1.22	$ 2.02	$ 1.25	$ 2.07	$ 1.27	$ 2.11	$ 1.38	$ 2.29	$ 1.63	$ 2.70	$ 1.71	$ 2.52	$ 1.71	$ 2.52	$ 1.93	$ 3.20
retrofit installed cost	$ 5.47	$ 6.27	$ 5.50	$ 6.32	$ 5.52	$ 6.36	$ 5.63	$ 6.54	$ 5.88	$ 6.95	$ 5.96	$ 6.77	$ 5.96	$ 6.77	$ 6.18	$ 7.45
Stucco cost	$ 63,117.00	$87,541.00	$63,319.00	$87,821.00	$63,482.00	$88,048.00	$64,270.00	$89,140.00	$66,009.00	$91,551.00	$65,240.00	$90,486.00	$65,240.00	$90,486.00	$68,170.00	$94,549.00
Stucco installation labor, basic	$ 22,194.00	$53,007.00	$22,710.00	$54,283.00	$23,127.00	$55,235.00	$25,140.00	$60,043.00	$29,584.00	$70,656.00	$27,620.00	$65,965.00	$27,620.00	$65,965.00	$35,108.00	$83,849.00
Stucco installation job supplies	$ 3,803.00	$ 4,326.00	$ 3,816.00	$ 4,340.00	$ 3,825.00	$ 4,351.00	$ 3,873.00	$ 4,405.00	$ 3,978.00	$ 4,525.00	$ 3,931.00	$ 4,472.00	$ 3,931.00	$ 4,472.00	$ 4,108.00	$ 4,673.00
Option: remove siding	$ 3,721.00	$ 8,887.00	$ 3,807.00	$ 9,093.00	$ 3,877.00	$ 9,260.00	$ 4,215.00	$10,066.00	$ 4,960.00	$11,846.00	$ 4,631.00	$11,059.00	$ 4,631.00	$11,059.00	$ 5,886.00	$14,058.00
Stucco debris details	$ 4,074.00	$ 4,635.00	$ 4,087.00	$ 4,650.00	$ 4,098.00	$ 4,662.00	$ 4,149.00	$ 4,720.00	$ 4,261.00	$ 4,848.00	$ 4,212.00	$ 4,791.00	$ 4,212.00	$ 4,791.00	$ 4,401.00	$ 5,006.00
Stucco installed cost	$ 9.69	$ 15.84	$ 9.77	$ 16.02	$ 9.84	$ 16.16	$ 10.16	$ 16.84	$ 10.88	$ 18.34	$ 10.56	$ 17.68	$ 10.56	$ 17.68	$ 11.77	$ 20.21
retrofit and stucco finish	$ 15.16	$ 22.11	$ 15.27	$ 22.34	$ 15.36	$ 22.51	$ 15.79	$ 23.38	$ 16.76	$ 25.29	$ 16.52	$ 24.44	$ 16.52	$ 24.44	$ 17.94	$ 27.66
Coverage, ft2	1000															
	33101		77001		30301		21201		60601		55401		55801		99701	
housewrap	Miami, FL		Houston, TX		Atlanta, GA		Baltimore, MD		Chicago, IL		Minneapolis, MN		Duluth, MN		Fairbanks, AK	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
material	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60
labor	$ 909.89	$ 1,203.60	$ 931.03	$ 1,231.56	$ 948.14	$ 1,254.19	$ 1,030.67	$ 1,363.37	$ 1,218.85	$ 1,605.35	$ 1,323.33	$ 1,497.84	$ 1,323.33	$ 1,497.84	$ 1,439.32	$ 1,903.62
supplies tools	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30
labor rate $/sf	$ 0.91	$ 1.20	$ 0.93	$ 1.23	$ 0.95	$ 1.25	$ 1.03	$ 1.36	$ 1.22	$ 1.61	$ 1.32	$ 1.50	$ 1.32	$ 1.50	$ 1.44	$ 1.90
Coverage, ft2	4000															
	33101		77001		30301		21201		60601		55401		55801		99701	
spray foam	Miami, FL		Houston, TX		Atlanta, GA		Baltimore, MD		Chicago, IL		Minneapolis, MN		Duluth, MN		Fairbanks, AK	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
labor	$ 1,233.34	$ 3,278.05	$ 1,261.99	$ 3,354.20	$ 1,285.18	$ 3,415.85	$ 1,397.06	$ 3,713.19	$ 1,644.00	$ 4,369.53	$ 1,534.85	$ 4,079.43	$ 1,534.85	$ 4,079.43	$ 1,950.97	$ 5,185.41
labor rate $/sf	$ 0.31	$ 0.82	$ 0.32	$ 0.84	$ 0.32	$ 0.85	$ 0.35	$ 0.93	$ 0.41	$ 1.09	$ 0.38	$ 1.02	$ 0.38	$ 1.02	$ 0.49	$ 1.30

Table 8. Cost assessment of the installation of an inflatable retrofit system with vinyl siding applied as separate step.

	33101		77001		30301		21201		60601		55401		55801		99701	
	Miami, FL		Houston, TX		Atlanta, GA		Baltimore, MD		Chicago, IL		Minneapolis, MN		Duluth, MN		Fairbanks, AK	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
retrofit material	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60	$ 0.60
retrofit manufacturing	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70	$ 1.70
retrofit insulation	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95	$ 1.95
retrofit on site assembly	$ 1.22	$ 2.02	$ 1.25	$ 2.07	$ 1.27	$ 2.11	$ 1.38	$ 2.29	$ 1.63	$ 2.70	$ 1.71	$ 2.52	$ 1.71	$ 2.52	$ 1.93	$ 3.20
retrofit installed cost	$ 5.47	$ 6.27	$ 5.50	$ 6.32	$ 5.52	$ 6.36	$ 5.63	$ 6.54	$ 5.88	$ 6.95	$ 5.96	$ 6.77	$ 5.96	$ 6.77	$ 6.18	$ 7.45
Vinyl siding cost	$ 27,382.00	$37,978.00	$27,469.00	$38,099.00	$27,540.00	$38,197.00	$27,882.00	$38,671.00	$28,636.00	$39,717.00	$28,303.00	$39,255.00	$28,303.00	$39,255.00	$29,574.00	$41,018.00
Vinyl siding installation labor, basic	$ 20,297.00	$48,476.00	$20,769.00	$49,602.00	$21,150.00	$50,514.00	$22,992.00	$54,911.00	$27,055.00	$64,617.00	$25,259.00	$60,327.00	$25,259.00	$60,327.00	$32,107.00	$76,682.00
Vinyl siding installation job supplies	$ 3,977.00	$ 4,524.00	$ 3,990.00	$ 4,539.00	$ 4,000.00	$ 4,550.00	$ 4,050.00	$ 4,607.00	$ 4,159.00	$ 4,731.00	$ 4,111.00	$ 4,676.00	$ 4,111.00	$ 4,676.00	$ 4,295.00	$ 4,886.00
Vinyl siding installation equip allowance	$ 54.00	$ 77.00	$ 54.00	$ 77.00	$ 54.00	$ 78.00	$ 55.00	$ 79.00	$ 56.00	$ 81.00	$ 55.00	$ 80.00	$ 55.00	$ 80.00	$ 58.00	$ 83.00
Option: remove siding	$ 3,721.00	$ 8,887.00	$ 3,807.00	$ 9,093.00	$ 3,877.00	$ 9,260.00	$ 4,215.00	$10,066.00	$ 4,960.00	$11,846.00	$ 4,631.00	$11,059.00	$ 4,631.00	$11,059.00	$ 5,886.00	$14,058.00
Vinyl siding debris details	$ 4,074.00	$ 4,635.00	$ 4,087.00	$ 4,650.00	$ 4,098.00	$ 4,662.00	$ 4,149.00	$ 4,720.00	$ 4,261.00	$ 4,848.00	$ 4,212.00	$ 4,791.00	$ 4,212.00	$ 4,791.00	$ 4,401.00	$ 5,006.00
Vinyl siding installed cost	$ 5.95	$ 10.46	$ 6.02	$ 10.61	$ 6.07	$ 10.73	$ 6.33	$ 11.31	$ 6.91	$ 12.58	$ 6.66	$ 12.02	$ 6.66	$ 12.02	$ 7.63	$ 14.17
retrofit and vinyl siding finish	$ 11.42	$ 16.73	$ 11.51	$ 16.93	$ 11.59	$ 17.08	$ 11.96	$ 17.85	$ 12.79	$ 19.53	$ 12.61	$ 18.79	$ 12.61	$ 18.79	$ 13.81	$ 21.62
Coverage, ft2	1000															
	33101		77001		30301		21201		60601		55401		55801		99701	
housewrap	Miami, FL		Houston, TX		Atlanta, GA		Baltimore, MD		Chicago, IL		Minneapolis, MN		Duluth, MN		Fairbanks, AK	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
material	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60	$ 165.70	$ 203.60
labor	$ 909.89	$ 1,203.60	$ 931.03	$ 1,231.56	$ 948.14	$ 1,254.19	$ 1,030.67	$ 1,363.37	$ 1,218.85	$ 1,605.35	$ 1,323.33	$ 1,497.84	$ 1,323.33	$ 1,497.84	$ 1,439.32	$ 1,903.62
supplies tools	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30	$ 179.60	$ 204.30
labor rate $/sf	$ 0.91	$ 1.20	$ 0.93	$ 1.23	$ 0.95	$ 1.25	$ 1.03	$ 1.36	$ 1.22	$ 1.61	$ 1.32	$ 1.50	$ 1.32	$ 1.50	$ 1.44	$ 1.90
Coverage, ft2	4000															
	33101		77001		30301		21201		60601		55401		55801		99701	
spray foam	Miami, FL		Houston, TX		Atlanta, GA		Baltimore, MD		Chicago, IL		Minneapolis, MN		Duluth, MN		Fairbanks, AK	
	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high
labor	$ 1,233.34	$ 3,278.05	$ 1,261.99	$ 3,354.20	$ 1,285.18	$ 3,415.85	$ 1,397.06	$ 3,713.19	$ 1,644.00	$ 4,369.53	$ 1,534.85	$ 4,079.43	$ 1,534.85	$ 4,079.43	$ 1,950.97	$ 5,185.41
labor rate $/sf	$ 0.31	$ 0.82	$ 0.32	$ 0.84	$ 0.32	$ 0.85	$ 0.35	$ 0.93	$ 0.41	$ 1.09	$ 0.38	$ 1.02	$ 0.38	$ 1.02	$ 0.49	$ 1.30

9. SUMMARY

A novel approach for retrofitting older structures has been demonstrated. The advantages are cost and flexibility to accommodate different building typologies. The current limitations are related to finishing. It's certainly amenable to stucco type finishes and several of the layers to receive stucco can be integrated into the inflatable element thereby lowering cost. Despite these advantages, the application of stucco finishes remains labor intensive and the higher cost option. One possibility is to apply the stucco finish using automated methods such as some the approaches used, or demonstrations used to apply spray foam insulation. In fact, Energiesprong has demonstrated the feasibility of automated methods to apply finishes to building facades. This approach certainly has the potential to reduce cost. The installed cost will certainly depend on the insulation value. The higher the insulation value, the higher the material cost. At an insulation value of R 20, the installed cost is in the range of $11 to $28 per square foot depending on location and cladding material. Additional work with respect to integration with details also needs to be addressed. This work demonstrated, to a limited degree, that the approach is amenable to integration but did not demonstrate examples beyond the installation adjacent to the edge of window. In aggregate, feasibility of an inflatable retrofit system filled with polymer foam insulation was demonstrated and the flexibility over conventional exterior insulation approaches was highlighted. Customization of the inflatable retrofit system to accommodate a variety of building typologies and deliver exterior insulation with minimal labor are certainly advantages. The next step is to develop the ancillary elements to integrate the system with doors, windows, and service penetrations and to demonstrate installation on larger structures to better understand and quantify the benefits with respect to labor compared to the application of exterior insulation on site or the installation of prefabricated cladding systems.

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