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High Impact Project: Support of Standards Development–Dense-pack Airflow Resistance, Final Research Report

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Christopher Schumacher

Abstract:

Historically, weatherization programs have required that cellulose insulation materials be dense-packed to a minimum installed density of 3.5 pcf. This density limit was, in part, required to realize beneficial reductions in air leakage. The Building Performance Institute (BPI) currently has under development two standards that will set requirements for the airflow resistance of insulations used in retrofit cavity (i.e. dense-pack) installations (BPI-102) and define acceptable test methods to measure the airflow resistance of insulation materials used in dense-pack applications (BPI-103).

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

11.4.2 High Impact Project
Support of Standards Development: Dense-pack Airflow Resistance, Final Research Report

C. J. Schumacher
Building Science Corporation

November 2011

Building America
U.S. Department of Energy

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Definitions

BA	Building America Program. More information about BA can be found at www.buildingamerica.gov
BPI	Building Performance Institute
BSC	Building Science Corporation. More information about BSC can be found at www.buildingscience.com
CIMA	Cellulose Insulation Manufacturer's Association
DOE	U.S. Department of Energy
EDU	Energy Design Update
HEM	Home Energy Magazine
IECC	International Energy Conservation Code. More information can be found at http://www.energycodes.gov/
NAIMA	North American Insulation Manufacturer's Association
RH	Relative humidity
WAP	Weatherization Assistance Program

Abstract

This document reports on work undertaken for Building America in 2011 as part of BSC Task 11.4.

Historically, weatherization programs have required that cellulose insulation materials be dense-packed to a minimum installed density of 3.5 pcf. This density limit was, in part, required to realize beneficial reductions in air leakage. The Building Performance Institute (BPI) currently has under development two standards that will set requirements for the airflow resistance of insulations used in retrofit cavity (i.e. dense-pack) installations (BPI-102) and define acceptable test methods to measure the airflow resistance of insulation materials used in dense-pack applications (BPI-103).

An experimental apparatus and test method were developed for the purpose of measuring the airflow resistance of dense-packed fiber insulation installed as a retrofit to empty wood-frame wall cavities. The resulting apparatus and method will form the basis of the proposed BPI-103 test standard.

The use of the apparatus and application of the test method have been demonstrated through testing of over 30 test wall specimens that were prepared using cellulose materials from 10 different insulation manufacturers.

Dense-packed cellulose insulation, installed to densities of 3.5 pcf and higher, was shown to provide a significant resistance to airflow. On the basis of the limited data available, we would expect these installations to result in an airflow resistance of 0.33 cfm50/ft^2 in the long path test and 1.0 cfm50/ft^2 in the short path test.

Recommendations are made for further testing to demonstrate reproducibility of the test apparatus & method, to expand the data set available for setting material standards, and to further explore parameters that influence airflow through dens-packed insulation materials.

1 Introduction and Background

1.1 Introduction

Since the beginnings of weatherization, blown loose fill insulations have been added to stud and rafter cavities to improve the thermal performance of wall and roof assemblies. Pioneers of the weatherization movement developed insertion tube methods to prevent insulation voids and ensure that cavities were completely filled with higher densities of cellulose insulation. Fitzgerald, Nelson & Shen provided one of the earliest explanations of the dense-pack insulation technique in an article for the January 1990 Home Energy Magazine (HEM 1990).

The U.S. Department of Energy's (DOE) Weatherization Assistance Program (WAP) and many state-run weatherization programs have since adopted the technique, advocating the use of cellulose insulation, dense-packed to a minimum of 3.5 pcf, to improve thermal performance by reducing both conductive heat loss and air leakage through wall and roof assemblies. However, two recent developments have raised questions about this practice. First, the required use of cellulose insulation has been questioned; alternative fibrous insulation materials (e.g. fiberglass) have recently been developed specifically for use in dense-pack applications. Second, the minimum density of 3.5 pcf has been questioned; insulation manufacturers and building scientists have pointed out that the term dense-pack has no real meaning or definition.

1.2 Background

Jacobson, Harrje & Dutt conducted some of the earliest organized research on the airflow resistance of cellulose-insulated assemblies in 1984 (EDU 1986).

In a January 1990 Home Energy Magazine article, Fitzgerald, Nelson & Shen reported pre- and post-retrofit blower door test results for four houses that were retrofit using *only* dense-pack cellulose insulation: air leakage rates (i.e. cfm50) were reduced by at least 39.6% and as much as 54% (HEM 1990).

The industry is currently working towards the development of standards to set the maximum allowable air permeance for dense-pack insulations of all types (e.g. cellulose, glass fiber, mineral fiber, etc.) and to establish the requirements for measuring the air permeance these materials. These efforts will provide better understanding and regulation of the material properties and methods necessary to ensure adequate energy performance.

1.3 Scope of this Work

This report describes the development of an apparatus and test method that will form the basis for test standard, BPI-103 and inform material standards BPI-102.

An experimental program was established to demonstrate the use of the apparatus and application of the test method through testing of over 30 test wall specimens prepared using cellulose materials from 10 different insulation manufacturers. This work will inform future round robin testing and the final BPI-103 standard.

Finally, it is a goal of this work to estimate the airflow resistance of a generic cellulose insulation material that is dense-packed to 3.5 pcf. This scenario represents most dense-pack applications implemented over the last three decades. The estimates will inform the final BPI-102 standard.

2 Experimental Apparatus & Method

This section of the report describes the experimental apparatus and method that were developed to measure the airflow resistance of dense-packed fiber insulation when installed as a retrofit to empty wood-frame wall cavities. Fabrication details of the test apparatus are provided, along with manufacturer names and model numbers of the components used to construct the test apparatus that was employed in the testing undertaken for this BA task. Recommendations are made for minimum equipment requirements for future testing work.

2.1 Apparatus

The necessary apparatus equipment can be divided into three groups:

- The empty test wall assembly
- Equipment for preparing the test specimen
- Equipment for measuring the airflow resistance

Each of these is explained in great detail in the sections that follow.

2.1.1 Test Wall Assembly

The test wall assembly is designed to be representative of typical uninsulated wood-frame wall assemblies that are encountered in retrofit and weatherization work in all regions of the United States. The assembly, pictured in Figure 1, comprises three full-height 2x4 stud bays that each have inside (i.e. clear) dimensions of 14.5 in. wide x 94 in. high.

Figure 1 – Empty Test Wall Assembly as seen from front (left image) and back (right image)

The test wall assembly can be separated into two pieces: the ‘front panel’ and the ‘back panel’. Eight (8) under-center draw latches (around the perimeter) and fourteen (14) wing nuts (in the field) secure the back panel to the front panel. The latches and wing nuts can be quickly and easily opened to permit the removal of insulation and cleaning of the test wall assembly between tests.

Front Panel

The front includes the 2x4 @ 16 in. O/C wood stud wall frame. It is finished with ¼ in. thick polycarbonate plastic sheets (one upper & one lower) and a built-up plywood flange (located at mid-height). The flange and both of the plastic sheets are fixed & sealed to the wood studs to form the ‘front panel’. Two (2) 36 in. long 2x4 and plywood feet, visible in Figure 2, are attached at the bottom of the front panel to stand the test wall assembly vertical and prevent it from tipping over during use.

Nine (9) 2.5 in. dia. install holes were drilled through the polycarbonate sheets to permit various options for installing the insulation in the test wall assembly. Three holes (1 in each studspace) are located at the ‘lower’ position, 24 in. up from the bottom of the front panel; three are located at the ‘upper’ position, 24 in. down from the top of the panel; and three are located at the ‘top’ position, 6 in. down from the top of the panel. The nine install holes can be seen in the photograph of Figure 2.

Figure 2 – Install Holes in Front Panel as seen from back (with Back Panel removed)

The transparent polycarbonate sheets allow the installer to see the progress of the dense-packing. Stakeholders debated the use of the polycarbonate sheet during development of the apparatus and methodology for preparing test specimens. Installers would not have the advantage of a see-through wall assembly in the field; however, researchers from the glass fiber and cellulose industries both agreed that it was a desirable feature for the wall test assembly as it would permit the identification of problem samples prior to testing, thus saving precious laboratory time.

Each polycarbonate sheet is fixed to the stud frame with forty two (42) No. 8 x 1-1/2 in. wood screws around the perimeter and four (4) No. 8 x 2 in. wood screws in the field. Two 1/16 in. thick washers were installed as spacers on the four screws in the field to create a 1/8 in. high gap between the polycarbonate sheet and the wood frame as pictured in the right image of Figure 3. This controlled and repeatable gap is intended to be representative of the gaps between the wood framing and sheathing commonly found in existing wall assemblies. The gap plays a critical role in the preparation of the test specimen as it allows air to move between one studspace and the next when the wall is pressurized by the fiber moving equipment.

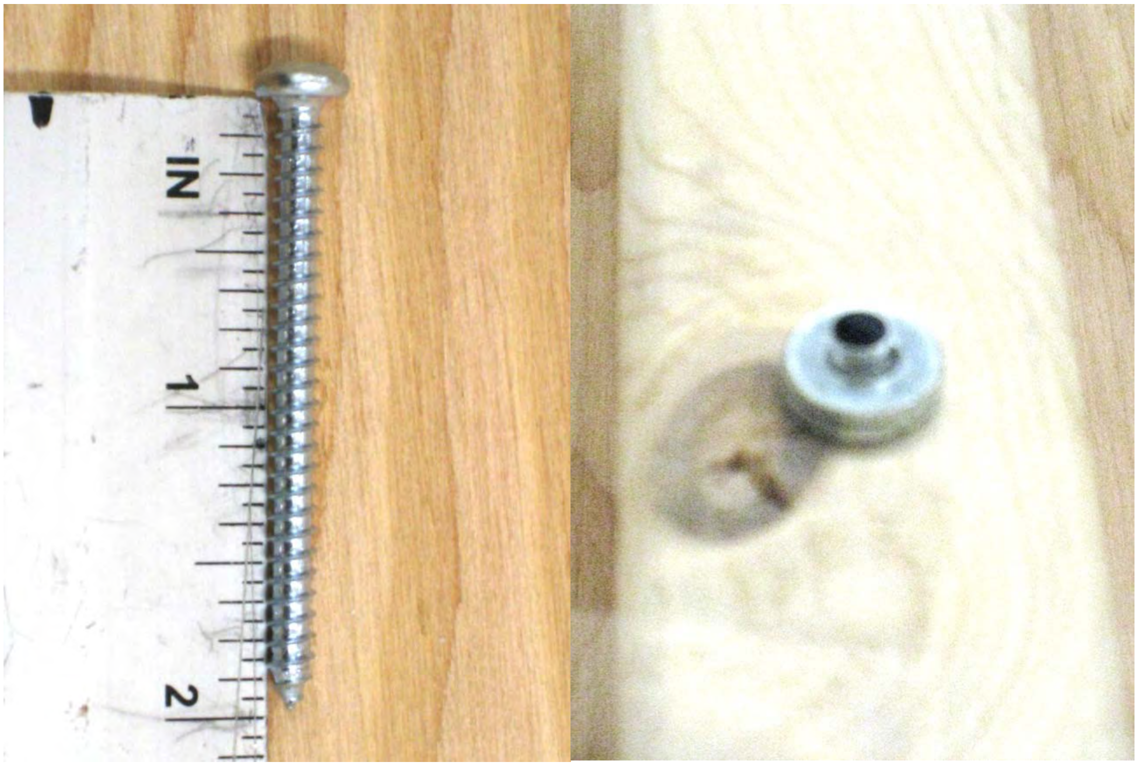


Figure 3 – No. 8 x 2" wood screw (left) and two 1/16" washers (right) to fix and gap plastic sheet

The gap between the polycarbonate and the frame is maintained at the perimeter of through the use of a ½ in. wide x 1/8 in. thick closed-cell foam gasket. The gasket, visible in Figure 4, also provides backup for a wet sealed joint that prevents air leakage between the perimeter of the polycarbonate sheet and the wood frame.

The built-up plywood flange serves two functions: first it provides structural support for and seal to the air pressure manifold that gets attached to the test wall assembly during the airflow measurement portion of the test; second, the manifold permits the installation of custom air outlet orifices. A 1 in. wide slot, visible in Figure 5, was used for the testing undertaken in this BA task. The inside of the slot was finished with a 1/8 x 1/8 in. plastic screen.

Figure 4 – Closed-cell foam gasket & wet seal around perimeter of polycarbonate sheet

Figure 5 – Exit orifice plate with 1" wide slot opening

In the case of our test wall assembly, the flange is built-up using two layers of ¾ in. thick plywood with perpendicular inset blocks to support keepers (visible in Figure 6) for under-center draw latches. A two-stage closed-cell foam gasket provides the seal between the flange on the test wall assembly and a similar flange on the air pressure manifold.

Alternate flange assemblies (e.g. welded metal or plastic) could be employed in future test wall assemblies provided that they:

- Can be made planar
- Create a repeatable, airtight seal
- Remain dimensionally stable

Figure 6 – Built-up plywood flange showing inset block, keeper and two-stage foam gasket

The flange is fixed to the frame using twelve (12) No. 10 x 3 in. wood screws attached through a continuous bead of sealant to prevent air leakage between the flange and the frame. Initial tests revealed a small amount of air leakage through the edge of the plywood flange (i.e. between the plys). A heavy polymer roofing paint was applied to the perimeter of the flange to seal the minute joints and eliminate this air leakage.

Figure 7 – Air seal coating applied to perimeter of flange

Back Panel

The back of the panel comprises a ½ in. thick plywood sheet with a built-up lumber & plywood frame. Figure 8 shows a photograph of the back panel as seen from the front side (i.e. the side that faces the studspace).

Figure 8 – Back Panel as seen from the front side

Twelve (12) sets of ½ in. dia. air inlet orifice holes were drilled through the plywood sheet to facilitate 'long' and 'short' flow path tests. The long flow path inlet holes are located 2-3/4 in. from the top and bottom edges of the panel (i.e. 45-1/4 in. above and below the air outlet orifice); the short flow path inlet holes are located 32 in. from the top and bottom edges of the panel (i.e. 16 in. above and below the air outlet orifice).

Each set of air inlet orifice holes comprises twenty-one (21) ½ in. dia. holes, arranged in one row of ten (10) and one row of eleven (11). The hole pattern is set up so that there is a 1 in. center to center spacing between all holes. A template, pictured in Figure 9, was used to ensure that each set of holes had the same pattern.

The twenty-one-hole pattern was selected to provide a means of controlling the air leakage rate of the empty wall. Researchers can seal and leave open various numbers of holes to study the relationships between empty wall tightness, ease of material installation, machine settings, etc.

The inside of each set of holes was finished a piece of 1/8 x 1/8 in. plastic screen. The screens, visible in Figure 8, were stapled at ½ in. spacing and taped around the perimeter with a durable industrial tape that has a thick adhesive layer (e.g. Gorilla Tape ®).

Figure 9 – Air inlet orifice hole template

The outside of each set of holes is finished with a piece of polycarbonate that is wet sealed and screwed to the back of the plywood sheet as pictured in left image of Figure 10. This plastic sheet was added to reduce background leakage identified during commissioning tests. The smooth and durable surface of the polycarbonate permits easy, effective and repeatable air seals using a quality painter's masking tape (e.g. 3M ScotchBlue ™ Painter's Tape 2090) as seen in the right image of Figure 10.

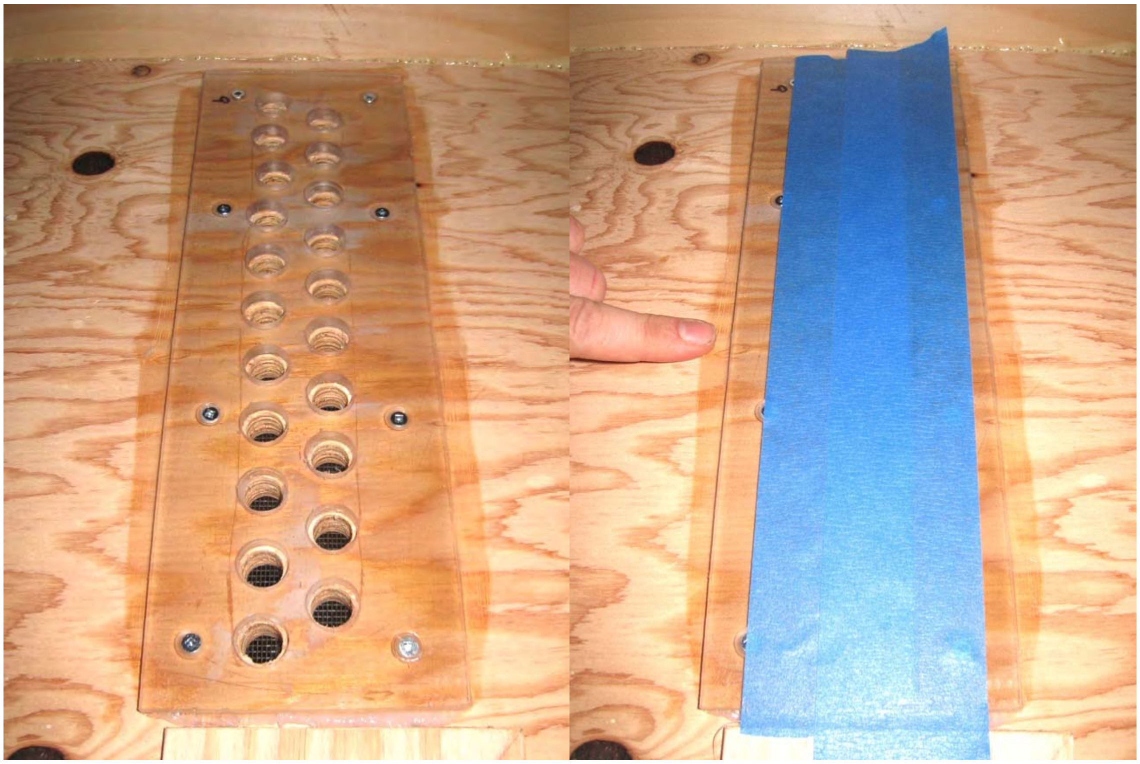


Figure 10 – Polycarbonate faceplate over air inlet orifice holes (left) and tape air seal (right)

Commissioning tests revealed a small amount of leakage through the edge of the plywood sheet at the top & bottom of the back panel. These leaks were flowing through to short (i.e. 4 in.), small diameter flow paths that ran parallel with the wood plys between the top (and bottom) set of air inlet orifice holes and the top (and bottom) edge of the plywood. The leakage path was similar to that that was identified through the edge of the flange. The edges of the plywood were sealed with the same heavy polymer roofing paint that was used to seal the flange (Figure 11).

Figure 11 – Air seal coating applied to top & bottom edge of plywood on back panel

The back panel is attached to the front panel to close and complete the test wall assembly. Eight under-center draw latches (e.g. Southco® part no. 91-812-52), mounted on the outside of the front panel stud frame (3 each side, 1 top & 1 bottom), pull on 'keepers' or catch plates that are mounted on the back panel frame as pictured in Figure 12.

Figure 12 – Under-center draw latch and keeper (i.e. catch plate) at perimeter of panels (typ. of 8)

A 1/8 in. thick x 1 in. wide closed-cell foam gasket was installed around the perimeter of the wood stud frame to create an airseal between the front and the back panels. Background leakage tests indicated that small air leaks occurred between tiny gaps between the foam gasket and the fine grain of the plywood. Industrial tape was installed around the perimeter of the plywood on the back panel, as pictured in Figure 13, to improve the airseal. The tape's thick adhesive layer filled the gaps in the grain of the plywood while the smooth face on the top side of the tape ensured a good sealed with the foam gasket.

Figure 13 – Tape edge around back panel perimeter for airtight seal to foam gasket on front panel

The force from the under-center draw latches is transmitted through the back panel frame so that is applied uniformly around the perimeter. In contrast, pressure is applied at discrete locations in the field of the panel.

Fourteen wing nuts secure the back panel through 1/8 in. x 2 in. hanger bolts (e.g. Spaenaur part no. 034-010) to the wood stud frame of the front panel. Figure 14 shows the hanger bolts, which have a wood screw thread on the end that is installed in the wood studs and a machine screw thread on the end that receives the wing nut. Fender washers and ¼ in. thick plywood bearing plates, pictured in Figure 15, distribute the load of the bolt to minimize the potential for damage to the plywood in the event that the assembly is over pressurized during installation of the insulation material.

Figure 14 – Hanger bolt, washer & wing nut for attaching back panel to front panel frame

A 1/16 in. thick washer and a tapered, sleeved rubber bushing (e.g. Spaenaur part no. 315-598) were installed on each hanger bolt as pictured in Figure 16. Together, the washer and bushing create a 1/8 in. thick gap between the wood stud frame and the plywood sheet. The rubber bushing also ensures a good airseal between the bolt and the plywood.

Figure 15 – Wing nut, washer and bearing plate in the field of the back panel (typ. of 14)

Figure 16 – 1/16" thick washer and tapered, sleeved rubber bushing to gap & seal plywood sheet

Alternate back panel constructions (e.g. plastic sheet with aluminum frame) could be used for future tests provided that they:

- Employ the same air inlet orifice hole pattern & locations
- Are of sufficient stiffness to limit deflections to less than 1/16 in. when the insulation is installed

A complete test wall assembly will typically weigh 200-250 lb. when empty and 300-350 lb. when dense-packed with insulation.

2.1.2 Equipment for Preparing Test Specimens

Test specimens should be prepared using the same manufacturer- and industry-approved equipment and techniques as those employed in the field. The Building Performance Institute (BPI) offers training courses and certifies individuals in the installation of dense-packed insulation. The BPI recommended equipment and techniques represent current industry best practice and were used as the basis for the testing undertaken for this BA task.

Preparation of the test specimens requires a fiber-moving machine, hoses & insertion tubes for installing the insulation in the test wall assembly; a calibration box & electronic scale for establishing the appropriate settings for the fiber moving equipment; and a wall balance or load cell for measuring the mass of the installed insulation.

Fiber-Moving Machine

The BPI certification course sets following requirements for the fiber-moving machine:

1. Portable electric airlock machine with 1 or 2 blower fans described as 2-stage or 3-stage
2. Listed for use with all fibers
3. Air control that can be operated independently from feed + air
4. Blower / airlock pressure listed above required minimum test pressure of 2.9 psi or 80 inches W.C.

A Krendl Model 450A All-Fiber Machine, pictured in Figure 17, was used to prepare the cellulose fiber wall specimens that were tested in this BA task. The machine met and exceeded the aforementioned requirements.

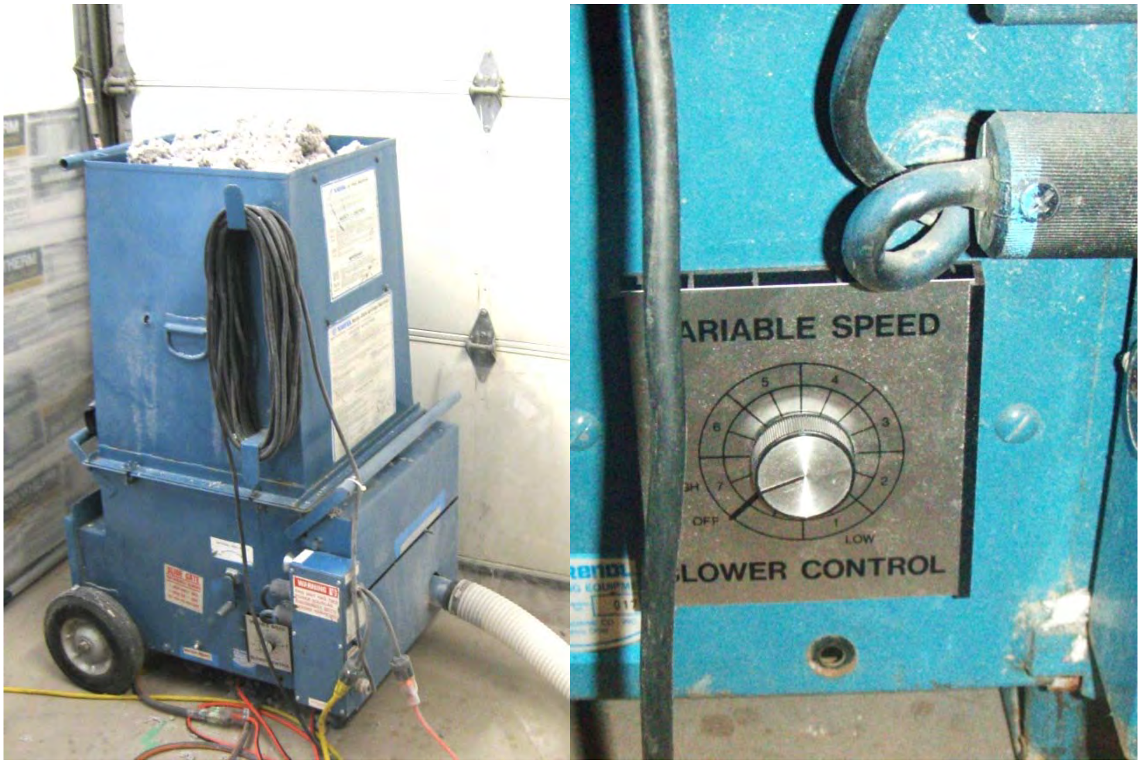


Figure 17 – Krendl 450A All-Fiber Machine (left) with variable speed blower control (right)

Hoses and Insertion Tubes

The BPI certification course sets following requirements for hoses and insertion tubes:

1. Provide 150 feet of blowing hose with no more than 50 ft. of 3” with smooth transitions to a 2.5” section and a final section of 2” diameter ribbed hose to a
2. 2” x 1.25” ID reducer and 8’ length of insertion tube with curl/memory removed by heat, angled tip
3. Insertion tube length from the tip marked in 1ft increments on the tube to show blocker location or end of cavity.

For the purposes of our testing, we used 150 ft. of blowing hose and an 8 ft. long insertion tube. A 50 ft. length of 3 in. dia. ribbed wall polyethylene hose (e.g. Mark II ™ Hose, J&R Products Inc. part no. MK-2550) was attached to the airlock outlet of the fiber-moving machine as visible in Figure 18. A 3 in. to 2-1/2 in. steel reducer connection (e.g. J&R Products part no. RC-325) was then used to transition from the 3 in. dia. hose to 100 ft. (2 x 50 ft.) of 2-1/2 in. dia. ribbed wall polyethylene hose (e.g. J&R Products part no. MK-2050). The hoses were coiled in a figure 8 to encourage the conditioning of the fibers as they moved from the machine to the insertion tube. The figure 8 coil was suspended from a mezzanine, as depicted in Figure 19, to reduce trip hazards and free up floor space in the testing area.

Figure 18 – 3" dia. ribbed hose attached to outlet of the Krendl 450A

Figure 19 – 50 ft. of 3" dia. (white) & 100 ft. of 2-1/2" dia. (green) hose suspended in a 'figure 8'

An 8 ft. long 1-1/4 in. dia. smooth-wall PVC tube (e.g. J&R products ST-125), visible in Figure 20, was used as the insertion tube. The tube was heated, as illustrated in the left image of to

Figure 21, remove the memory (i.e. the tendency to curl) that remains from the manufacturing process. The end of the tube was cut at a 45° angle, to prevent it from plugging, and it was marked at 1 ft. increments as a visual guide to insertion depth.

The transition between the insertion tube and the 2-1/2 in. dia. hose was accomplished using a 2-1/2 in. to 2 in. steel reducer (e.g. J&R Products part no. RC-252), a short section of 2 in. inside dia. hose, and a 2 in. to 1-1/4” steel reducing nozzle (e.g. J&R Products part no. RN-214), as illustrated in Figure 21. All joints were secured with steel hose clamps and covered with tape to protect installers from sharp edges.

Figure 20 – 1/1/4 in. inside dia. smooth-walled PVC insertion tube

Figure 21 – Removing insertion tube memory (left) and transitioning to the 2-1/2" hose (right)

Calibration Box

The calibration box is used to establish the fiber-moving machine settings that are necessary to achieve the desired installed material density. These settings include the blower speed (i.e. control of air pressure) and gate opening (i.e. control of material feed rate).

The calibration box is based on the BPI density test box that is illustrated in Figure 22. The density test box is one of a series of props that BPI recommends be constructed for teaching installers techniques for dense-packing insulation. The density box has volume of 2 sq. ft. and inside dimensions that are similar to those found in uninsulated stud walls.

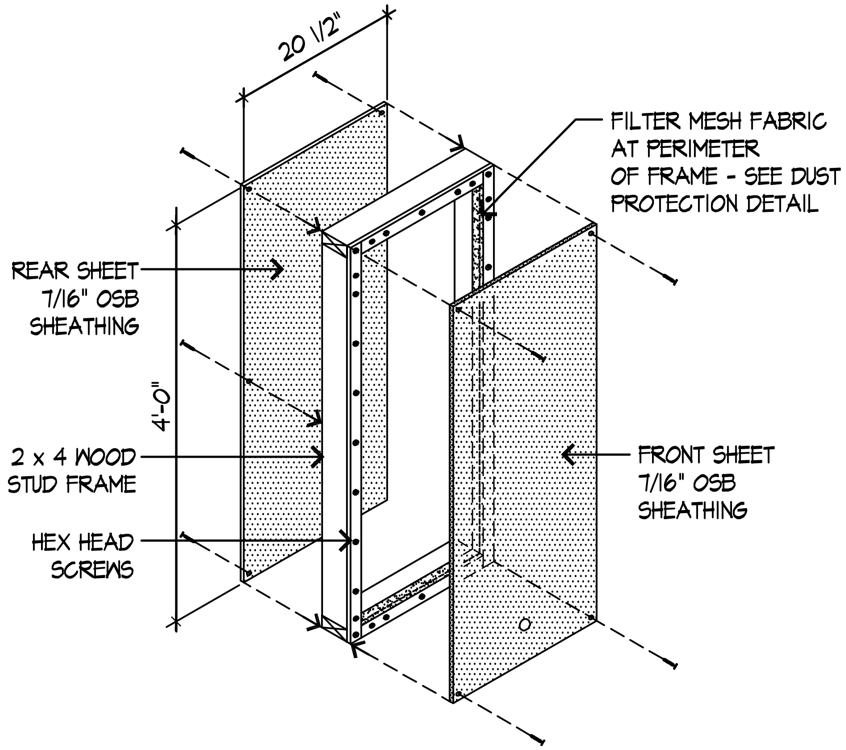


Figure 22 – Exploded Axonometric of Density Test Box (BPI, 2010)

The calibration box has the same volume and structure as the test box but differs in a number of ways:

1. A ¼ in. thick plastic front sheet in lieu of the 7/16 in. thick OSB
2. The install hole is located in the bottom of the frame rather than in the front sheet
3. The front sheet has been made into a door that is hinged on one side and fixed shut with two latches on the other side
4. A U-bolt is attached through the top of the frame to allow the calibration box to be hung on a hook at a comfortable working height for installation of the insulation

Figure 23 shows the calibration box after it has been dense-packed with cellulose insulation. In the photograph the door of the box is open to facilitate inspection and removal of the insulation material.

A completed calibration box will typically weigh around 30 lb. when empty and up to 40 lb. when dense-packed with insulation.

Figure 23 – Calibration box filled with insulation and opened for inspection and cleaning

Electronic Scale

An electronic scale is used to measure the mass of the calibration box before and after the installation is installed. The density of the insulation is easily be calculated by taking the difference between the two mass measurements and dividing by 2 (recall that the box volume is 2 cu. ft.)

A general use electronic scale is sufficient for the purposes of determining the density of the insulation installed in the calibration box. For the purposes of our calibration work, we used a Pelouze model 4010 with a maximum capacity of 150 lb. and a resolution of 0.2 lb.

Wall Balance / Load Cell

A general use electronic scale is *not* sufficient for determining the density of the insulation installed in the test wall assembly. For a nominal installed insulation density of 3.5 pcf and a desired density uncertainty of +/-1% or +/-0.035 pcf, the maximum allowable scale uncertainty must be less than +/-0.311 lb. The measurement can be made with sufficient accuracy using a quality panel meter (e.g. Omega DP41-W) and a high-accuracy 500 lb. load cell (e.g. Omega LCCA-500); however, for the purposes of our testing we have opted to use a Wall Balance.

The wall balance is a device that was developed to study the small changes in the mass of a wall that occur as the result of wetting or drying phenomena. The device, developed at the Pennsylvania State University (Schumacher et. al., 2003) and depicted in Figure 24, uses a balance and counter weight system to offset the dry or empty weight of a test wall assembly so that changes in mass can be measured with smaller capacity load cells that have much better absolute uncertainty (i.e. fractions of an ounce).

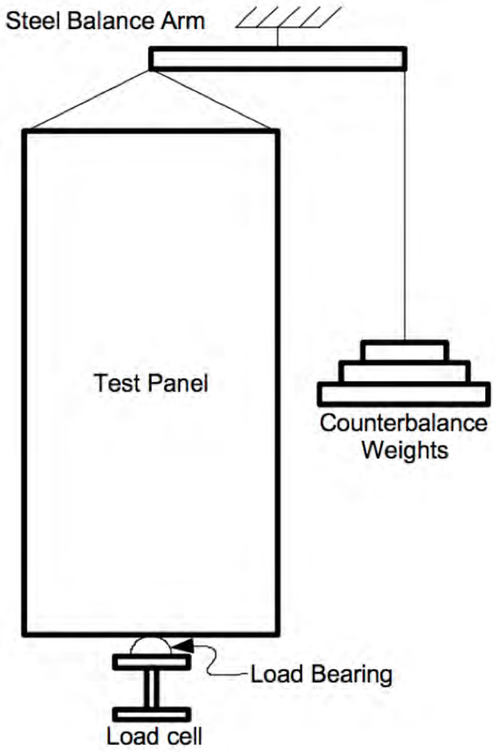


Figure 24 – Conceptual diagram of wall balance

For these tests the balance was modified to locate the load cell above the balance arm. With this modification, the test wall assembly can be lowered so that it rests on the floor. This provides better stability and puts the install holes at a working height comparable to field installations.

The density uncertainty was reduced to better than +/-0.01 pcf through the use of the wall balance device.

2.1.3 Equipment for Measuring Airflow Through Test Specimens

A variable speed fan is used to induce airflow through the test specimen. Figure 25 shows the two flow paths that are evaluated during testing: the short and long flow paths.

The fan depressurizes the wall assembly so air is drawn in through the air inlet holes in the back panel. The top & bottom inlet holes are used for long path tests while the upper & lower inlet holes are used for short path tests. The air travels through the dense-packed insulation and out of the wall assembly at the air outlet slot that is located at mid-height on the front panel. The outlet air is collected in a manifold, visible in the photo of Figure 26, and drawn through a series of flow measurement devices before travelling through the fan and being expelled to the laboratory. This arrangement maximizes the uniformity of airflow, pressures and temperatures.

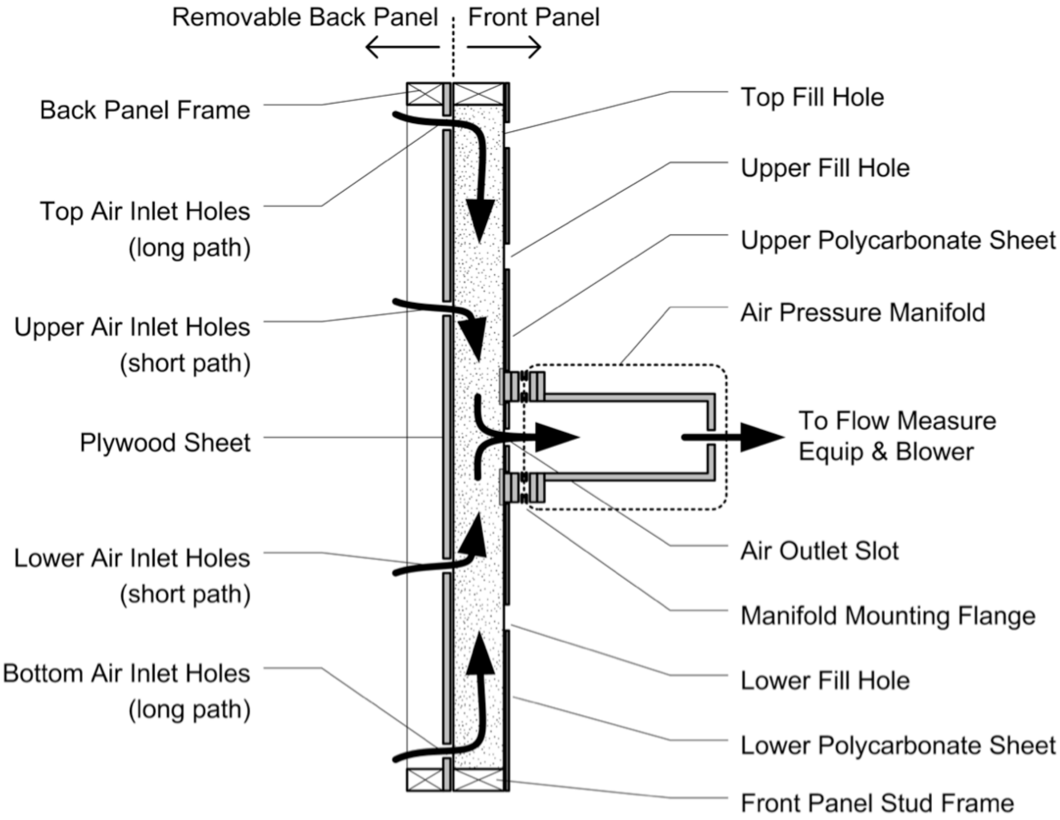


Figure 25 – Schematic of airflow paths through test wall assembly

Figure 26 – Test specimen prepared and connected to manifold for airflow testing

Air Pressure Manifold

The air pressure manifold ensures that an even pressure field is applied across the air outlet slot. The manifold, pictured in Figure 27, is a five-sided box with a heavy mounting flange on the open end. This flange matches and mates to the mounting flange on the front panel of the test wall assembly. Six (6) under-center draw latches are used to attach the manifold to the test wall assembly. The box hangs from a system of chains so it doesn't consume any floor space.

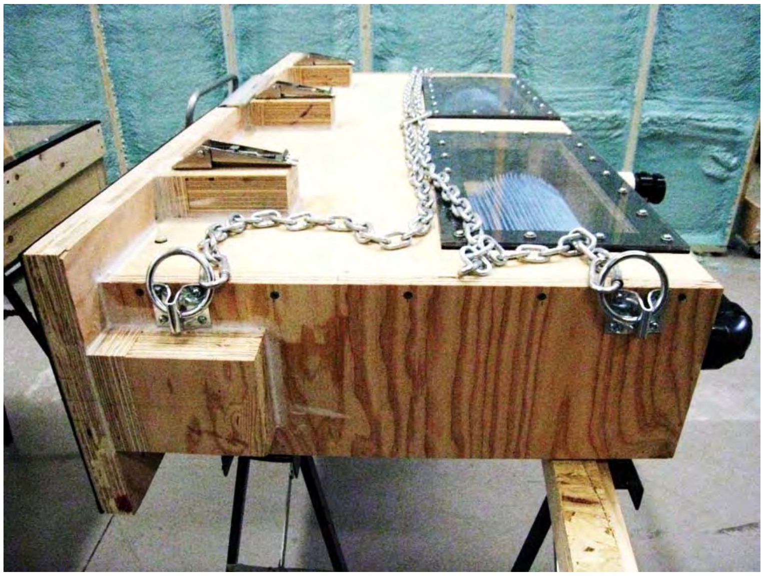


Figure 27 – Air pressure manifold (disconnected from test wall assembly)

The air pressure manifold is constructed of ¾ in. plywood. Joints are glued & screwed then air sealed inside (with silicone) and out (with tape). A stack of 3 in. wide strips of plastic signboard, visible in Figure 28, acts as a flow straightener and divides the manifold into two compartments: the outer (upstream) and inner (downstream).

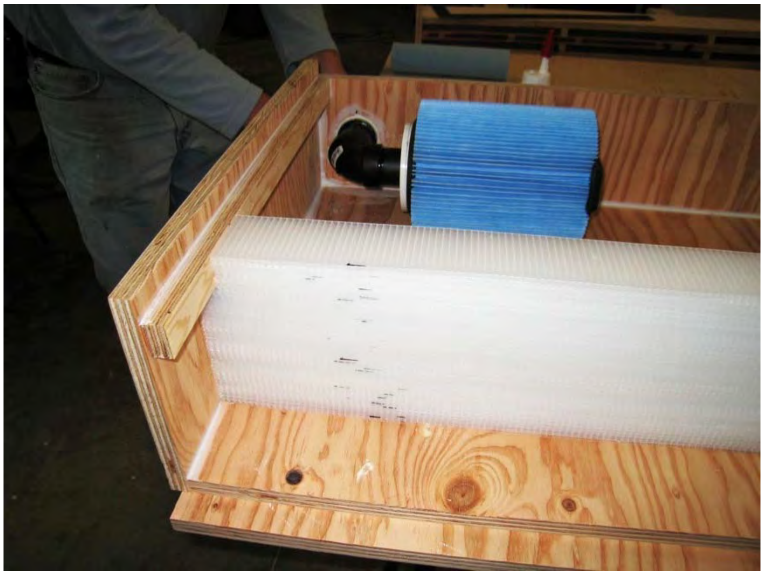


Figure 28 – Manifold shown open during construction (flow straightener and air filter visible)

The outer compartment interfaces with the wall assembly while the inner compartment houses two (2) air filters and bulkhead fittings that connect through external piping back to the fan. The air filters, visible in the left image of Figure 29, are primarily provided to protect the flow measuring equipment from insulation fibers; however, they also improve uniformity of the pressure field at the open end of the manifold. Airtight access hatches, visible near the top edge of Figure 30, facilitate cleaning of the filters.

Figure 29 – Partially completed manifold with top installed (left) and latch blocks attached (right)

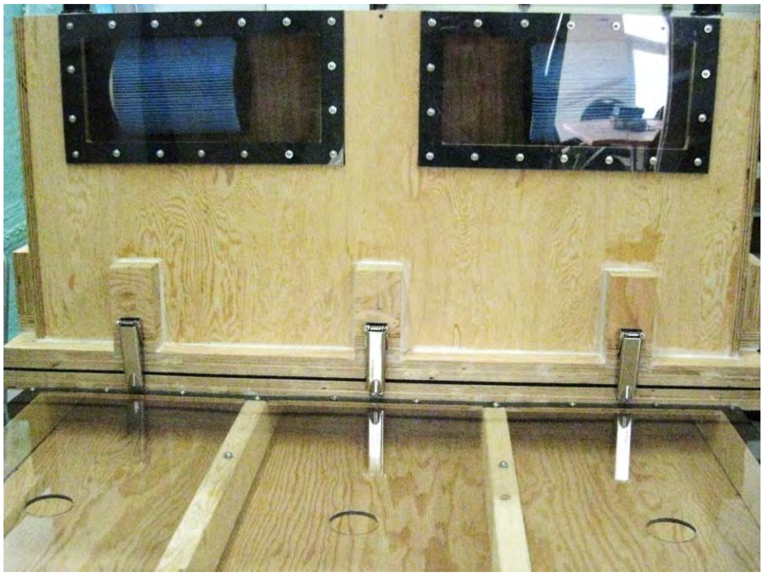


Figure 30 – Completed Manifold with mounting flange, latches and filter access hatches installed

Built-up plywood blocks were installed on the outside of the open end of the manifold, as visible in the right image of Figure 29. These blocks provide rigid support for the latches and mounting flange, visible in Figure 30, that connect the manifold to the test wall assembly.

Finally, the manifold was completed through the installation of four (4) pressure taps that facilitate measurement of the pressure field on the outside of the air outlet slot. The taps were located at 3 in. and 16 in. from the left & right sides of the box. Barbed nylon adapter fittings (e.g. 1/8 in. ID tube to ¼-18 NPT, Spaenaur part no. 210-207) were threaded and glued into the top of the manifold box as shown in Figure 31. Tubing and barbed nylon tee fittings (e.g. 1/8 ID x 1/8 ID x 1/8 ID, Spaenaur part no. 210-246) were installed as visible in Figure 32, to physically average the pressure field.

Figure 31 – Installing a pressure tap (typ. of 4) in top of manifold

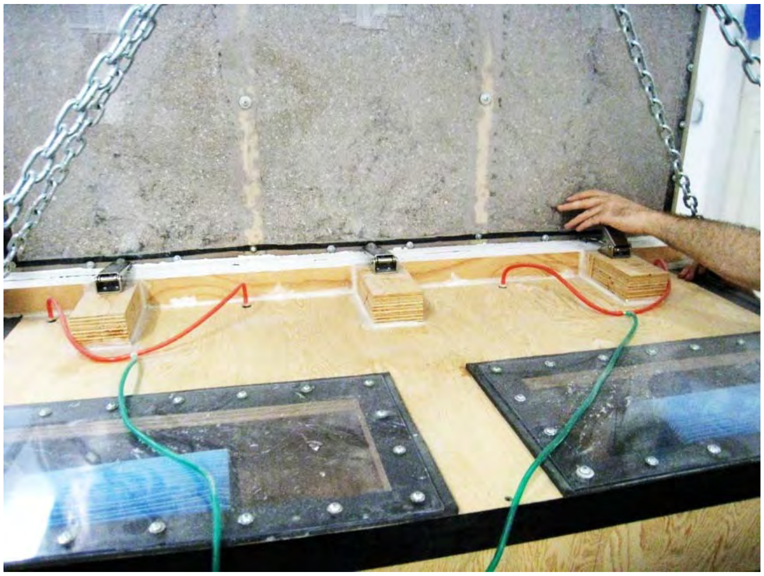


Figure 32 – Pressure tap tubing arranged to average pressure at 4 locations

Alternate manifold constructions could be developed for future testing provided they:

- Produce a uniform pressure field at the outlet slot. For the purposes of these tests a uniform pressure field is defined as a maximum tap-to-tap pressure difference of 1 Pa when a 50 Pa pressure difference is applied across a dense-packed (i.e. filled) test wall assembly
- Provide filtration of the outlet air to prevent damage to and influence on the flow measuring devices

Fan, Controls & Flow Measurement

The airflow resistance of the dense-packed test wall specimen is characterized by measuring the pressure differences that are associated with different flow rates. Several pieces of equipment are required for this activity:

1. A variable speed fan capable of producing pressures in excess of 600 Pa
2. An electronic fan control and/or bleed valve setup capable of setting and holding a steady airflow rate
3. A flow measurement device or devices capable of measuring flows in the range of 5 scfh to 30 scfm
4. A pressure measurement device or devices capable of measuring pressure differences in the range of 5 to 1000 Pa

For the testing conducted under this BA task, we used the fan and control from a CAN-BEST Model 283A200 window test kit. The kit, pictured in Figure 33, comprises a fan, an electronic fan speed control, two magnehelic gauges to measure differential pressures and a set of three (3) rotometers to measure airflow rates. The magnehelic gauges measure pressures in the range of 0 to 500 Pa with an accuracy of +/- 2% full scale. The 3 rotometers are piped in parallel to measure flows in the range of 0.33 to 23 scfm. The smallest reading possible is 20 +/- 4 scfh.

Figure 33 – CAN-BEST window test kit

The built-in magnehelic gauges and rotometers were used to measure pressures and flows in initial tests; however these were quickly replaced with other standalone devices to improve range, resolution and accuracy. An Energy Conservatory DG-700 digital pressure gauge, visible in Figure 34, was used to measure the pressure differential across the test wall assembly. This device has a measurement accuracy of +/- 1% of reading. A new set of Dwyer RMC series low-flow rotometers, visible in Figure 35, was setup to permit measurements down to 5 +/-0.6 scfh.

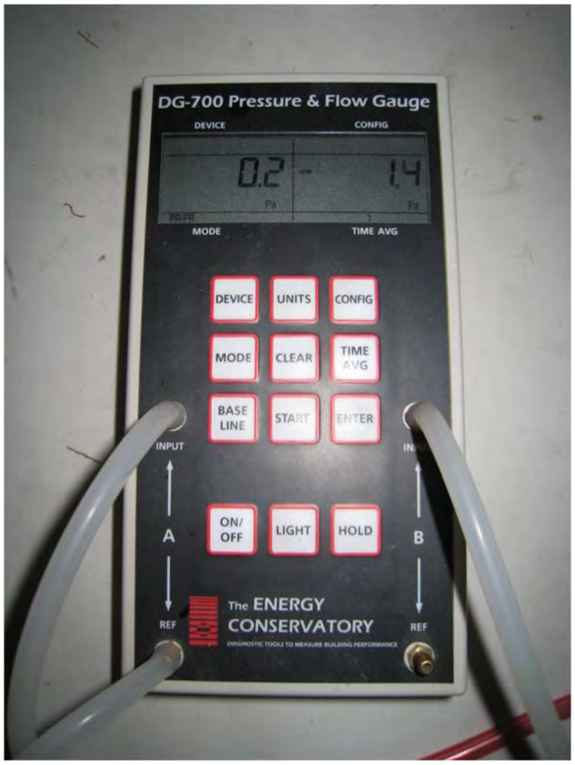


Figure 34 – DG-700 digital pressure gauge

Figure 35 – Low-flow rotometer array (0-50 scfh, 0-390 scfh & 2x 0-30 scfm)

Air Temperature, RH & Barometric Pressure

Laboratory air temperature, relative humidity and Barometric pressure were measured at the beginning of each flow measurement test. An NK Kestrel 3000 Pocket Wind meter, pictured in Figure 36, was used to measure air temperature (+/- 1.8°F) and relative humidity (+/- 3%). A Swift Scientific Model 477 barometer was used to measure Barometric pressure.

Figure 36 – Kestrel 3000 for measuring lab air temperature & relative humidity

Figure 37 – Swift Model 477 Barometer

2.2 Preparation of Test Specimens

The method for preparing the test specimens is based on techniques from the BPI contractor training materials; these reflect current industry best practice.

There are three major steps for preparing test specimens:

- Collection & documentation of the insulation material
- Establishing the machine settings
- Dense-packing the test wall assembly

These are explained in the sections that follow.

2.2.1 Collection & Documentation of the Insulation Material

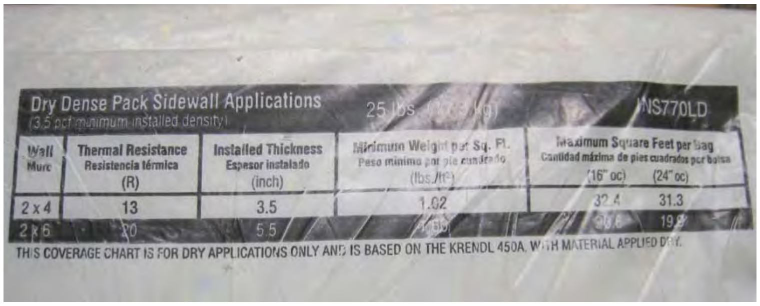
Sufficient fiber insulation material should be collected prior to beginning work in the laboratory. We recommend securing seventy pounds of material for each test wall that you intend to prepare. Some of this insulation will be used for calibrating the machine settings while some will be used to prepare the test wall specimens.

Insulation materials should also be well documented prior to beginning laboratory work. We recommend photo documentation of the at least one bag of material from each shipment or manufacturing run. Figure 38 through **Error! Reference source not found.**Figure 41 show photographs of a sample bag of cellulose insulation material. Sufficient photos are taken to capture as much information from the bag as possible.

Figure 38 – Photo of front of sample insulation bag showing manufacturer, material type & name

Figure 39 – Photo of back of sample insulation bag showing product SKU & ES report no.

Figure 40 – Photo of side of sample insulation bag showing manufacturing plant, date & time



Dry Dense Pack Sidewall Applications 25 lbs ([illegible]) NS770LD

(3.5 pcf minimum installed density)

Wall Muro	Thermal Resistance Resistencia térmica (R)	Installed Thickness Espesor instalado (inch)	Minimum Weight per Sq. Ft. Peso mínimo por pie cuadrado (lbs./ft²)	Maximum Square Feet per bag Cantidad máxima de pies cuadrados por bolsa (16" oc)	 (24" oc)
2 x 4	13	3.5	1.02	32.4	31.3
2 x 6	20	5.5	[illegible]	[illegible]	19.9

THIS COVERAGE CHART IS FOR DRY APPLICATIONS ONLY AND IS BASED ON THE KRENDL 450A, WITH MATERIAL APPLIED DRY.

Figure 41 – Photo from sample insulation bag showing close-up of dense-pack sidewall fill chart

Basic material information should also be recorded with the data sheets for the specimen preparation and testing. The left column of Table 1 presents the basic information list that was developed for the testing work of this BA task. The right column of the table has been populated with the information from the sample insulation bag that was photographed in . Figure 38 through **Error! Reference source not found.**Figure 41.

Some product packaging does not provide sufficient information to fill in all of the information fields; however, effort should be made to provide as many identifying details as possible.

Table 1 - Basic information to document insulation material

Field No.	Field Name	From sample insulation bag
1	Material Type	Cellulose fiber insulation
2	Material Name	Retrofit wall & attic insulation SKU 29477 0770
3	Manufacturer	Greenfiber
4	Facility Name	Albany NY 12086
5	Sampling Procedure	Random sample of 10 bags shipped from plant stock
6	Lot No.	N/A
7	Date of Manufacture	2010.03.03 17:57

2.2.2 Establishing the Machine Settings

Fiber insulation products differ not only between material types (i.e. cellulose vs. fiberglass) but also between manufactures. Different products will require different machine settings to achieve the target installed density.

In the field, best practice has the installer establish the machine settings using a test box before dense-packing the building enclosure. In the laboratory, the machine settings are established using the calibration box prior to dense-packing the test wall assembly. The following procedure is recommended:

1. Break-up the insulation material into softball-size pieces and place it in the fiber-moving machine hopper (Figure 42).
2. Set the gate for a typical material feed rate. On the Krendl 450A the gate was set at ‘4’ to start the calibration procedure (Figure 43). Note the gate setting.
3. Set the blower control for a fan pressure of 80 in. W.C. (Figure 44). This step is most easily done with two people.
    A. Block the end of the insertion tube with a pressure gauge to deadhead the blower (Figure 45).
    B. Turn on only the blower (leave the agitator off) and confirm that the pressure is 80 in. W.C. If not, adjust the blower control up or down as necessary.
    C. Turn on the agitator and confirm that the pressure stays around 80 in. W.C. as the seals pass through the airlock. If not, adjust the control as necessary.
    D. Note the blower control setting.

4. Measure the mass of the empty calibration box, M_{empty} (Figure 46).
5. Dense pack the calibration box (Figure 47). The calibration box must be mounted in the vertical position for dense-packing. A hook can be used to hang the calibration at a comfortable working height.
6. Determine the installed density of the insulation.
    - A. Measure the mass of the dense-packed calibration box, M_{filled} (Figure 48)
    - B. Installed density = $(M_{filled} – M_{empty}) / 2$
    - C. Note the installed density.
7. Decide whether or not to proceed
    - A. If the installed density is close to the target density, *verify that the gate setting, blower control setting, blower pressure and density are recorded*, then proceed to dense-packing of the test wall assembly.
    - B. If not, adjust *either* the gate *or* the blower control, and repeat steps 4 through 7. Continue this process until the target density is achieved. This can usually be accomplished within 2-4 iterations.

Table 2 – Recommended data form for establishing machine settings

Field No.	Field Name	Trial 1	Trial 2	Trial 3
1	Gate position			
2	Fan control			
3	Fan pressure (in. W.C.)			
4	Mass of empty box (lb.)			
5	Mass of filled box (lb.)			
6	Mass of insulation (lb.) (field 5 – field 4)			
7	Installed Density (pcf) (field 6 / 2 cu. ft.)			

Machine settings are recorded to facilitate faster calibration of the machine during future tests of the same material. Note however that the required machine settings will likely change as the blower and air lock seals wear. Care should be taken to maintain the machine in good working order.

Figure 42 – Fiber-moving machine hopper filled with insulation material

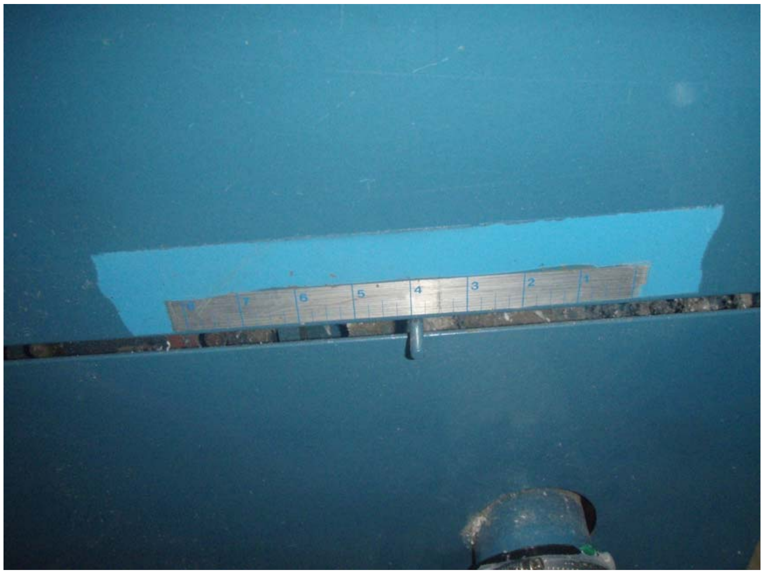


Figure 43 – Fiber-moving machine gate setting

Figure 44 – Fiber-moving machine blower setting

Figure 45 – Measuring fiber-moving machine blower pressure

Figure 46 – Measuring the mass of the empty calibration box

Figure 47 – Dense-packing the calibration box

Figure 48 – Measuring the mass of dense-packed calibration box

2.2.3 Dense-Packing the Test Wall Assembly

In the field installers develop a sense for whether or not the insulation material is being packed to the target density. There is no easy way to measure the installed density in a stud bay, joist space or other cavity. Installers typically estimate installed density by checking the number of bags of insulation used and the area of enclosure insulated against fill charts provided by the manufacturer (e.g. see Figure 41).

In the laboratory it is not only possible to measure the installed density of dense-packed insulations, it is critical; airflow resistance is highly dependent on the installed density of the fiber insulation material.

The following procedure is recommended for dense-packing the test wall assembly:

1. Note the preparation date and the initials of the technician(s) preparing the specimen
2. Seal the test wall assembly to a ‘representative field condition’. For the testing undertaken for the BA task, this meant:
    A. Seal the upper & lower air inlet holes on the back panel (left image in Figure 49)
    B. Seal the air outlet slot, and the upper & top install holes on the front panel (right image in Figure 49)
    C. The top & bottom air inlet holes on the back panel were left open as representative leaks in an existing, uninsulated wall assembly.

   D. The lower install holes on the front panel were left open as access points for the insertion tube.

3. Measure the tare weight of the wall assembly (i.e. before dense-packing the stud bay). If a wall balance is used, the test wall assembly will be lifted off the floor (Figure 50).
4. Dense pack one stud bay (Figure 51).
5. Determine the installed density of the insulation added to the stud bay
   A. Measure the change in mass of the test wall panel (Figure 52).
   B. Installed density = $M_{\text{change}} / V_{\text{stud bay}}$
   C. Record the change in mass and the installed density
6. Decide whether or not to proceed
   A. If the average and standard deviation of the installed densities for the completed stud bays are within allowable limits, proceed to complete dense-packing of the remaining stud bays (i.e. repeat steps 3 through 5) then continue to airflow testing.
   B. If the average or standard deviation are not within allowable limits, assess and address the problem then proceed to empty the test wall panel and start again at step 1.

For purposes of testing related to the BA task the average stud bay density was considered to be acceptable if it was in the range of 3.4 to 4 pcf. The limit for acceptable standard deviation was 0.15 pcf.

Figure 49 – Seal test wall assembly to ‘representative field condition’

Figure 50 – Measure the mass of the empty test wall assembly

Figure 51 – Dense-packing the first stud bay

Figure 52 – Measuring the change in mass of the test wall assembly

2.3 Test Method

The following procedure is recommended for connecting the dense-packed test wall assembly to the airflow control and measurement equipment:

1. Lower the air pressure manifold into position and line it up with the mounting flange on the front of the test wall assembly (Figure 53).
2. Close the top latches to lock the pressure manifold in place against the test wall assembly (Figure 54).
3. Close the bottom latches to compress the gaskets and create an airseal between the flange on the manifold and the flange on the test wall assembly (Figure 55).
4. Connect the airflow hose between the air pressure manifold and the flow measuring devices (Figure 56). Connect the flow measuring device to the fan in an arrangement that will cause the test wall panel to be depressurized when the fan is powered.
5. Connect the pressure tap between the air pressure manifold and the pressure-measuring device (Figure 57).
6. Confirm that the background leakage is in the expected range (Figure 58). This is easily accomplished by checking the measured pressure difference against a single airflow rate (e.g. at a flow rate of 10 scfh the pressure difference should exceed __ Pa).

If the background leakage is not in the expected range, the problem must be addressed before continuing. In our testing, the usual culprits were improperly closed latches or poor tape seals over the insulation fill holes or air inlet holes.

Figure 53 – Lowering the air pressure manifold into position

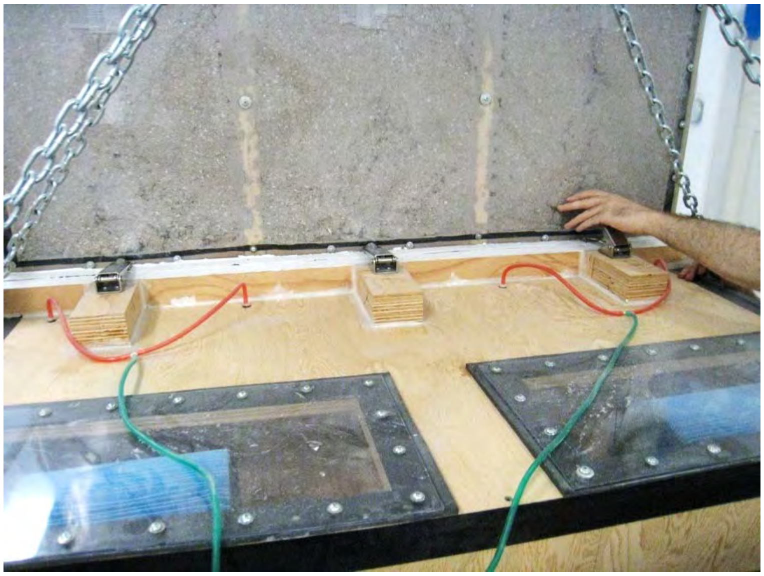


Figure 54 – Closing the top latches

Figure 55 – Closing the bottom latches

Figure 56 – Connecting the airflow hose

Figure 57 – Connecting the pressure tap

Figure 58 – Checking the background air leakage

Three flow vs. pressure tests are conducted to characterize and quantify the airflow resistance of the dense-packed insulation in the test wall assembly:

- Background Leakage Test – all install holes on the front panel sealed; all air inlet holes on the back panel sealed; no holes open.
- Long Path Airflow Test – all install holes on the front panel sealed; upper & lower (i.e. short path) air inlet holes on back panel sealed; top & bottom air inlet (i.e. long path) holes on back panel open.
- Short Path Airflow Test – all install holes on the front panel sealed; top & bottom air inlet (i.e. long path) holes on back panel sealed; upper & lower (i.e. short path) air inlet holes on back panel open.

The tests should be completed in the order listed above. For each test:

1. Note the test date & time and the initials of the technician(s) performing the test
2. Measure and record barometric pressure and laboratory temperature & RH
3. Power the fan to depressurize the manifold to draw air into the test wall assembly
4. Adjust the fan control and rotometer valve(s) to set a desired flow rate. Wait until the pressure reading stabilizes. Note that we are controlling flow rather than pressure because the system is tight and it takes time for the pressure reach equilibrium. Be careful not to overheat the fan or over pressurize the wall assembly or other components.
5. Measure and record the flow rate readings. In our case this means reading the array of four rotometers that is located after the manifold and before the fan.
6. Measure and record the pressure difference (deltaP) between manifold chamber and the laboratory. In our case this means reading the digital pressure gauge.
7. Repeat steps 4 through 6 for a minimum of 5 flow rates and pressures between 10-500 Pa

The following procedure is recommended for breaking down, cleaning and preparing the test wall assembly for the next test:

1. Disconnect the pressure tap (Figure 57) and airflow hose (Figure 56) from the manifold.
2. Release the bottom (Figure 55) and top latches (Figure 54) to free the manifold from the mounting flange on the front of the test wall assembly.
3. Raise the air pressure manifold (Figure 53) to free workspace around the test wall panel.
4. Remove the wing nuts (total of 14) from the field of the back panel (Figure 59).
5. Release the latches (3 on each side) on the left and right side of the assembly (Figure 60) and on the top and bottom (1 each) of the assembly (Figure 61).
6. Remove the back panel from the assembly (Figure 62), inspect and document the quality of the dense-packed insulation (Figure 64).
7. Remove the insulation using shovel, leaf blower and/or vacuum to make the assembly for the next test specimen (Figure 64). Take care to remove insulation that may be trapped between the wood studs and the polycarbonate sheets. Ensure that the air inlet screens (on the back panel) and outlet screen (on the front panel) are also cleaned.

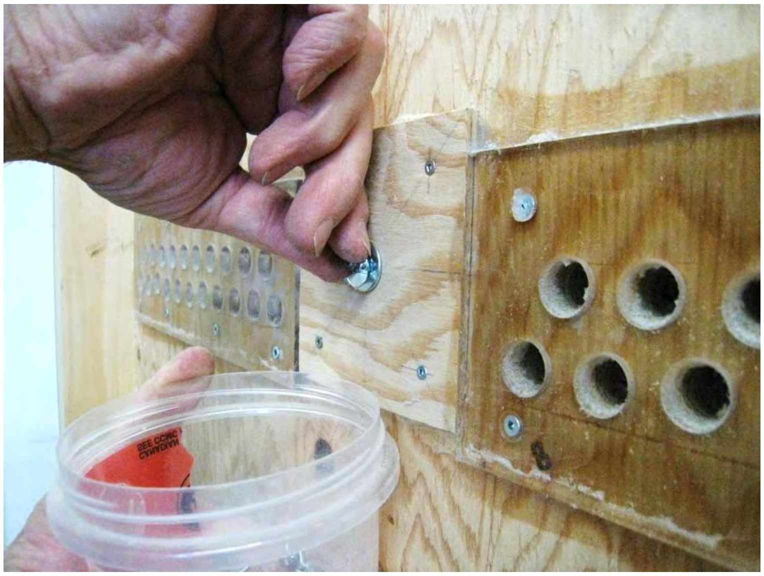


Figure 59 – Removing the wing nuts (qtty of 14) from the field of the back panel

Figure 60 – Releasing the latches (qtty of 6) on the sides of the test wall assembly

Figure 61 – Releasing the latches at the top & bottom (1 each) of the test wall assembly

Figure 62 – Removing the back panel from the test wall assembly

Figure 63 – Inspecting & documenting the back of the dense-packed insulation

Figure 64 – Back & Front panels cleaned and ready for the next test specimen

3 Testing, Analysis & Results

This section of the report describes the testing work that was undertaken to characterize & quantify the airflow resistance of cellulose fiber insulation materials that were dense-packed to the historical minimum density of 3.5 pcf.

3.1 Test Program

The test program was developed through consultation with BSC industry partners and stakeholders in the development of the BPI-102 and 103 standards. Three (3) wall assemblies were to be prepared using material from each of ten (10) different manufacturers for a total of thirty (30) test wall panels.

CIMA, the Cellulose Insulation Manufacturer’s Association, provided a list of twenty-one (21) manufactures that supply the construction markets of the Northeast, Midwest, Northwest, Southwest and Southeast. Ten (10) bags of cellulose fiber insulation were collected from fourteen (14) of these manufacturers. Ten (10) of these manufacturers were randomly selected for testing.

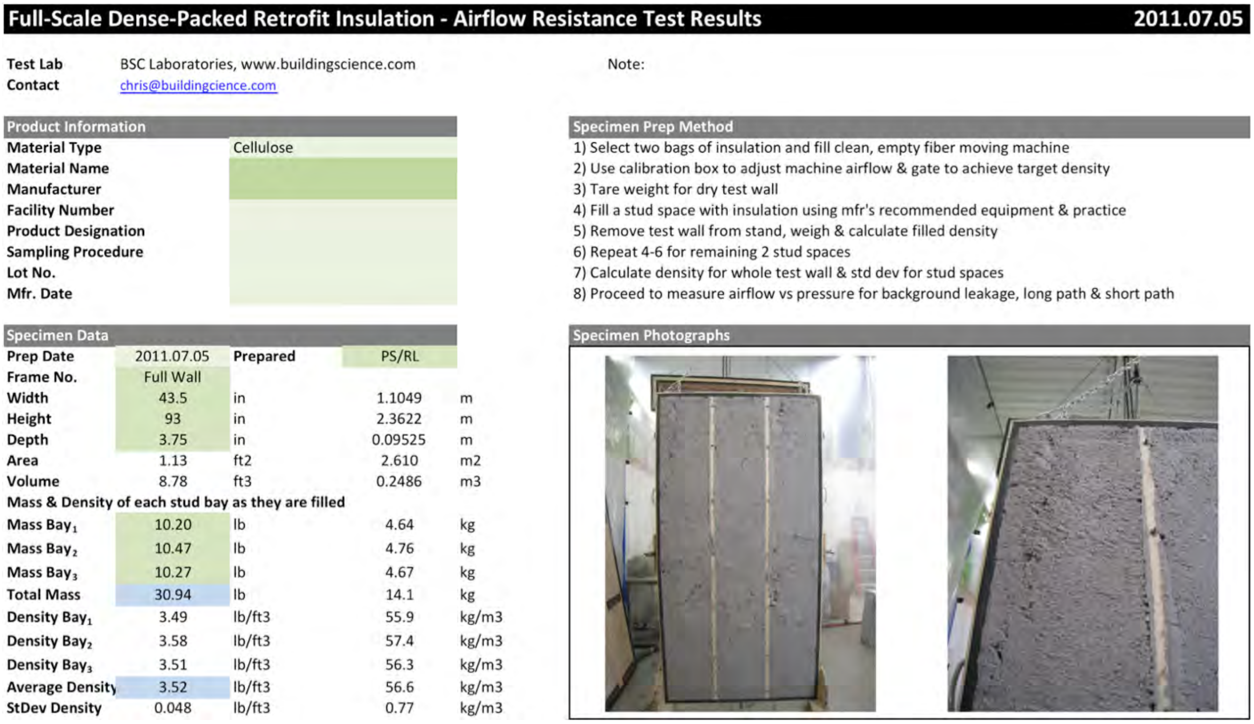
Only BSC staff know which manufacturer’s materials were used in the testing; the reporting is done using material codes (e.g. tests A1, A2 & A3 represent tests 1, 2 & 3 conducted using material from manufacturer A).

3.2 Analysis Spreadsheet

A spreadsheet was created to simplify test documentation and data analysis. The first section of the spreadsheet, reproduced in Figure 65, summarizes information on the insulation product and pertinent details of the specimen preparation: the date of preparation, the initials of the lab technicians that prepared the specimen, and the installed density for each of the three stud bays.

The remaining three sections of the spreadsheet, presented in Figure 66, Figure 67 and Figure 68, facilitate entry and analysis of data collected during the background leakage, long path airflow and short path airflow tests respectively.

For each airflow test, the date, time and lab technician’s initials are recorded. Barometric pressure and lab air temperature & relative humidity are then recorded to permit density correction of flow measurements. Finally, a table is provided for the user to enter raw flow meter and pressure readings. A graph of the measurements is automatically updated as the user enters data. Built in functions instantly perform regression, assuming a power law relationship (i.e. $Q = C\Delta P^n$) and the flow coefficient (C) and exponent (n) are displayed. The data analysis is summarized in a single value: the regression results are used to predict the total airflow (in cfm) at 50 Pa and this is normalized by the total cross-sectional flow area (6 x stud bay depth x stud bay width).



Full-Scale Dense-Packed Retrofit Insulation - Airflow Resistance Test Results 2011.07.05

Test Lab BSC Laboratories, www.buildingscience.com

Contact chris@buildingscience.com

Note:

Product Information

Material Type	Cellulose
Material Name	
Manufacturer	
Facility Number	
Product Designation	
Sampling Procedure	
Lot No.	
Mfr. Date	

Specimen Prep Method

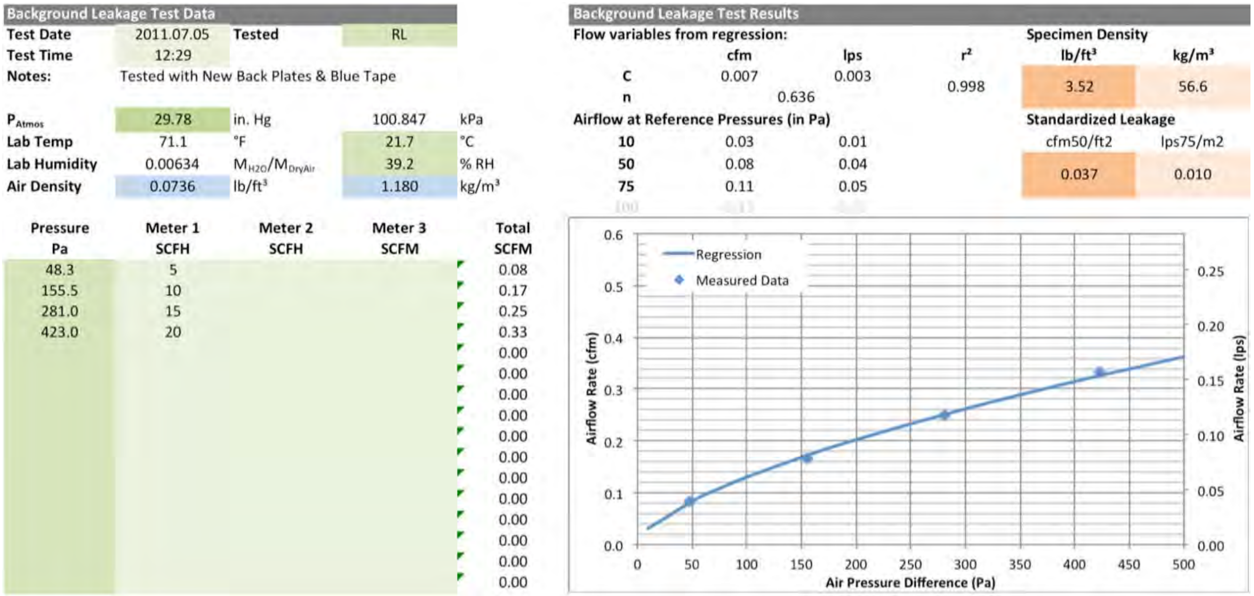
1) Select two bags of insulation and fill clean, empty fiber moving machine
2) Use calibration box to adjust machine airflow & gate to achieve target density
3) Tare weight for dry test wall
4) Fill a stud space with insulation using mfr's recommended equipment & practice
5) Remove test wall from stand, weigh & calculate filled density
6) Repeat 4-6 for remaining 2 stud spaces
7) Calculate density for whole test wall & std dev for stud spaces
8) Proceed to measure airflow vs pressure for background leakage, long path & short path

Specimen Data

Prep Date	2011.07.05	**Prepared**	PS/RL	
Frame No.	Full Wall			
Width	43.5	in	1.1049	m
Height	93	in	2.3622	m
Depth	3.75	in	0.09525	m
Area	1.13	ft2	2.610	m2
Volume	8.78	ft3	0.2486	m3
Mass & Density of each stud bay as they are filled				
Mass Bay$_1$	10.20	lb	4.64	kg
Mass Bay$_2$	10.47	lb	4.76	kg
Mass Bay$_3$	10.27	lb	4.67	kg
Total Mass	30.94	lb	14.1	kg
Density Bay$_1$	3.49	lb/ft3	55.9	kg/m3
Density Bay$_2$	3.58	lb/ft3	57.4	kg/m3
Density Bay$_3$	3.51	lb/ft3	56.3	kg/m3
Average Density	3.52	lb/ft3	56.6	kg/m3
StDev Density	0.048	lb/ft3	0.77	kg/m3

Specimen Photographs

Figure 65 – Test Results Spreadsheet, Section 1: Product Info & Test Specimen Data



Background Leakage Test Data

Test Date	2011.07.05	**Tested**	RL	
Test Time	12:29			
Notes:	Tested with New Back Plates & Blue Tape			
P_{Atmos}	29.78	in. Hg	100.847	kPa
Lab Temp	71.1	°F	21.7	°C
Lab Humidity	0.00634	M_{H2O}/M_{DryAir}	39.2	% RH
Air Density	0.0736	lb/ft³	1.180	kg/m³

Pressure Pa	Meter 1 SCFH	Meter 2 SCFH	Meter 3 SCFM	Total SCFM
48.3	5			0.08
155.5	10			0.17
281.0	15			0.25
423.0	20			0.33
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00

Background Leakage Test Results

Flow variables from regression:

	cfm	lps	r²
C	0.007	0.003	0.998
n	0.636		

Airflow at Reference Pressures (in Pa)

10	0.03	0.01
50	0.08	0.04
75	0.11	0.05

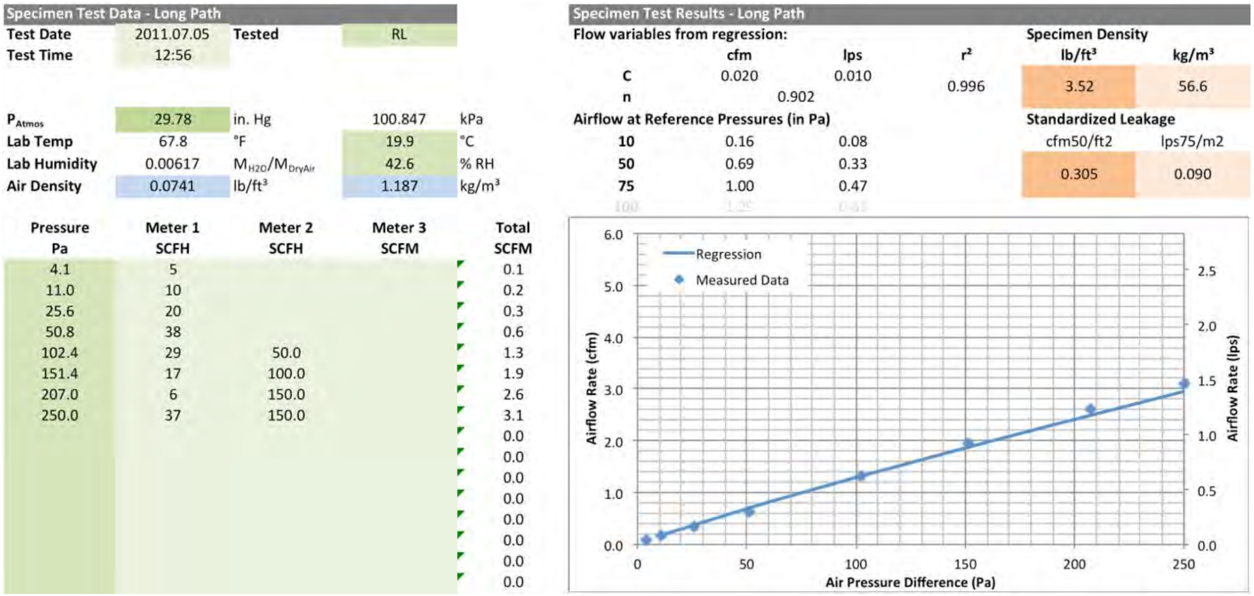
Specimen Density

lb/ft³	kg/m³
3.52	56.6

Standardized Leakage

cfm50/ft2	lps75/m2
0.037	0.010

Figure 66 – Test Results Spreadsheet, Section 2: Background Leakage Test Data



Specimen Test Data - Long Path

Test Date	2011.07.05	**Tested**	RL	
Test Time	12:56			
P_{Atmos}	29.78	in. Hg	100.847	kPa
Lab Temp	67.8	°F	19.9	°C
Lab Humidity	0.00617	M_{H2O}/M_{DryAir}	42.6	% RH
Air Density	0.0741	lb/ft³	1.187	kg/m³

Pressure Pa	Meter 1 SCFH	Meter 2 SCFH	Meter 3 SCFM	Total SCFM
4.1	5			0.1
11.0	10			0.2
25.6	20			0.3
50.8	38			0.6
102.4	29	50.0		1.3
151.4	17	100.0		1.9
207.0	6	150.0		2.6
250.0	37	150.0		3.1
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0

Specimen Test Results - Long Path

Flow variables from regression:

	cfm	lps	r²
C	0.020	0.010	0.996
n	0.902		

Airflow at Reference Pressures (in Pa)

10	0.16	0.08
50	0.69	0.33
75	1.00	0.47

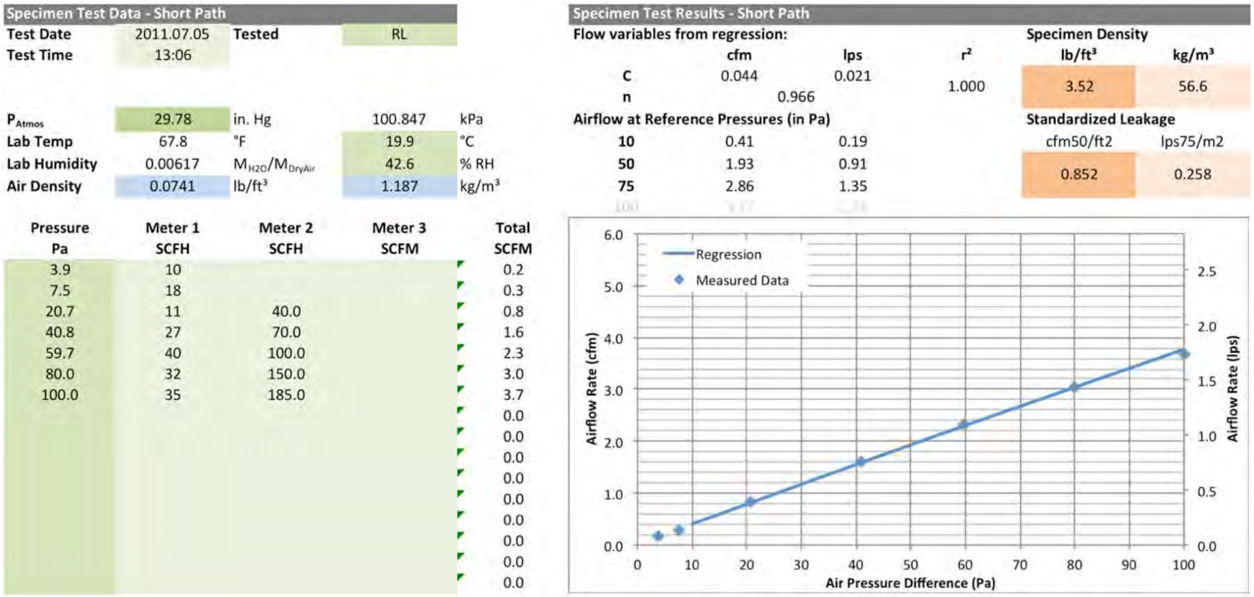
Specimen Density

lb/ft³	kg/m³
3.52	56.6

Standardized Leakage

cfm50/ft2	lps75/m2
0.305	0.090

Figure 67 – Test Results Spreadsheet, Section 3: Long Airflow Path Test Data



Specimen Test Data - Short Path

Test Date	2011.07.05	**Tested**	RL	
Test Time	13:06			
P_{Atmos}	29.78	in. Hg	100.847	kPa
Lab Temp	67.8	°F	19.9	°C
Lab Humidity	0.00617	M_{H2O}/M_{DryAir}	42.6	% RH
Air Density	0.0741	lb/ft³	1.187	kg/m³

Pressure Pa	Meter 1 SCFH	Meter 2 SCFH	Meter 3 SCFM	Total SCFM
3.9	10			0.2
7.5	18			0.3
20.7	11	40.0		0.8
40.8	27	70.0		1.6
59.7	40	100.0		2.3
80.0	32	150.0		3.0
100.0	35	185.0		3.7
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0
				0.0

Specimen Test Results - Short Path

Flow variables from regression:

	cfm	lps	r²
C	0.044	0.021	1.000
n	0.966		

Airflow at Reference Pressures (in Pa)

10	0.41	0.19
50	1.93	0.91
75	2.86	1.35

Specimen Density

lb/ft³	kg/m³
3.52	56.6

Standardized Leakage

cfm50/ft2	lps75/m2
0.852	0.258

Figure 68 – Test Results Spreadsheet, Section 4: Short Airflow Path Test Data

One BSC engineer and two laboratory technicians were trained and certified in the dense-packing best practice methods that are promoted by BPI. Over thirty test specimens were prepared and tested under the BA task. Samples were prepared to target densities between 3.4 and 3.8 pcf with the goals of:

1. Quantifying the airflow resistance of dense-packed cellulose installed at the historically recommended and often required minimum density of 3.5 pcf
2. Characterizing the relationship between airflow resistance and installed density

Figure 69 and Figure 70 summarize the test results with a plot of corrected long path and short path airflow resistance versus installed density. In these plots the airflow resistance is expressed in cfm50/ft^2 of cross sectional flow area, corrected for background leakage; the installed density is an average density of the three stud bays that make up the test wall assembly.

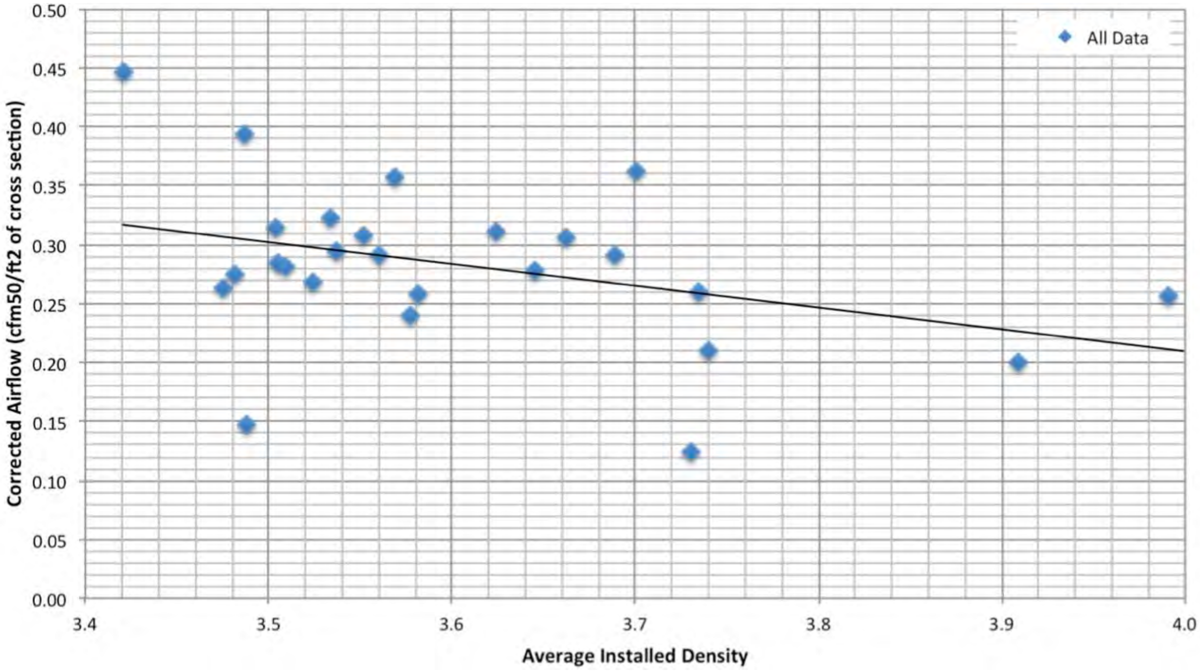


Figure 69 – Long path Airflow vs. Density for all materials & tests

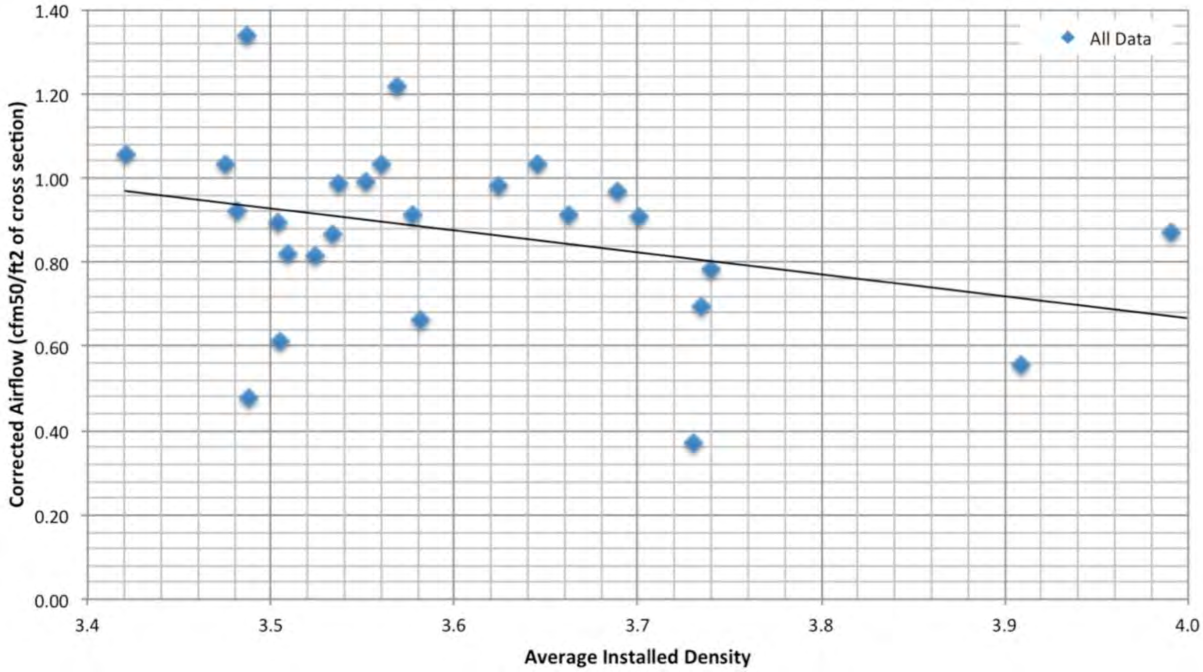


Figure 70 – Short path Airflow vs. Density for all materials & tests

4 Discussion

This section of the report provides a discussion of some interesting and important issues identified and observations made through preparation and testing of the specimens and further analysis of the data collected.

4.1 Material Variability

Not all of the materials tested were developed specifically for dense-packed retrofit applications. In fact, most cellulose insulation manufacturers do not manufacture specific products for dense-packing and, in many regions, it is common for installers to use the same materials for dense-packed retrofits as they use for open blowing (e.g. for attic applications).

Manufacturers use a variety of raw materials to make their cellulose fibers. They are typically secretive of their sources and reluctant to reveal the mix that goes into any product. Recycled paper and cardboard are usually the primary fiber sources; however, some manufacturers have admitted to using some cloth and fiber materials. Inspection of the fibers can sometimes reveal significant contaminants such as large pieces of aluminum foil, plastic bags and even pieces of plastic bottles.

Finally, manufactures use different processes and methods for producing, treating and screening their fibers.

Different raw materials and manufacturing methods result in products that exhibit different fiber sizes, nodule (i.e. fiber clusters) sizes, percentage of fines, presence of contaminants, etc. These in turn affect the ‘flow’ of the material (as it is dense-packed into the wall cavities), the airflow resistance (i.e. resistance to flow through the space) and the degree to which the material seals off cracks & small openings (i.e. resistance to flow into and out of the space).

The differences between materials became evident both in the preparation of the samples and through the testing. Some materials did not install consistently while others could be installed time and time again to the same density, even when installed by different people. Some materials performed very predictably during airflow tests, producing either consistently good or poor results, while others were less consistent.

Figure 71 reproduces the results plot of Figure 69 but here the data points are identified by material (i.e. product). The measurements for some materials fall close to a straight line suggesting a clear relationship between airflow resistance and density; measurements for other materials do not exhibit the same clean relationship, suggesting greater variability. Further testing will confirm the repeatability of installation and airflow resistance for any given material. For future testing work we recommend that, where variability is suggested in the first three tests, an additional two tests be conducted.

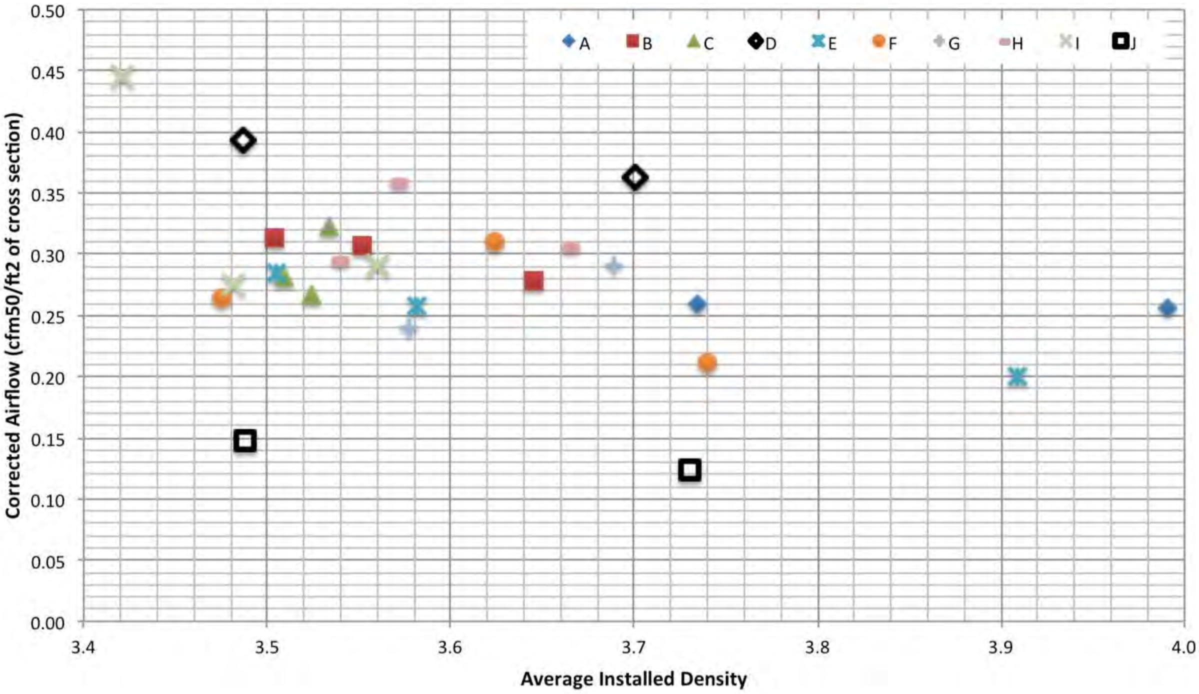


Figure 71 – Long path Airflow vs. Density for all tests, by material

While the plot in Figure 71 suggests the possibility of variability within a given material, it clearly demonstrates the performance differences that exist between different materials. Many of the measurements fall in a cluster between 0.25 and 0.35 cfm50/ft^2; however, other materials produced results that were consistently and decidedly higher or lower. Material D, identified by the open, black-outlined diamonds in the upper part of the plot, had the most contaminants and largest fiber size. It was consistently difficult to blow, demonstrated lower airflow resistance and produced measurements in the range of 0.35 to 0.4 cfm50/ft^2. In contrast, material J, identified by the open, black-outlined squares in the lower part of the plot, was consistently easy to blow, exhibited a noticeable amount of fines, and demonstrated much higher airflow resistance, producing measurements of 0.15 cfm50/ft^2 and less.

4.2 Installer Variability

Variability in the specimen preparation and airflow test measurements may also result from differences in the techniques of different installers. Special effort was made to ensure that all three installers that participated in this study received the same training and certification; however, dense-packing requires that the installer sense and respond to the feedback of the machine and material movement. This is inherently a subjective process and it is impossible to eliminate all variability between installers.

A significant number of tests were conducted as part of this study but only a few tests were conducted on each material and there was not time or budget to complete a proper study of installer variability. Some installer-related patterns are presented here as a starting point for further studies on reproducibility between installers.

Figure 72 presents plots of the corrected airflow versus density for materials B & E. The measurements for both materials suggest a near linear relationship between density and airflow.

Furthermore, both linear fits exhibit similar slopes and these tend to agree with a pattern identified in earlier testing (Schumacher 2010).

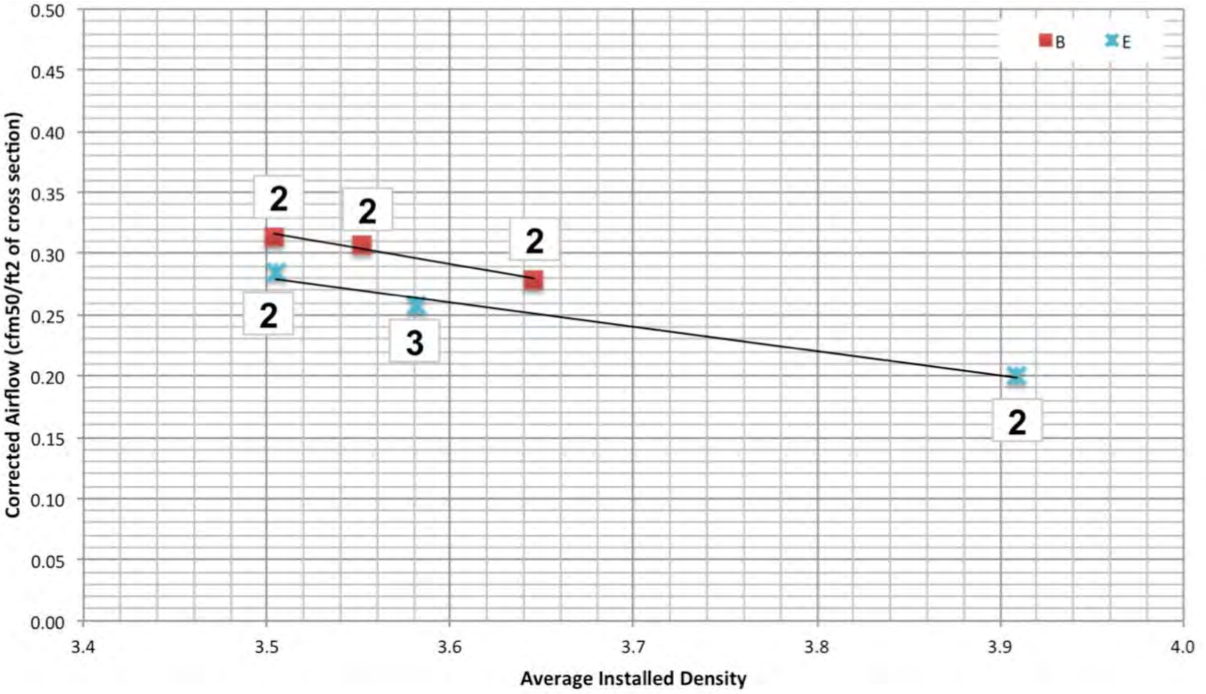


Figure 72 – Installer variability for material B & E long path flow tests

Numbers have been overlaid on the plots of Figure 72 to indicate the installer that prepared each test specimen. Installer 2 prepared all three of the material B specimens. If the installer used the same technique for each, there should be no installer-related variability in this test series and the results should provide a good indication of the relationship between airflow and density for material B.

Installer 2 prepared the lowest and highest density specimens for material E while Installer 3 prepared the middle density specimen. The fact that the three measurements fall on a straight line is encouraging. This suggests that the specimen preparation and airflow tests were not influenced by installer variability; however, further study is recommend to confirm this trend.

Some plots for other materials are not as easily interpreted. Figure 73 presents plots of the corrected airflow versus density for materials C & I. For both materials Installer 3 prepared the lowest density specimen while Installer 2 prepared the middle and higher density specimens. Neither plot exhibits the straight line relationship and negative slope expected.

The three material C measurements are very closely clustered. The scatter may be explained by measurement uncertainties and small material variations.

If one were to eliminate Installer 3’s specimen for material I, and draw a straight line through the reaming two points, the slope of the line would be positive. This observation suggests that something other than installer variability is responsible for differences between tests. It is possible that the differences are related to the material properties previously identified.

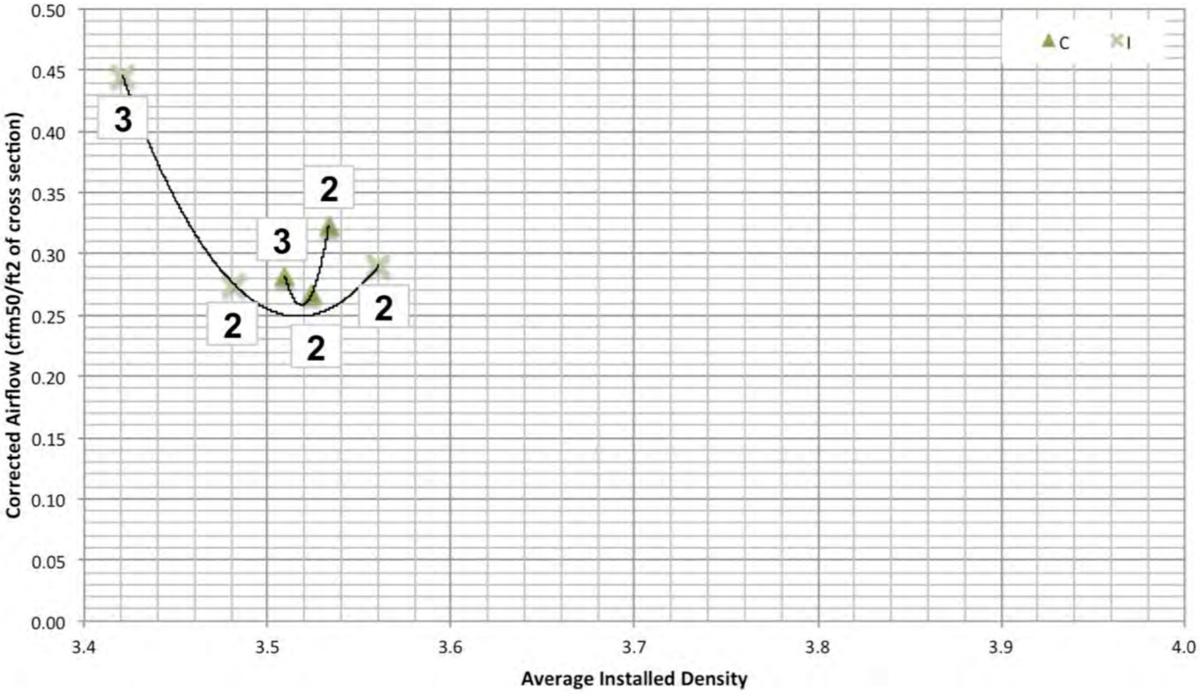


Figure 73 – Installer variability for material C & I long path flow tests

Clearly further study is needed to better understand possible installer-related variability and reproducibility of the test results. A round robin test program has been proposed as the next step in demonstrating reproducibility. Through this round robin, 3-5 manufacturer labs will prepare multiple test specimens from samples of the same insulation material. We recommend that each lab have two (2) installers prepare at least three (3) specimens. This would generate 6-10 sets of data to demonstrate reproducibility and identify the potential impact of installer variability.

4.3 Apparatus Variability

Future round robin tests should demonstrate reproducibility not only from one installer to another but also between one test apparatus and another.

An early look at reproducibility between one apparatus and another is possible through a comparison between the tests conducted for this BA task in 2011 and those conducted under private contract for CIMA, using the original version of apparatus, in 2010. This comparison is made in Figure 74.

The blue diamonds in Figure 74 represent the corrected airflow measurements made in the 2011 tests (using the final version of the apparatus) while the red squares represent the corrected airflow measurements made in the 2010 tests, using the original version of the apparatus. The original version of the apparatus was similar in size but had 1 in. high continuous slots for air inlets while the final version of the apparatus has a pattern of twenty-one, ½ in. dia. holes as air inlets at the top and bottom of each stud bay.

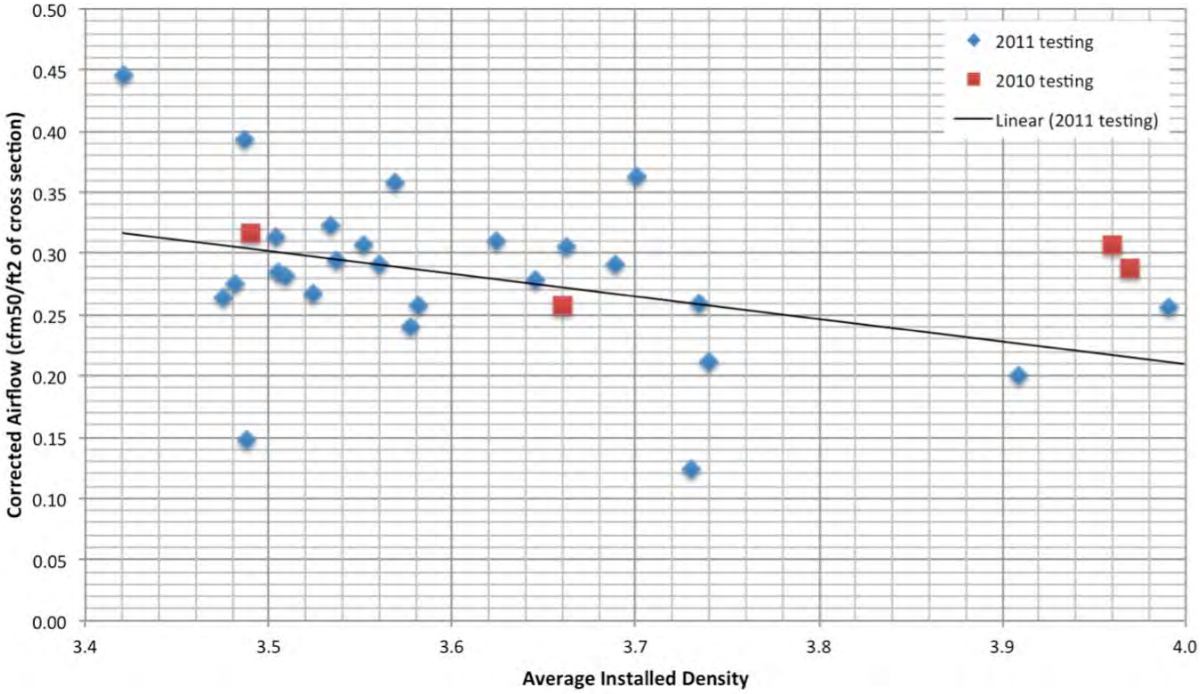


Figure 74 – Comparison of 2011 and 2010 test results (long path)

There appears to be good agreement between at least some of the measurements made with the two different apparatuses. The left two red squares represent two different cellulose materials; both fall near the line that represents a linear regression through the 2011 data. The right two red squares represent a third cellulose material tested as part of the 2010 work. These appear to fall well above the 2011 regression line; however, the difference may be due to material properties as it appears that these points exhibit the same deviation as some of the higher airflow materials tested in 2011.

4.4 Background Leakage

The original (i.e. 2010) dense-pack cellulose test apparatus and method suffered from significant background air leakage. The background leakage was roughly 40% of the total measured airflow. In developing the final apparatus and test method, significant effort was put into

1. Reducing the background leakage to approximately 10-15% of the total airflow
2. Making the air seals (and therefore the background leakage) as repeatable as possible

These goals were accomplished through attention to sealing tiny air leakage paths that were initially thought to be insignificant and through the introduction of plastic faceplates to improve tape seals over the air inlet orifice holes. The specific details are described in Section 2.1 of this report.

Figure 75 plots the background leakage measured for each test specimen. Background leakage rates of approximately 0.03 cfm50/ft^2 can reliably be established test after test. For most tests these leakage rates represent less than 10% of the total measured long path airflow; for materials and installations that exhibit higher airflow resistance, these leakage rates represent approximately 15% of the total measured long path airflow.

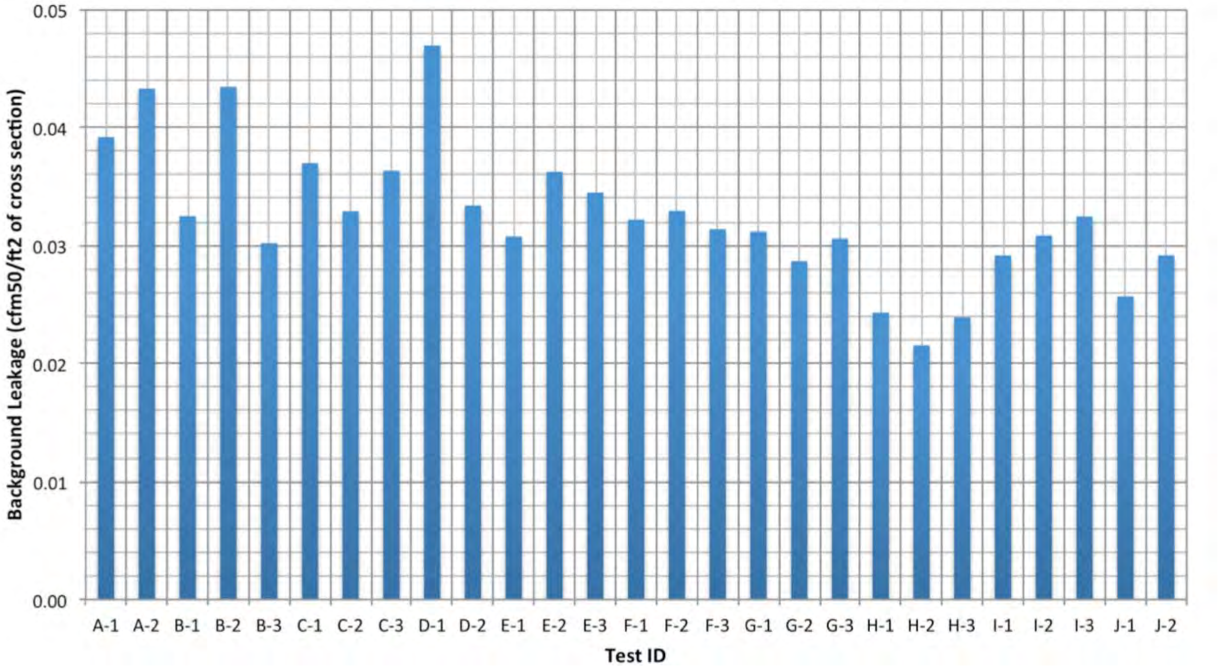


Figure 75 – Background leakage for all tests

4.5 Flow Regime & Pressure Range

Dense-packed fiber insulation provides significant resistance to the flow of air. When the fibers completely fill a stud bay or other framed cavity, air must flow through the fiber matrix rather than through open voids. The resulting airflow should be laminar and, if data regression is performed assuming a power law relationship, the flow exponent (n) should be close to 1.

Figure 76 plots the flow exponents calculated for the background leakage (blue squares in lower part of plot), long flow path (red squares in upper part of plot) and short flow path (green triangles in upper part of plot) tests for each test specimen. For all of the long and short flow path tests the flow exponent is 0.9 or higher. Many are indeed close to 1. This suggests that laminar flow is dominant and that the dense-packed fiber insulation is largely effective in eliminating open voids that would permit higher rates of airflow.

The flow exponents for the background leakage tests tend to fall in the range of 0.6 to 0.7 with a few approaching 0.8. These flow exponents suggest that the background leakage occurs through mixed flow paths. A flow exponent of 0.5 would be indicative of airflow through one or a few discrete holes.

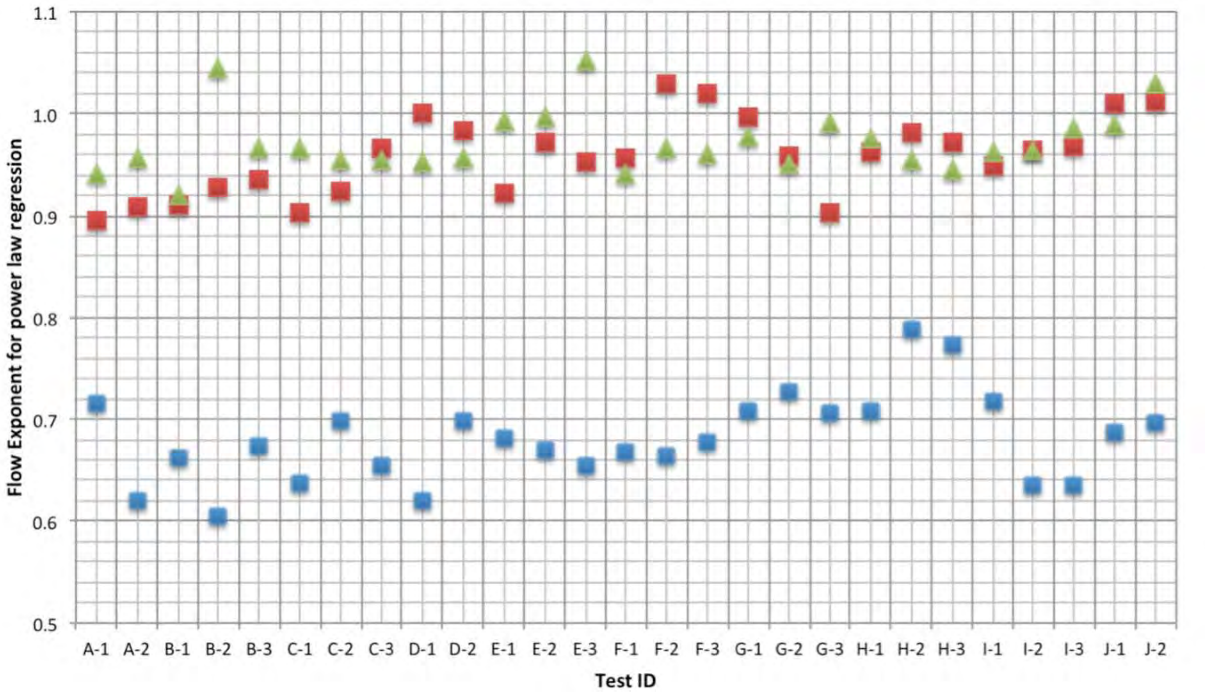


Figure 76 – Flow Exponents for all tests

To maximize flow measurement resolution and minimize uncertainty, the airflow tests are conducted at relatively high pressures (up to 250 Pa). The test pressures can be a hundred times greater than those experienced by the assembly under real operating conditions (typically 4-10 Pa) and there is a danger that the test flow regime is not representative of the operating flow regime; however, the good fit of the regression, examples of which can be seen in Figure 67 and Figure 68, justifies the test pressures used.

4.6 Retrospective assessment of historical applications

This report describes an apparatus and test method that were developed to measure the airflow resistance of dense-packed fiber insulation when installed as a retrofit to empty wood-frame wall cavities. No prior test methods have ever been standardized for this purpose; however, the apparatus and method described in this report are to be used as the basis for proposed standard BPI-103, “Standard Test Method for Determining the Air Permeance of Fibrous Thermal Insulation Materials Used in Air Retarder Applications”.

Proposed standard BPI-102, “Standard for Air Resistance of Thermal Insulation Used in Retrofit Cavity Applications – Material Specification”, will set requirements for the minimum airflow resistance of insulation materials (cellulose, glass fiber and any other possible loose-fill fibers) used for dense-pack retrofits. As a starting point it makes sense to have the required airflow resistance reflect the performance of dense-packed cellulose insulation retrofits that have been installed to the historically required minimum density of 3.5 pcf.

One of the major objectives of this study was a retrospective assessment of the airflow resistance that might be provided by dense-packed cellulose insulation materials. Three materials (C, E & F) have been identified as being “representative” of the ten materials tested. Figure 77 and Figure 78 present the long path and short path test results for these three materials.

Further testing (e.g. through the planned round robin process) will produce more data points and improve predictions of the airflow resistance of historical dense-packed cellulose insulation applications. On the basis of the limited data available, we estimate that generic dense-packed cellulose insulation materials, installed to 3.5 pcf, would provide an airflow resistance of 0.33 cfm50/ft^2 in the long path test and 1.0 cfm50/ft^2 in the short path test.

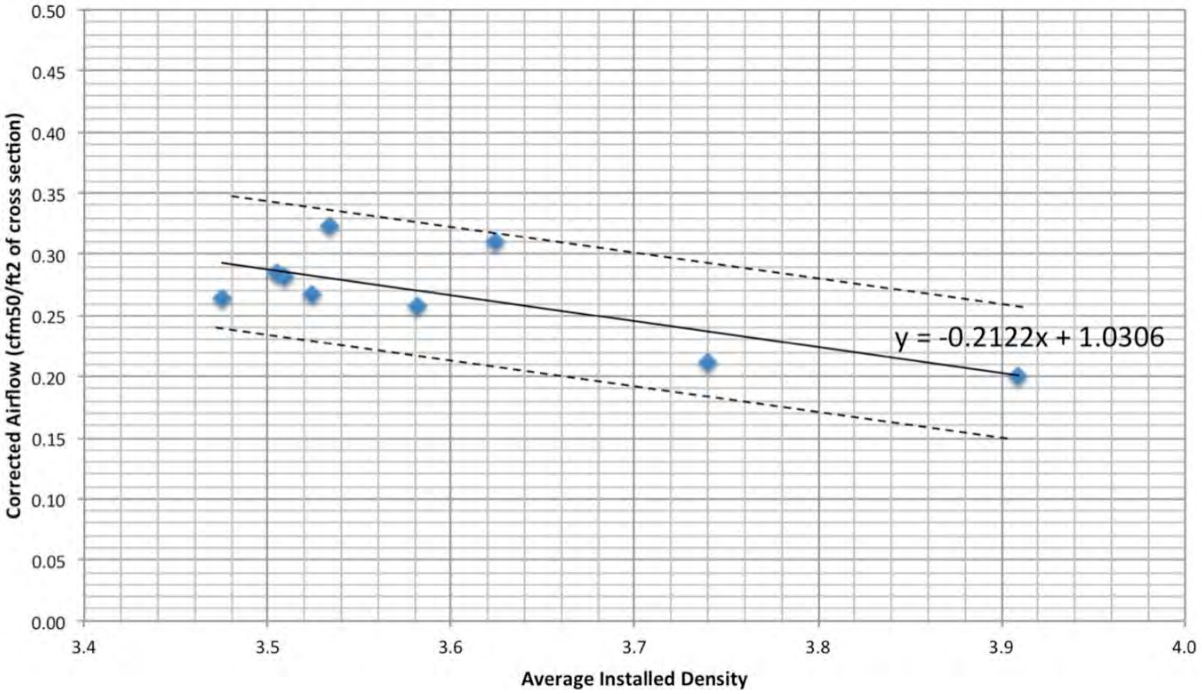


Figure 77 – Long path Airflow vs. Density for representative materials C, E & F

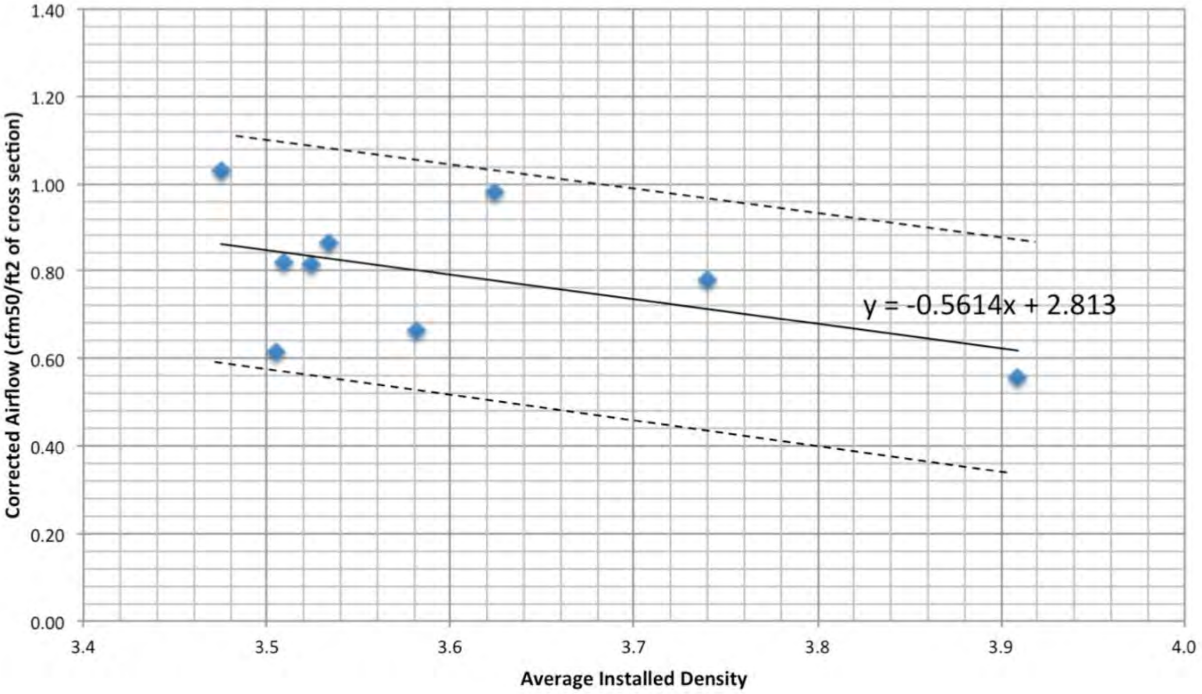


Figure 78 – Short path Airflow vs. Density for representative materials C, E & F

5 Conclusions

An experimental apparatus and test method were developed for the purpose of measuring the airflow resistance of dense-packed fiber insulation installed as a retrofit to empty wood-frame wall cavities. The resulting apparatus and method will form the basis of the proposed BPI-103 test standard.

The use of the apparatus and application of the test method have been demonstrated through testing of over 30 test wall specimens that were prepared using cellulose materials from 10 different insulation manufacturers.

Dense-packed cellulose insulation, installed to densities of 3.5 pcf and higher, was shown to provide a significant resistance to airflow. An inverse relationship between density and airflow was demonstrated (i.e. higher density insulations provide greater airflow resistance). Based on initial and limited testing, the relationship appears to be linear over the range of densities considered (e.g. 3.4 to 4.0 pcf).

Initial tests also suggest that the airflow resistance is a function of material variability. It was not clear how much of the variability between tests was a function of installer technique although it was clear that some materials were easier than others to dense-pack.

The ability to achieve low and repeatable background leakage was demonstrated.

Regression of the test data established that laminar flows dominate the long and short path flow tests (i.e. the flow exponent, n, was approximately equal to 1). This confirms that airflows primarily occur through the insulation material and not through open gaps, further demonstrating the air sealing benefits of dense-packed fiber insulations.

The data regression also confirmed validity of the range of pressures tested. Laminar flows dominated throughout the entire range of air pressures tested so the test flow regime reflects the flow regime that will exist during in-service conditions.

Finally, an effort was made to estimate the airflow resistance of generic dense-packed cellulose insulation materials installed to 3.5 pcf. On the basis of the limited data available, we would expect these installations to result in an airflow resistance of 0.33 cfm50/ft^2 in the long path test and 1.0 cfm50/ft^2 in the short path test.

Further testing (e.g. through a round robin test program) should be conducted to confirm the ‘historical’ airflow resistance numbers, to demonstrate reproducibility of the test apparatus and method and to further explore the influence material variability.

References

[BPI] Building Performance Institute (2010) BPI–103 “Standard Test Method for Thermal Insulation Materials Used in Air Retarder Applications,” Malta, NY.

Derome, D. and Fazio, P. (2000) “Large-Scale Testing of Two Flat Roof Assemblies Insulated with Cellulose.” *Journal of Architectural Engineering*, Vol. 6, No. 1, March 2000

Derome, D. (2005). “Moisture Accumulation in Cellulose Insulation Caused by Air Leakage in Flat Wood Frame Roofs.” *Journal of Building Physics*, Vol. 28, No. 3, January 2005, 269-287.

[EDU] Energy Design Update, (1986). “Research Shows Increased Building Tightness with Cellulose Insulation” Vol. 5 No. 12, December 1986.

Fitzgerald, Jim, Gary Nelson, and Lester Shen. “Sidewall Insulation and Air Leakage Control.” *Home Energy Magazine,* Jan. 1990: 13-20.

Fitzgerald, J. (2010). Personal communication.

ICC. (2009). *International Energy Conservation Code*. Country Club Hills, IL: International Code Council

Lstiburek, J.W. (August 2010). “Building Sciences: Don't Be Dense with Insulation.” *ASHRAE Journal* (vol. 52); pp. 54-57.

Schumacher, C. (June 2010) "BSC Comments on BPI-103 Public Comment Draft Standard Test Method for Thermal Insulation Materials Used in Air Retarder Applications", a public comment submitted to the BPI-103 standard development committee.

Schumacher, C. (June 2010) "A Full-Scale Test Method to Determine the Air Permeance of Loose-Fill Insulation for Retrofit of Wood-Frame Wall Assemblies", a proposed alternate test method submitted to the BPI-103 standard development committee.

U.S. Census Bureau (2008) Current Housing Reports, Series H150/07, “*American Housing Survey for the United States: 2007*” U.S. Government Printing Office, Washington, DC, 20401

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This report was prepared with the cooperation of the U.S. Department of Energy's, Building America Program.

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