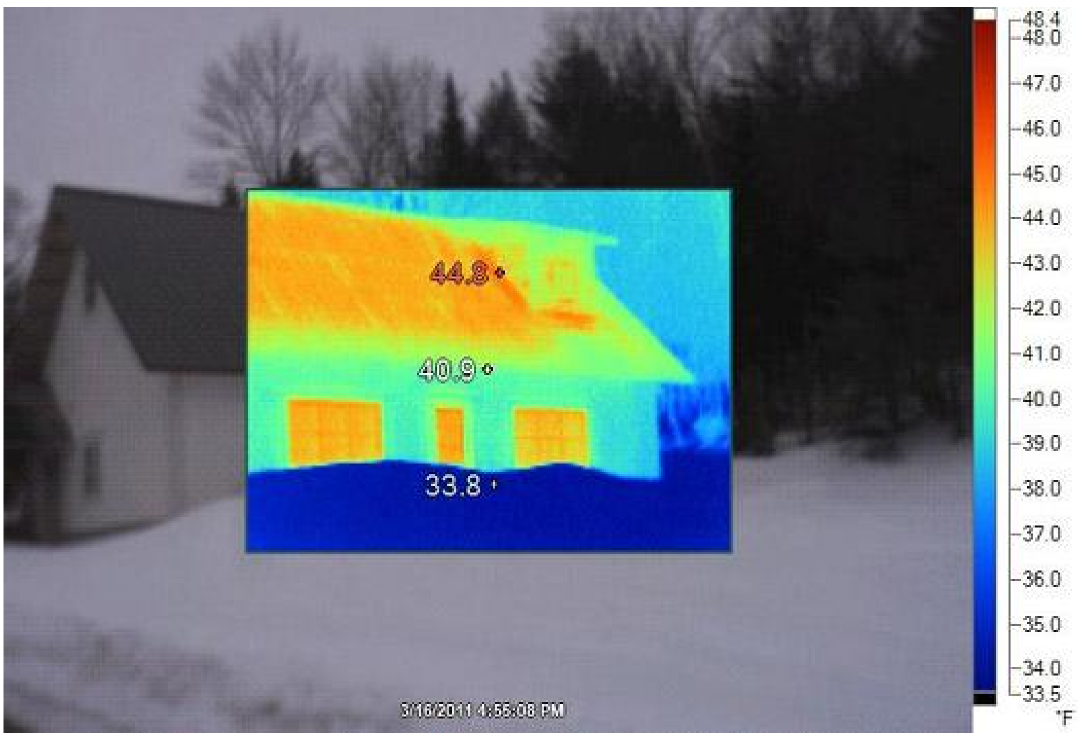
Final Report for Energy Performance of Straw Bale Buildings Research Program

December 12, 2011



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Final Report for Energy Performance of Northeast Straw Bale Buildings Research

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Funding Support From:

New Frameworks Natural Building, LLC, Montgomery, VT
And the generous support of 33 community backers coordinated through Kickstarter.com

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Section 1 – Introduction

Straw bale construction has evolved beyond the realm of owner-builders and niche enthusiasts, and has been adopted by thousands of builders world-wide. There are straw bale construction code standards in numerous U.S. and Canadian jurisdictions, with developed code standards currently being presented for inclusion in the International Building Code (IBC). Originally developed in the Sand Hills region of Nebraska during the Westward Migration of the turn of the last century as a response to a lack of available timber or sod for settlement construction, the practice of straw bale construction was revitalized in the early 1990s in the southwestern United States as a contemporary form of low-skill, ecologically-sound alternative construction. Since this time, the use of plastered straw bale wall systems – drawing upon a global legacy of thousands of years of using straw, clay, and lime as building materials – has spread throughout the world, and is rapidly developing in a contemporary trades environment that is responsive not only to ecological sensitivity and social justice, but to issues of cost, aesthetics, code compliance, and performance.

Despite the wealth of laboratory and field testing proving the viability of straw bale construction as a legitimate architectural style, there are still barriers to its broader acceptance. This is particularly true in the northeastern United States – the location of this research project – where the climate is colder and wetter than in most other parts of the country, and where the building community is increasingly concerned with the high performance and durability of the building envelope. While there are owner-built straw bale homes in the northeast that are nearly 20 years old, it is only since the late 1990s that straw bale buildings have been built consistently by professional crews, responsively developing and refining techniques into best common practices. This work has largely been done by many of the professionals associated with Natural Builders NorthEast, a professional network of natural builders (www.nbne.org).

The early work of straw bale construction in the northeast largely focused on stability of the wall system, integration with the structural system (frequently timber frame) and other components of the building, plastering details, and especially moisture control. As these practices became further refined and standardized as a regional building style, the focus began to shift towards the performance of the straw bale envelope itself. As the conversation of whole-envelope energy performance in buildings has been developing within the green building community at large, so too has the straw bale building community been exploring how to improve the efficiency of their systems. After years of continuing to develop construction techniques maximizing the thermal performance of these wall systems (as discussed in Section 2 – Overview of Relevant Construction Details), a growing need has emerged for empirical data to aid in understanding the efficacy of these techniques, in order to develop the next generation of high-performance straw bale enclosures.

To address this need for data, in the winter of 2011 New Frameworks Natural Building, LLC contracted primarily with Brad Cook of Building Performance Services, and supplementally with Matt Sargeant of Efficiency Vermont and Dick Robinson of Advanced Energy Solutions to perform building performance testing on seven structures the company had built, in part or in whole, over the previous four years (described in detail below in Section 4 – Testing Methodology). In developing the testing program, a goal was set to not only document the performance of existing buildings, but to identify the strengths and weaknesses of the construction practices as they have developed over time in order to identify improvements for efficiently creating high performance natural enclosure systems. An additional goal, and the intention in formally presenting this research, is to be able to communicate more effectively with the green building community at large the potential that straw bale building has to achieve many of the shared goals of thermal performance and durability, while utilizing materials that also have a much lower ecological impact than those commonly used today.

As test sponsors, report authors, and builders of most of the straw bale wall enclosures that were tested, we have a clear conflict of interest present in this study. We contracted with independent energy efficiency companies to acquire objective data, and hope this work will encourage more of such testing to be replicated on these and other structures in the Northeastern United States.

Section 2 – Overview of Relevant Construction Details

What follows are some basic components and principles of straw bale construction in cold-climates as background to the presentation of this research.

1. Structural Framing

Straw bales can be integrated into building envelopes in many different ways: as load-bearing walls, built into stud walls, and wrapped around exposed post-and-beam frames, to name some of the most common designs.

> **All of the projects in this report reflect the most common form in the northeast: straw bales wrapped around a structural post-and-beam frame, which in all but one project are timber frames utilizing mortise and tenon joinery.**

2. Plaster Type

A straw bale wall must have a base coat of plaster on either side for it to perform effectively as a wall system. This plaster coat serves multiple purposes: gives the wall strength, protects from fire, protects from insects and pests, manages moisture, controls form, lends beauty, and serves as the primary air barrier. The wall can then be finished either in plaster, with wood siding/panelling, or with other finish of choice. Particularly in a cold and wet climate where both precipitation from outside and condensation from within threaten the durability of walls, we rely upon a vapor-permeable wall system that allows for drying potential to either side of the wall assembly. Therefore, we specifically refer to the plaster as an ‘air barrier’, not as a ‘vapor barrier’. The use of heavily vapor-retarding finishes such as multiple coats of latex paint or cement plaster will dramatically increase the potential of moisture damange in the walls over the long term. We highly favor the use of clay-based primary coats because of clay’s hydrophilic nature. We frequently, but not exclusively, use lime as both interior and exterior finishes because of its durability.

> **The wall systems in this test all utilize base coats of primarily clay, and all except one have finish top coats of lime plaster.**

3. Secondary Air Barriers, or “Air Fins”

Because the straw bales in these projects are wrapping around the timber frame, the interior plaster skin is frequently interrupted by the framing. This means that the plaster, our primary air barrier, is repeatedly compromised, necessitating a permanent seal to the timber frame. We call this secondary or supplemental air barrier an “air fin”. These materials, which can include drywall, tar paper (with metal, plastic, or fiber lath for suitable plaster adhesion), homosote, and masonite, are installed onto the frame prior to the installation of bales any place where the plaster will come to a wood edge. The base coat of plaster overlaps the edge of the fin, which seals the gap that forms between the plaster and the timber. As we will discover, the air fins perform best when sealed to the frame, to ensure air is not able to pass between the air fin and the timber.

This, however, can be very difficult to achieve, primarily because of the difference in behavior between the two materials in response to changes in moisture content. Whereas the plaster is very static and will remain stable unless completely saturated, the wood of the frame is dynamic and will continue to expand and shrink as it uptakes and releases moisture from the atmosphere, long after its initial drying phase is complete. This means that creating a permanent bond between the plaster and the wood cannot be relied upon by simply abutting the plaster to the wood. Caulk or sealant is not accepted as a viable standard practice to fill the gap that may ultimately form, due to the difficulty of executing a solid, long-lasting caulk bead in a narrow cavity formed in part by a dynamic material, and the inevitable aesthetic compromises.

The tested structures in this report all utilize air fins of some type and of differing levels of installation quality. Specifications for each structure are detailed in the results.

4. Plaster Edges: Stand-Aways or Rabbets

It is often common practice to install the plaster up to an inch behind the edge of trim or visible framing. This is achieved by creating a notch on the back side of the trim or framing that we call either a "stand-away", or rabbet, depending on its mode of execution. The stand-away creates, and the rabbet is, a space between the straw bales and the frame into which the plaster can be applied. This is best achieved when a channel can be routed into the frame or trim itself (the rabbet). When this is not possible, in the case of the timber frame raised without rabbeting in advance, ¾" furring strips called 'stand-aways' are pre-installed behind the frame. This process adds both an extra step and an extra thickness to the wall, and can have ramifications for air sealing, as we will explore through presentation of the research. The practice of installing stand-aways or rabbets serves not only to further interrupt the direct passage of air into the wall cavity, but to provide a cleaner aesthetic finish and protect the vulnerable edge of the plaster.

The projects tested in this report all utilize stand-aways or rabbets. Specifications are detailed for each wall system.

Section 3: Overview of Tested Projects

Seven projects were selected across Vermont and New York based upon their level of completion, the attempt at a complete building envelope, and their active or near-active use. All but one of the structures are private single-family residences; the exception is a music/recreation studio building. Appendix A – Energy Performance of Straw Bale Buildings Research Program Aggregated Results Chart gives a comparative overview of the projects and the testing results. For more context, a brief narrative is provided on each project. Please note that references to the square footage of the project are of total heated area, which includes unfinished basements.

Project #1: Brookfield, VT

Date completed: 2009
Building square footage: 1,300 sq ft
Number of stories: 1.5 stories
Framing type: structural timber frame, exposed
Enclosure type: straw bale wall system
Plaster type: clay base coat, lime finish coat
Air fin type: 1/8" masonite, 30# roofing felt
Air fin installation: owner-installed under professional advice
Foundation type: slab on grade, 2" foam, ICF knee wall on North
Roof type: SIPS roof
Heat source: Masonry heater
Ventilation source: HRV
Domestic hot water source: on-demand hot water heater, solar hot water panels
Renewable energy source: off-grid solar PV

Two-thirds of the building is a cathedral ceiling and loft open from the first floor, with the balance an enclosed second-story room.

The project was owner-built/contracted. The owner, who works in the renewable energy field, is well-versed in construction practices and project management, and was able to efficiently execute the project from design through finish. Among the sub-contractors was New Frameworks Natural Building, who aided in design and logistical consultation, helped facilitate a community straw bale wall raising, and performed all plastering over the straw bale walls.

Project #2: Barnet, VT

Date completed:	**addition completed 2008, cabin completed 1998**
Building square footage:	**2,100 sq ft**
Number of stories:	**2.5 story addition, 1.5 story cabin, connected by breezeway**
Framing type:	**structural timber frame, exposed**
Enclosure type:	**straw bale wall system**
Plaster type:	**clay base coat, lime finish coat**
Air fin type:	**30# roofing felt**
Air fin installation:	**professionally installed to moderate quality, cabin air fins unknown**
Foundation type:	**full basement in addition, crawl space in cabin, slab in breezeway**
Roof type:	**common rafter roof, cellulose insulation**
Heat source:	**wood stove**
Ventilation source:	**none**
Domestic hot water source:	**40 gallon propane hot water heater and storage**
Renewable energy source:	**off-grid solar PV**
Other:	**breezeway stud-framed with cellulose insulation**

A cupola at the very peak of the building is stud-framed and minimally-insulated with no effective air barrier. There is no separation in the building between the cupola, any of the floors, the basement, or the breezeway; a hand-built door separates the cabin from the breezeway. The cathedral ceiling finishes are a mix of drywall and wood panelling.

The original cabin was contracted, with the straw bale walls built by Greenspace Collaborative of Greenfield, MA, an experienced and qualified operation who can be credited with pioneering may of the cold-climate-specific techniques in use today. The addition was also fully contracted. New Frameworks Natural Building constructed the straw bale walls with support from Natural Design/Build, as well as all plastering and the interior wood chip-clay insulated walls. Blower-door testing of this home was conducted first on the addition and breezeway, with the original cabin sealed, and then again with the door open and the entire structure tested as a whole, as can be noted in Appendix A – Energy Performance of Straw Bale Buildings Research Program Aggregated Results Chart.

Project #3: Newbury, VT

Date completed:	**2011**
Building square footage:	**1,537 sq ft**
Number of stories:	**1.5 stories**
Framing type:	**reclaimed, hand-hewn structural timber frame, exposed**
Enclosure type:	**straw bale wall system**
Plaster type:	**clay base and finish coat with exterior lime paint**
Air fin type:	**½ inch drywall**
Air fin installation:	**professionally installed to high level of quality**
Foundation type:	**slab-on-grade, ICF footer, concrete block stem wall, cellulose-insulated stud-framed knee wall to raise straw bales above grade**
Roof type:	**common rafter roof system, 16", blown with cellulose, 1" foam board as thermal break**
Heat source:	**wood stove**
Ventilation source:	**HRV**
Domestic hot water source:	**on-demand propane hot water heater**
Renewable energy source:	**off-grid solar PV**
Other:	**breezeway stud-framed with cellulose insulation**

The cathedral ceilings are finished with drywall.

The design and straw bale wall construction, including air fins and plastering, was conducted by Natural Design/Build with support from New Frameworks Natural Building. Further build-out of the structure is also fully-contracted.

Project #4: Middlesex, VT

Date completed:	**2010**
Building square footage:	**2,448 sq ft**
Number of stories:	**2.5 stories**
Framing type:	**structural timber frame, exposed**
Enclosure type:	**straw bale wall system**
Plaster type:	**clay base coat; lime, clay and gypsum finish coats**
Air fin type:	**1/2 inch homosote and 30 # roofing felt air fins, caulked with rubberized acoustical sealant**
Air fin installation:	**student-installed under professional direction to high level of quality**
Foundation type:	**ICF block full walk-out basement, thermally connected to building**

Roof type: **Framed lattice rafter roof with 8" purlins over 8" rafters, yielding a 16" cavity dense-packed with cellulose**
Heat source: **wood stove, direct-vent propane space heater backup**
Ventilation source: **HRV**
Domestic hot water source: **on-demand propane hot water heater**
Renewable energy source: **off-grid solar PV**
Other: **clapboard rainscreen siding over gables**
air-tight drywall approach used on cathedral ceiling, also sealed to plastered straw bale walls to attempt continuous air tight connection

The building was professionally designed, and constructed both by contractors and in an educational environment. The foundation, mechanicals, and majority of interior framing and finishing was professionally-built. The majority of the shell, including timber frame, exterior walls, roof framing and insulation, and window and door installation was conducted by students as part of a 12-week building program run through the Yestermorrow Design/Build School, with additional contracting support from New Frameworks Natural Building.

Project #5: Warren, VT

Date completed: **2009**
Building square footage: **456 sq ft**
Number of stories: **1.5 stories**
Framing type: **structural timber frame, exposed**
Enclosure type: **straw bale wall system**
Plaster type: **clay base and lime finish coat plasters finish coats**
Air fin type: **1/2 inch homosote and 30 # roofing felt air fins, caulked with rubberized acoustical sealant**
Air fin installation: **student-installed under professional direction to high level of quality**
Foundation type: **slab on grade, double-stud, cellulose insulated knee wall to raise bales above grade**
Roof type: **16" double-rafter parallel trusses roof assembly, insulated with dense-pack cellulose**
Heat source: **in-slab radiant tubing powered by propane boiler, Rumford fireplace**
Ventilation source: **none**
Other: **non-residence, 4 season structure, no plumbing**
12" thick double-stud cellulose-insulated clerestory wall
18" thick East gable double stud cellulose-insulated wall
cathedral ceiling is air-tight drywall

The project serves as a music rehearsal studio/recreation space for the client's teen-age children; it is comprised essentially of a large open space, with a small mudroom/utility room separated by an interior wall.

The slab, electrical, and radiant systems were professionally installed. The rest of the building was built as part of a 12-week educational program run through the Yestermorrow Design/Build School, led by members of New Frameworks Natural Building with design support from Natural Design/Build. An attached carport is built off the west side of the building within the same roof and timber frame structure on an adjacent slab-on-grade, separated thermally by 2" foam board. This building also featured a whole host of salvaged materials, including all of the windows, that were installed either in class or by volunteers.

Project #6: Granville, NY

Date completed:	**2010**
Building square footage:	**3,000 sq ft**
Number of stories:	**2.5 stories**
Framing type:	**structural timber frame, exposed**
Enclosure type:	**straw bale wall system**
Plaster type:	**clay base coat, lime finish coats**
Air fin type:	**1/8 " masonite and 30# roofing felt air fins, caulked with rubberized acoustical sealant**
Air fin installation:	**owner-installed with professional advice to high level of quality**
Foundation type:	**full walk-out basement of poured concrete, partially insulated with 2"foam board, thermally connected to building**
Roof type:	**site-constructed foam panels**
Heat source:	**in-slab radiant tubing in first floor powered by dual fuel (wood and propane) boiler**
Ventilation source:	**none**
Domestic hot water source:	**dual fuel boiler**
Renewable energy source:	**off-grid solar PV**
Other:	**clerestory ceiling and interior wall finish are stud-framed and cellulose-insulated, finished with tongue and groove wood paneling running through the building envelope**

The building is owner-built in its entirety, with the exception of the straw bale wall system. The owner installed the air fins, New Frameworks Natural Building installed the straw bales and the finish plaster, and Greenspace Collaborative installed the rough plaster.

Project #7: Clinton, NY

Date completed:	**2009 (enclosure)**
Building square footage:	**1,200 sq ft**
Number of stories:	**1.5 stories**
Framing type:	**structural post-and-beam, exposed**
Enclosure type:	**straw bale wall system**
Plaster type:	**clay base coat, lime finish coats**
Air fin type:	**1/2" homosote and 30# roofing felt air fins, caulked with rubberized acoustical sealant**
Air fin installation:	**professionally-installed to high level of quality**
Foundation type:	**ICF frost walls, earthen floor insulated with 2" foam board**
Roof type:	**raised-heel truss roof insulated with dense-pack cellulose**
Heat source:	**wood stove**
Ventilation source:	**none**
Renewable energy source:	**off-grid solar PV**
Other:	**cathedral ceiling finished with tongue and groove wood panelling that runs through the building envelope**

The building is owner-designed and contracted, with certain features - such as portions of the interior straw-clay walls - constructed by the owner. The rest of the structure was professionally-built, with New Frameworks Natural Building providing design and logistical consultation and constructing the straw bale walls (including air fins and all plastering), earthen floor, and interior straw-clay walls.

Section 4 - Testing Methodology

All of the tests were completed by independent home energy auditors. The majority of the testing was executed by Brad Cook of Building Performance Services (BPS) of Waitsfield, VT. Project #4 - Middlesex, VT, was conducted by Matt Sargent of Vermont Energy Investment Corporation (VEIC) as part of the certification process for the Vermont Energy Star Homes program. Project #7 - Clinton, NY, was conducted by Dick Robinson of Advanced Energy Systems (AES), Utica, NY. Overall, the testing done by BPS was more thorough. The blower-door testing conducted by all three companies was complete, however, the infrared (IR) camera testing performed by VEIC and AES was limited. The quality of the equipment and thoroughness of the scanning was of lower quality compared to the testing done by BPS. The description of the testing methodology below refers to that conducted by BPS, and was not as fully executed for Projects #4 and #7.

First, a full scan of the exterior walls was executed using an IR camera (Fluke TiR-2FT), followed by an interior initial scan. This provided a baseline of the building's performance at atmospheric pressure, prior to the depressurization of the blower door test. It also brought to light thermal patterns that would suggest irregularities such as moisture spotting, which proved particularly relevant on exterior plastered walls.

Next, the blower-door testing equipment was placed in an exterior door. This device (TEC BD4) uses a metered and regulated fan to depressurize the house to 50 Pa (equivalent to 20 MPH winds blowing on the house from all directions), regulated by pressure and flow gauges and a controller (TEC DG-700) that interface with computer-controlled data logging software. Readings were taken at 10 Pa intervals to create a clear graph of the quantity of air used to maintain different pressure rates to ensure consistency and accuracy in the results. The resulting value in cubic feet per minute at 50 Pa (CFM50) was then used to calculate two different metrics for evaluating the air-tightness of the building. The first, air changes per hour at 50 Pa (ACH50), is volumetric and refers to the number of times in an hour the full volume of air in the building is able to leak through the envelope at a 50 Pa pressure difference from the interior to the exterior of the building. It should be noted that this metric favors larger buildings, which have larger surface-to-volume ratios than smaller buildings and therefore are able to contain more air relative to the area of the envelope, where leaks occur. Therefore, the air leakage relative to the building's surface area was also calculated, CFM50/exterior square foot (CFM50/ext.sq.ft.). The ext.sq.ft. value includes the entire surface area of the exterior of the heated volume of the structure, including basements, slabs, and all roof and ceiling area coupled to the interior of the building. See Appendix A – Energy Performance of Straw Bale Buildings Research Program Aggregated Results Chart or Section 5 for ACH50 and CFM50/ext.sq.ft. values for each project.

The interior of the building was then re-scanned with the IR camera while it was depressurized to 50 Pa. This second scan clearly highlighted the effects of convection (air leakage) losses in the building, exacerbated by the depressurization of the blower door test. The scans showed the patterns of convective loss, in most cases accentuating the losses identified in the previous scan, and in others displaying new areas of loss. Where the IR showed areas of particular concern, verification was done with a 'smoke pencil', a hand-held unit that creates a stream of smoke that shows the intensity and direction of air flow at the point of the leak.

Throughout the IR testing process - both the initial and second scans - careful notation of the results were tracked by region in the building, both where leaks were notable and where a high level of tightness was observed. Anomalies and relevant features in the building affecting the results were also recorded. In addition to the thermal imaging, digital photographs were also taken of the structure to reference in evaluation of the results at a later date.

Finally, a series of moisture tests were conducted throughout the building. In most structures, probe tests with the Delmhorst F-2000 18" Hay Probe Moisture Meter were taken for a set of three readings: directly behind the interior plaster, in the approximate center of the wall, and directly behind the exterior plaster. Results of the probe tests are given as a percentage of moisture content (%MC). This allowed for comparison of moisture readings in these three different locations in the wall section. Tests were taken on each wall, at low and high points in the building, and also at areas of perceived or supposed vulnerability, such as at visible plaster cracks or where possible moisture patterns were detected in the IR scans of the exterior plaster surface. Surface scans (Delmhorst TechChek) were also taken in many of the buildings. These scans evaluated the concentration of moisture in the contacted surface based on electrical resistance, with results displayed on a range of 0-300. The same meter was also used to conduct pin testing in the wall surfaces, in which small pin sensors were inserted into the surface. Results for the pin testing are %MC. In some cases, areas with elevated scan or pin readings prompted probe testing, allowing for an analysis of moisture migration from the plaster body to the straw within at a series of depths.

Section 5 – Results

In this section of the report, we will evaluate the results of the testing for the program as a whole, followed by the results for each individual project. Further information can be found in Appendix A – Energy Performance of Straw Bale Buildings Research Program Aggregated Results Chart.

PROJECT	BDT (CFM50)	HEATED SqFt	VOLUME CuFt	EXT. SURFACE SqFt	ACH-50	ACH-NAT	CFM50/ Ext.SqFt
#1 – Brookfield, VT	557	1272	13360	3748	2.50	0.18	0.15
#2 – Barnet, VT	2139	2096	27329	5829	4.70	0.40	0.37
#2 – Barnet, VT	3015	2692	32117	7705	5.63	0.49	0.39
#3 – Newbury, VT	767	1537	13400	4539	3.43	0.25	0.17
#4 – Middlesex, VT	850	2448	19844	6506	2.57	0.20	0.13
#5 – Warren, VT	552	456	5028	2535	6.59	0.36	0.22
#6 – Granville, NY	2057	2931	33221	7091	3.72	0.34	0.29
#7 – Clinton, NY	1756	1190	8921	2888	11.81	1.02	0.61
Vermont State Energy Code Requirements*					<=5.0		
Vermont Energy Star Program Requirements**					<=3.0		

BDT(CMF50) = Rate of air leakage during testing conditions, expressed as cubic feet per minute at 50 pascals
ACH-50 = Rate of air leakage during testing conditions relative to the building's volume, expressed as air changes per hour at 50 pascals, where one air change equals the interior volume of the building
ACH – Nat = Projected rate of air leakage under atmospheric, or "natural," conditions relative to the building's volume, expressed as air changes per hour
CFM50/ext.sq.ft = Rate of air leakage during testing conditions relative to the surface area of the building, expressed as cubic feet per minute at 50 pascals per square foot of exterior surface area
* Vermont State Energy Code Handbook, Section C.1b, p. 56, Version 3.0, effective October 1, 2011, Vermont Department of Public Service
** Efficiency Vermont Residential New Construction Requirements - Vermont Energy Star Homes, Thermal Performance Requirements, p. 5, 2011, Efficiency Vermont

Project #1 – Brookfield

This building measured 557 CFM50 for a 1,272 sq ft building having a volume of 13,360 cu ft and surface area of 3,748 sq ft, resulting in 2.5 ACH50 and 0.15 CFM50/ext. sq. ft. This building exhibited a lack of stratification; at 32ºF outside temp (a temperature difference of 36ºF) there was less than 1ºF difference between the peak of cathedral ceiling to base of back bedroom.

Moisture Readings – Project 1: Brookfield, VT

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
East wall crack 2nd Floor	7.4 – 12 – 19.9	
West- north of south window	8.5 – 10.2 – 13.2	10% to sides, 25% below
West – 6-8" below south window, 2' up	8.5 – 10.1 – 12.7/13	
Interior surfaces		0-50 nominal; 115 behind stove
Exterior surfaces		80-100 south; 150-300 west gable (visible moisture)

Project #2: Barnet, VT

This building was tested in two phases: first the Basement/Breezeway/House/Cupola only, followed by that space plus the 10-year-old cabin featuring air fins of unknown quality.

The results of the first test were a CFM50 of 2,139 for 27,329 cubic feet of heated space and 5,829 exterior square footage of shell, yielding 4.7 ACH50 and 0.37 CFM50/ext. sq. ft. Factoring for the increased volume and surface area of the cabin, the results were 5.63 ACH50 and 0.39 CMF50/ext. sq. ft.

Moisture Readings – Project 2: Barnet, VT

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
North 1st floor 5' up near stair	8.5 – 9.8 – 13.3	
West 2nd floor under window 3' up – leak	8.4 – 10.3 – 10.6	
South 2nd floor under eave – leak	9.2 – 10.2 – 10.3	

Project #3: Newbury, VT

The Newbury project test resulted in 767 CFM50 for a 13,400 cu. ft. and 4,539 ext. sq. ft., this resulted in 3.43 ACH50 and 0.17 CFM50/ext.sq.ft.

Moisture Readings – Project 3: Newbury, VT

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
Northwest closet 4' up	13.2 – 16.8 – 18.7/23.8 (possible plaster contact on higher reading)	
East gable 3' up	10.9 – 13.2 – 17.4	
West gable 2.5' up	12.6 – 14 – 18.4	
South wall through truth window, 4' up	10.6 – 14.9 – 16.7	

Project #4: Middlesex, VT

This building tested at 850 CFM50 for 19,844 cu.ft. of heated space and 5,656 ext. sq. ft. of shell, for results of 2.57 ACH50 and 0.15 CFM50/ext. sq. ft. surface area.

Moisture Readings – Project 4: Middlesex, VT

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
Northeast corner – north wall/basement	10.6 – 17.5 – 27/28	
North wall, west side under plate (in closet)	13.9 – 13.0 – 36/38 12.4 – 10.3 – 27.9 10.7 – 10.2 – 35.5	
South wall, west side under plate (behind bed)	10.9 – 14.9 –26.8 10.9 – 10.9 – 25.7	
East wall, southeast corner under gable (behind TV)	11.3 – 17.3 – 27.9	
Northeast corner, east wall in knee brace cavity	10.0 – 15.7 – 26.6	

Project #5: Warren, VT

At 552 CFM50 for 5,028 cu.ft. heated space and 2,535 ext. sq. ft. of shell, the results were 6.59 ACH50 and 0.22 CFM50/ext. sq. ft.

Moisture Readings – Project 5: Warren, VT

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
East wall below girt plate – center of bay	9.5 – 12.9 – 19.3	
East wall below girt plate – north knee brace cavity	8.7 – 11.4 – 16.8	
East wall below girt plate – center knee brace cavity	9.5 – 14.2 – 17.8	
North wall below girt plate – center main room	8.8 – 12.4 – 15.3	
North wall – utility room, 5' up	10.2 – 12.7 – 12.6	
West wall – high gable	8.2 – 11.0 – 16.0	
North interior		20-50, 60-85 above windows
North interior knee wall, above plate		0-20
West gable interior		20-40
East wall exterior		100-140
South wall exterior		30-50, 60-80 over windows
South wall exterior under west window above knee wall		120-180; 6%
West wall exterior		100-140
North wall exterior		40-80

Project #6: Granville, NY

At 2,057 CFM50 for 33,221 cu.ft. of heated space and 7,091 ext. sq. ft. of shell, the results were 3.72 ACH50 and 0.29 CFM50/ext. sq. ft.

Moisture Readings – Project 6: Granville, NY

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
South wall, 2nd floor top of wall center	8.2 – 9.0 – 11.0	
West wall, 2nd floor below plate near south @ crack	9.0 – 10.2 – 12.4	
East wall, 2nd floor center 5' up	8.1 – 9.1 – 13.1	
North wall, 2nd floor top of wall center	8.4 – 10.3 – 13.4	
West wall, 1st floor 18" up through box	9.4 – 12.4 – 15.6	
North wall, 1st floor center 10" up	9.0 – 9.4 – 10.2	

Project #7: Clinton, NY

At 1,756 CFM50 for 8,921 cu. Ft. of heated space and 2,888 ext. sq. ft. of shell, the results were 11.81 ACH50 and 0.61 CFM50/ext. sq. ft.

Moisture Readings – Project 7: Clinton, NY

Location	Int – Mid – Ext (%MC)	Surface/pin scans (# / %MC)
East wall, near southeast corner 18" up (first bale)	9.2 – 12.0 – 17.9	
North wall, near northeast corner 30" up (under counter)	9.4 – 12.7 – 15.0	
North wall, center in hot water closet 48" up	10.4 – 12.8 – 15.3	
West wall, center in battery closet 36" up	9.0 – 12.7 – 13.0	
West wall, upstairs near northwest corner in cold closet 36" up	8.4 – 10.4 – 12.0	

Section 6: Discussion

In this section, we first evaluate the overall performance of buildings across the research project, then discuss observations for the individual buildings in greater detail, and finally present conclusions and recommendations based upon these evaluations.

General Project Evaluation

- The tightest results were 2.50 ACH50 (Project #1) and 0.l3 CFM50/ext.sq.ft (Project #4), while the leakiest results were 11.81 ACH50 and 0.61 CFM50/ext.sq.ft (Project #7), with the balance of projects falling somewhere in the middle
- The primary locations of air leakage were in roof assemblies. Of these, significant or repeated bypasses included:
    1) around chimneys and plumbing vent stacks
    2) around blocking between rafters on the exterior
    3) where tongue-and-groove ceiling/clerestory wall paneling extends through the envelope to the exterior as soffit material
    4) at framing transitions where air barriers (such as air-tight drywall or gaskets) were either non-existent or inadequately detailed
- Windows and doors were also consistently leaky. These leaks occurred:
    1) between the plaster edge and the window framing/trim, particularly on older buildings with less-thorough air fin detailing
    2) between the rough opening (R.O.) and the window sash where foam sealants were inadequately installed
    3) within the window units themselves, especially in salvaged windows but also in new windows
- A significant percentage of the observed losses is accounted for by elements of the building unrelated to the natural wall system and its boundary conditions with other structural elements. Overall, plaster transitions to timbers and bottom- and top-of-wall transitions were generally tight, with occasional deficiencies. Timber joints themselves were also predominantly tight. Issues of creep, air fin failure, or poorly-designed transitions were not systemic or building-wide, pointing towards the potential for measured improvements in attending more closely to installation procedures in the field, and in minimizing plaster edge in design. **The most significant and widespread thermal bypasses occured in situations that could have been avoided or easily fixed, rather than systemic failures of the design.**
- There was a consistent pattern of occasional thermal bypasses in the plaster-edge transitions in most of the buildings. Most of these areas were found at tops of posts and where posts and knee braces connected, as well as at tops of gable walls and plaster-to-window and door transitions. Timbers passing through the envelope, such as in Project #1, were another notable weakness. The interrupted and irregular nature of these bypasses suggests issues of workmanship and on-site detailing, rather than a wholesale failure of the approach.
- Improvements in the thoroughness of execution and type of air fin and caulking material were directly associated with improvements in reduced plaster-edge

bypasses, as evidenced by improvements in thermal performance for similar construction details over a span of three years' worth of air sealing technique enhancements.

- Cracks or chips in the plaster often resulted in air bypasses. In other cases, however, cracks that upon visual inspection would seem to indicate a compromise of the interior air barrier proved to remain air tight, indicating **the difficulty of assessing the air bypass potential of a plaster crack by visual inspection alone.**
- Students, volunteers, and owner-builders were able to successfully install air fins, straw bales, and plaster into a wide variety of wall conditions, including more complex wall forms such as cathedral ceiling gable end walls, while still maintaining high levels of thermal performance – in many cases, higher than those found by professionally-built non-straw bale components of the envelope.
- **Moisture levels were predominantly safe, most frequently in the 8%-17% moisture content (MC) range, lower than levels required for mold or decomposition.** Occasional higher readings were noted in regions where obvious moisture loads were present, such as interior cracks acting as air bypasses and condensation vectors. No obvious indications of decomposition (smell, visible mold) were observed in these cases. Project #4 – Middlesex, VT, exhibited significantly elevated moisture levels, which were identified as a result of recent construction-sourced moisture (plaster application).
- High levels of moisture in the exterior plaster did not migrate to the adjacent straw sufficiently to create a danger of moisture damage. Scan and pin testing of plaster where moisture levels were very high were compared to probe tests of the straw within 1" of the tested plaster area. **These tests showed the straw to be within safe levels of moisture content, despite its proximity to the moisture-laden plaster.**

Individual Project Discussion

Specific discussion is now provided relevant to each individual project.

Project #1 – Brookfield, VT

Heat loss, while minimal in this structure, occured in a number of locations:

1) Expected thermal patterns of heat loss at timber and fenestration edges were relatively few and inconsistent, indicating issues of workmanship or incidental anomaly rather than systemic systems failure. Plaster cracking that had developed as a result of frame settling was inconsistent in amount of air leakage. While larger cracks were indeed air bypasses, others assumed to be bypasses proved to be tight.
2) Losses were observed between the rough opening (RO) and window/door or within the window/door unit itself
3) Patterns of loss were observed in joints between the SIP roof panels
4) Small losses were found in the vicinity of exhaust and intake pipes for utilities, although the owner did an exceptional job of minimizing excessive leakage at these points
5) Heat loss at the point of protrusion of the timber brackets through the bale walls supporting the large roof overhangs was consistent and sometimes significant. These are very difficult areas to seal initially, are prone to disruption of the sealing joint over time as the brackets shrink and swell, are located in a vulnerable boundary area of the building (top-of-wall interface with fixed-form SIPS roof), and create a thermal bridge.
6) Heat loss seen at the wall-to-roof transition was occasional and incidental. This confirmed viability of this difficult transition, particularly where bale walls meet SIP roof panels in non-load-bearing construction

Interior surface scans were generally found to be quite dry, with localized moisture behind kitchen stove (no range hood, overhead cabinet) well below danger levels. Exterior scans, unsurprisingly, were higher, significantly so on gables, where we saw evidence of both visible wetting and cold spots indicating moisture in IR scans.

Probe testing in a large crack on the east gable (interior), where convection losses were identified, registered 7.4 – 12 – 19.9 inside-mid-out (these are percentages of moisture content of the straw, measured ~ 1” from interior plaster skin, half-way through wall, and ~1” from exterior plaster skin, respectively), indicating significant, localized condensation to the exterior. On the west side, where significant exterior surface moisture was identified below the window with surface and pin scans, probe testing registered 8.5 – 10.1 – 13, indicating that the plaster is safely storing moisture without transmitting to the bales within; a second regional probe gave similar results. Extensive moisture probe testing of this building enclosure in October 2010 revealed isolated regions of elevated moisture but an overall pattern of safely dry walls.

Project #2: Barnet, VT

There were a number of factors that led to the higher leakage rates of this project:

1) the lack of isolation between different parts of the building allowed for a significant amount of air movement throughout the structure, and kept leakier parts of the building from being isolated from tighter parts
2) The basement itself proved to be leaky, particularly in the band joist insulation. Where spray foam was used to insulate the band joist between the joists, the IR imaging showed occasional yet repeated air infiltration, proving that the initial foam installation was incomplete.
3) The breezeway performed as one of the leakiest spots in the assembly, notably along the south halves of both gable walls where the breezeway connected to both the original and new structures. An increased level of attention to detailing is needed when making these transitions to ensure an air-tight connection, and not merely a weatherproof transition.
4) The cupola appeared to be the worst offender of heat loss. It was difficult to tell if the walls were insulated; in between shrinkage gaps in the wood paneling, tar paper was visible with occasional glimpses of daylight. The IR imaging revealed walls that were riddled with cold spots and lines, and cobwebs (which are frequently located in drafty locations) were heavily present.
5) Plaster/window connections proved to be a regular, although not universal, source of weakness. Air sealing details on this structure were less rigorous than those installed in more recent buildings, and leakages seen through IR on this building point towards the relevancy of enhanced detailing in these areas. Post bottoms, knee brace-to-post connections, and post top-to-beam connections all proved to be regular points of leakage, perhaps due to a lack of sealing where air fins overlapped or joined. These leakages were more occasional than widespread, pointing towards the general efficacy of the design. Air leakage was also noted at the tops of walls in the gables.
6) This building did not feature baseboard trim, and the plaster runs down to the floor. Where the plaster has been damaged and fractured in places, particularly around doorways, air leakage was notable through IR scans.
7) There was significant air leakage where deformation of the framing occurred. A rafter plate had rolled up off the post towards the exterior – possibly indicating

thrust from the roof – and the edge surrounding this transition was noticeably leakier than at other points along the frame. Cracking in the plaster and the profile of the original plaster where it met the beam confirmed that this framing deformation occurred after the plaster work was complete. It appears that with the movement of the frame, the air fin was torn or otherwise compromised.

8) Air fins could not be confirmed to have been installed in the original house. Considering this, it is quite well-sealed, especially in the first floor. The second story, however, was much leakier, both at rafter-to-plate connections and all along the gable end wall to roof connection.

Moisture tests in this building were very favorable, showing a range of ~8% on interior readings to ~12% exterior, which is very good considering that testing occured during the heaviest wetting time of the year for a wall, when the frozen condensation accumulated during the winter begins to melt, drying conditions are poor, and precipitation levels are high. Moisture readings in the older house were comparable, only a few percentage points lower. RH in the building was around 30-40%. There is no ventilation system nor exhaust fans in this building. The dryer vents to the inside, in the basement.

Project #3: Newbury, VT

One benefit of this building is that, in that it was still under construction at the time of testing, there exists the opportunity to easily seal up identified leaks prior to finishing, making improving the final performance of building easier and therefore more likely to happen. The following points of heat loss were observed:

1) An unsealed chimney penetration through the roof was a major leak point, and will improve substantially once finally sealed.
2) connections between rafters and the wall top plate – especially where tongue and groove flooring protruded slightly into the wall cavity – were regular places of minor heat loss, illuminating the importance of detailing air-tight connections between framing systems.
3) Fenestration leaks, including window-to-RO connections and a particularly leaky door, were occasional sources of heat loss.
4) Some leaks were observed in mechanical chases in walls.
5) Heat loss occured at the plaster-to-timber frame boundary. In this building, efforts were made to caulk between joints of the drywall air fins, which proved to be unfavorable as an air fin material choice due to its fragility and issues of plaster delamination. This project featured stand-aways, or 3/4” strips of wood nailed and caulked to the back of the frame, to allow the plaster to pass behind the frame and cover the plaster-to-wood joint. Leakage at these transitions may not necessarily

have occured because of the air fins, but because of the difficulty in getting a seal between the stand-aways and the very rough and irregular plane (occasionally interrupted by remnant mortise pockets) of the antique timber frame. More air leakage through joints in the frame itself was observed in this building compared to others. Using old frames, especially those with looser joints and irregular faces, may contribute to difficulty in executing air sealing detailing.

Moisture testing was slightly higher in this building than the average of those found in the project, ranging from ~ 12% interior to ~ 17% exterior. It should be noted that the RH humidity of the building was in the 60% range. These numbers are expected to drop as mechanical ventilation is introduced to the building and construction moisture is removed.

Project #4: Middlesex, VT

As this is a Vermont Energy Star-rated Home, the program's technical advisor Matt Sargent administrated the testing for this project. The capabilities of Mr. Sargent's IR camera were more limited and we were therefore unable to capture IR images of publishable quality. However, with Mr. Sargent's extensive knowledge of building performance testing, a strong understanding of how heat loss was occurring in the structure was able to be determined. The following areas of heat loss were observed:

1) Cold patterns were seen around some of the shed dormer roof transitions, as well as in the ceiling near the west gable wall. Other than in those locations and one mentioned below, the airtight drywall approach proved to be highly effective, with little to no cold patterns seen through IR scans in the ridge, the purlin or rafter plate boundaries, or the roof-to-gable wall transitions. This was achieved in a complex and highly-interrupted ceiling pattern (three dormers of two styles, four exposed timber beams, and multiple light box penetrations).
2) The most significant bypass in the structure appeared to be the chimney penetration in the ceiling. An attempt to conduct air sealing between the chimney and the ceiling drywall could not be confirmed; formal inspection and diagnosis of this transition was impossible as it was hidden from view in a chase. However, IR imaging showed significant air infiltration under depressurization around all sides of the chase-to-ceiling boundary. This could indicate a greater air bypass around the chimney penetration than what can be seen through IR around the chase, which would help explain the source of some of the losses found in the blower-door test results.
3) The HRV ducts showed mild air infiltration even when 'sealed' on the exterior, perhaps indicating insufficient sealing during testing.
4) A consistent pattern of heat loss was also seen in the cracks between the ICF blocks in the basement walls, despite a thorough attempt at foam-sealing these joints. In that these areas were below grade, it can be assumed that these are conductive, rather than convective losses, although IR scans of these walls were not conducted prior to nor after the blower door test for a control image.

5) A dramatic improvement of plaster-to-timber transitions throughout the structure was observed. While the building is still young and movement and shrinkage of the timbers as the building continues to dry out can be expected, the performance of these transitions seems to improve commiserately with the enhancements of air-sealing details in these locations.
6) Inconsistent patterns of air leakage were seen around plaster-to-window transitions, as well as sash-to-casing transitions.
7) The second-story baseboard-to-plaster connection was observed to be leaky; air fins were installed after the fact due to a construction oversight and accordingly not fully caulked in place. Overall, plaster-edge bypasses were minor, and much less than those found in other projects, particularly older projects in which the air barrier detailing was less developed.
8) Of additional note in this structure was the placement of the knee braces to the interior of the posts, to remove a significant amount of plaster-to-frame edge. This frame also featured rabbets in the frame to receive the plaster, avoiding the need for stand-aways and their associated air bypass potential as discussed in Project #3.

This is the first project we tested that was not entirely contractor-built – in fact, the majority of the enclosure system, including much of the airtight drywall installation, was executed by students. Considering the heavy involvement of students in producing the enclosure system, we feel very optimistic about the accessibility of this simple technology to obtain high performance ratings for semi-skilled installers.

Moisture probe tests indicated very high moisture content in the exterior readings behind the plaster – mid-high 20s generally, with one reading in the 30s – but considering the time of year and the tremendous amount of construction moisture held in the wall, we expect these numbers to drop in the months to come (the interior plastering was applied as late as a couple of months prior to testing). Interior and middle-of-wall readings were very encouraging, generally in the mid-teens, pointing towards a concentration of moisture to the far exterior of the building (condensation plane) during a period of time of diurnal freeze-thaw and exterior moisture drive following months of plaster application and timber drying.

Project #5: Warren, VT

This was one of the leakier buildings that was tested. The heat loss patterns indicate that this poor performance was not a failing of the design or concept of the project, but more of the components and the execution of their installation:

1) The greatest bypasses were to be found in the salvaged windows, and the sealing between the windows and R.O. The salvaged operable windows consistently showed leakages within the sashes themselves. Additionally, sealing between the window units and the frames – attempted with spray-foam – was incomplete and, in some

cases, visibly non-existent. The clerestory windows were unfinished, with side casing not fully installed and window sealing not complete.

2) The other major source of leakage was the connection between the ceiling and the chimney. This detail was never fully completed during initial installation, and subsequent follow-up detailing was not executed, leading to significant air leakage. It is interesting to note that no perceivable air leakage was witnessed through the fireplace chimney itself when smoke-tested with the blower door test running, indicating a very effective top-mounted chimney damper.
3) Plaster-to-timber frame connections at post tops, particularly corner posts, proved to be a weak link for the plaster component of the air barrier, as observed in other buildings. The losses seemed about average across the testing program.
4) Upper corners of windows were again seen to be plaster edge vulnerabilities.
5) The ceiling-to-frame and ceiling-to-straw bale wall transitions were predominantly tight, with only incidental minor bypasses noted at those boundary areas. The ceiling drywall was installed with a moderate amount of airtight drywall approach detailing. Leakage at the blocking between rafters in the roof assembly on the exterior exacerbated the effects of those weaknesses, but were minor relative to the losses in the windows and the ceiling-to-chimney boundary.
6) A very tight transition was achieved between the slab, the cellulose-insulated stud-framed knee wall below the straw bales, and the plastered straw bale wall. A masonite air barrier was installed behind the 'finish' rough wood paneling on the knee wall, which lapped under the plaster base coat to create a seamless connection to the bale walls above. Almost no air loss was observed at these transitions.

Moisture testing proved largely consistent with other year-plus-old structures; 8-10% MC on the interior to the mid-teens on the exterior. We noticed one elevated spot – 19.3% - on the east gable, where a reduced overhang coupled with raw lime plaster (no limewash to fill in the plaster's porosity) points towards the potential of elevated moisture absorption; that said, without longer-term data logging or any obvious sign of moisture intrusion, a definitive wetting source is difficult to identify.

Project #6: Granville, NY

This project featured some significant air bypasses and high number of transitions in the envelope and interruptions of the interior plaster plane:

1) The greatest source of leakage in the building was observed to be unfinished windows in the basement, as well as a large pair of 12' doors that did not have complete weather-stripping or gasketing. Other windows throughout the structure – especially those in the clerestory – proved to be somewhat leaky in the sashes themselves, while

the plaster-to-window connection issues we had seen in previous projects were largely non-existent.

2) The other major contributing factors to air leakage came at the roof, in two primary locations: in one, tongue-and-groove ceiling paneling ran all the way to the exterior over the gable walls to create the exterior soffits, allowing for significant air infiltration through each of the joints along the rake ends and clerestory wall connections to the end-walls.
3) A lack of sealing between blocking in the rafters along the eave walls proved to be a consistent source of air entry during the blower door test, as visible from both interior and exterior scans of the building.
4) There was a strong improvement in the quality of the plaster-edge air-sealing detailing throughout the entire structure. With a few small exceptions, we found no obvious signs of air infiltration between the plaster connections with either the timber frame, the floor, the tops of walls, or the windows when scanning within a tight thermal range using the IR camera with the blower door test running. Improvements in materials, caulk detailing, and quality control brought the plaster-edge air-sealing performance up to exceptionally high standards, especially considering the high amount of edge against the exposed timber frame.

Moisture test results were very favorable, showing readings generally in the single digits on the interior of the walls, and mid-teens just behind the exterior plaster skins – even where surface and pin scans and visual inspection of the exterior plaster surfaces indicated saturation or near-saturation levels. Small voids in the foam insulation in the roof have resulted in localized moisture damage on the ceiling, indicating air leakage in the ceiling leading to condensation in the roof cavity.

Project #7: Clinton, NY

The testing for the Clinton project was not as rigorous as what we were able to achieve with BPS' assistance, owing to the combination of BPS' knowledge, experience, and top-of-the-line equipment. That said, enough valuable data was recorded from this simple structure to enable a thorough analysis of its performance. This was the poorest performing building of the project by a large margin, but at the same time, exhibited some of the tightest plaster-edge detailing:

1) An unfinished metalbestos chimney perforation in the roof created an approximately one foot-square hole leaking directly into the roof cavity; the importance of addressing this and other major bypasses was discussed with the owner.

2) A very leaky ventilation port for the battery box (part of the renewable energy system), located under the open stairs in the main floor living area, was another significant bypass.
3) A 'cold closet' on the second story was the source of significant bypasses in the transitions between the closet and the exterior walls.
4) Poor air sealing around the plumbing vent stack perforation and on-demand direct-vent hot water heater vent pipe resulted in the infiltration of large volumes of air.
5) Additionally, and similar to other structures throughout the project, losses at the blocking between rafters was a notable thermal bypass, as were joints in the post-and-beam frame, which were significantly looser than those of other timber frames we had tested. It should be noted that this was a post-and-beam frame attached with metal fasteners, and not a traditional wood-joined timber frame.
6) The trusses in this building are finished in tongue-and-groove paneling for the ceiling surface. While the ceiling planes seemed relatively tight across the fields – perhaps indicating an attempt at an air barrier behind the paneling – the paneled 4' knee-walls showed consistent air leakage throughout the gaps in the paneling while the building was depressurized, indicating a lack of air barrier in the knee wall.
7) Transitions from the ceiling and knee walls to the gable end wall framing were also very leaky, while the plaster connection (gable end wall enclosures are plastered straw bale construction) to this same framing was uniformly tight.

Given the very high CFM values, it was especially notable that the plaster connections to the frame were nearly flawless, with only a handful of incidental and relatively minor leakages (in one case a few pieces of chipped plaster, and in another an upper window corner). This house featured an exposed post-and-beam frame with the orientation of the braces to the centers of the massive roundstock posts, which allowed a continuous plane of plaster behind the braces, similar to project #4.

Moisture in the straw bale walls fell within approximately the same safe ranges as for most other projects in the study, with the only slightly elevated reading (17.9% to the exterior) occurring near a break in the interior plaster, where wetting of the exterior plaster was also witnessed.

Conclusions and Recommendations

The primary goal of this research program has been to evaluate the efficacy of straw bale wall systems as components of building enclosures from a thermal and moisture standpoint by identifying both successes and failures in design and construction detailing in order to improve upon existing, and develop new, best common practices and strategies for high-efficiency designs using natural materials. To that end, conclusions and recommendations for future practice based upon the results previously identified are now offered:

High performance standards: In evaluating the table in the beginning of section 5 – Results, it can be seen that the majority of buildings passed state energy code standards for air tightness, and two projects passed state high-performance certification program standards for air tightness. This was achieved using standard air sealing detailing, and without a clear design goal of achieving any such standards. Further testing of straw bale buildings that are designed intentionally to reach even higher performance standards is necessary to understand these buildings' potential for thermal performance. Adherence to the recommendations specified herein, when placed in the context of buildings designed for optimal thermal performance, can be expected to result in buildings that qualify for certification under the Vermont Energy Star Program or similar rating systems.

Further performance testing: While blower door testing and IR imaging has been conducted on many different straw bale buildings across North America and Europe, in many cases the testing has been inconsistent, poorly documented, and occasionally inaccurate. While the research presented in this report adds to the growing body of knowledge about the performance of straw bale wall systems, particularly in cold climates, much more work remains to be done to develop a thorough understanding of the performance characteristics of different design strategies utilizing natural materials for building enclosures. It is strongly encouraged that owners, builders, and architects alike – in coordination with regional energy advocacy and certification organizations – conduct similar performance testing on their structures. Specific future testing programs should include:

- testing of buildings featuring structural systems other than exposed post-and-beam frames, such as load-bearing (structural straw bale walls) and stud-wall construction
- evaluation of energy and fuel consumption in straw bale buildings, including electricity, fuel oil, propane, wood, and/or solar energy consumption
- continued testing of different air fin strategies, including variations in material selection, caulk selection, and installation detailing
- long-term moisture performance analysis of straw bale wall systems, perhaps through permanently-embedded in-wall humidity-temperature sensors or via routine moisture probe testing, which includes tracking of interior and exterior climatological data, as well as humidity metering of interior and exterior plaster skins of different compositions (i.e. clay, lime, lime-cement)

- development and testing of high-performance hybrid wall systems, such as cellulose/straw bale wall systems designed to exceed the nominal R-28 performance of a stand-alone straw bale wall system.

Design is critical: A thorough and comprehensive design process is essential to ensure a building's overall thermal performance. **Results for nearly every project clearly show that non-straw bale components of the envelope were most responsible for thermal bypasses in the buildings.** The thermal envelope of the building, including insulation and air barriers, must be designed for in each component of the envelope (walls, roof, foundation), especially at the boundary conditions between these components. In the projects evalauated, even small oversights in design or follow-through created significant performance weaknesses. The importance of communicating efficiently and emphatically with clients, designers, and all builders involved in the project about the importance and detailing of the structure's air barrier cannot be overstated.

Detailing pays off: It is worth the time and effort invested in high-level detailing of air fins to control air leakage in plaster-edge conditions. Specifically, the use of durable and relatively flexible solid-surface materials such as homosote as gaskets, the use of permanently-flexible sealants such as Tremco Acoustical Sealant, and the minimization and sealing of all joints in the air fin system are recommended best practices, as are designs of air fins at top- and bottom-of-wall conditions that seal the plaster to adjacent components of the building envelope. **Seeing near-perfect sealing details in two different contractor-built structures featuring two different air fin materials is a confirmation of the efficacy of the strategies presented herein in reducing plaster-edge air leakage.**

Minimize transitions: Avoiding interruptions in the interior and exterior plaster planes should be a design priority when possible to avoid potential air infiltration as a result of increasing plaster-edge conditions and the associated cost implications of increased air control detailing in these areas. Examples of this include the relocation of knee braces to the center or inside face of an exposed post-and-beam frame, or changing framing style to stud-wall or load-bearing construction to minimize plaster-to-timber edges.

Rabbet wood edges to receive plaster: Rabbets should be cut into timber frames, trim, or other visible elements that will connect to the plaster plane. This will improve the aesthetic finish and simplify the process of achieving an accurate finish edge, as well as protecting the vulnerable edge of the plaster, which is prone to cracking or chipping. This will also eliminate the need for "stand-aways", reducing air leakage where they connect to the frame. Where stand-aways are used, they should completely fill the entire area behind the framing to which they are installed to avoid void spaces in the wall between stand-aways which could contribute to convective heat loss. We postulate that the increased incidence of air leakage at corner posts in some of the projects was a result of vertical cavity space created by stand-aways that did not fill the entire depth behind the post. When stand-aways are used, care should also be taken to seal them completely to frames, particularly rough-faced frames.

Exposed frames are difficult to make air-tight: Analysis of the seven projects presented here suggests that straw-wrapped timber frames are inherently challenging to air seal. In addition to plaster-to-wood boundaries, gaps in joints of exposed frames are themselves potential air bypasses. The joints of antique or loosely-jointed frames should be presumed to be leaky and in need of sealing in some capacity. In designs requiring exceptional thermal performance – such as net-zero buildings or PassiveHouses, it is recommended that every timber joint be treated in some fashion to avoid air infiltration through the joint.

Protect the plaster air barrier: As the primary wall air barrier of the building, the protection of the plaster finish is important. This includes the judicious use of trim in vulnerable areas, such as wainscoting or baseboard trim. Routine repair and maintenance of plastered finishes should also be seen as a necessary component of ensuring the long-term performance of the building.

Avoid envelope penetrations: Avoiding through-wall penetrations, particularly of timber framing or any conductive materials such as metal, should be a design priority. In addition to the conductive heat losses these penetrations facilitate, they can be particularly difficult to seal effectively to the plastered finish. This is especially true of green timbered elements, which are expected to shrink upon drying in the first few years following construction, and in which cracks or 'checks' can readily transmit bulk volumes of air into or out of the building.

Quality control is critical: While air-sealing strategies are for the most part straight-forward to design and simple to execute, a process of quality control during and following installation is important to ensure the efficacy of the strategy, particularly when caulking or installing air fins. Irregularities and incidental thermal bypasses in air fin systems were observed in many buildings in the testing program, indicating problems most likely caused by field installation. Such bypasses may be avoided when a sound quality control process is implemented.

Regarding moisture, from the aggregated results of testing conducted in this program and in prior testing regimens, a few preliminary conclusions can be drawn.

Safe storage: The plaster system of one-to-two earthen base coats followed by a lime finish coat does a satisfactory job of storing exterior-sourced moisture and protecting the straw core within, as evidenced repeatedly by high moisture content plaster coats with relatively low moisture content straw immediately adjacent behind the exterior plaster.

Convection leads to moisture: There is a direct correlation of convective losses and increased moisture concentration, particularly in the upper half of the structure, as evidenced repeatedly by elevated moisture content in exterior readings taken in air bypass cracks in plastered straw bale walls.

Ventilation is only part of the solution: An active HRV and generally tight house are not necessarily enough to halt condensation from the convective losses that do exist, and further exploration and testing is needed to draw clear relationships between ventilation rates, overall building tightness, localized convective losses, and condensation concentrations to understand both conditions of condensation potential, safe tolerances of convective loss in regards to condensation loading, and mitigation strategies (such as post-construction sealing or controlling ventilation rates).

Moisture levels stabilize to a safe level: Based on the data accumulated in this research, for a well-designed structure, and disregarding incidental anomalies, plastered straw bale wall systems can be expected to normalize to a moisture content range of between 6-18%, varying seasonally and throughout the depth of the wall cavity, after construction moisture has dried out of the building. This stands true even for plastered multi-story buildings with high levels of exposure with nominal 24" overhangs. Further long-term study is needed to confirm these results.

These conclusions reinforce now-standard recommendations of moisture protection for straw bale wall systems, including but not limited to:

- **adequate bottom-of-wall protection**, including 18" minimum separation from grade and positive capillary and vapor breaks between straw bale wall and foundation
- **adequate top-of-wall protection**, including 24" minimum roof overhangs for all but the most well-protected (i.e. wood-sided) or sheltered single-story buildings
- **durable exterior protection**, either in the form of a rainscreen siding system, a lime plaster coat finished with limewash or siloxane, silicate, or other vapor-permeable sealer, or an earthen plaster coat stabilized with limewash or siloxane, silicate, or other vapor-permeable sealer, and regularly inspected for maintenance and upkeep
- **implemented strategies to reduce condensation**, including air-tight construction with careful control of all transitions and boundary conditions, appropriate design and installation of whole-house ventilation, and management of interior relative humidity between 30-50%.
- **allowance for drying potential of building envelopes**, including roof ventilation, use of vapor permeable surface materials such as plywood, drywall, and gypsum-, clay-, and lime-based plasters and paints, avoidance of vapor reducing surface materials such as bituthene, polyethylene vapor barriers, and cement stucco, and the use of hydrophilic materials such as cellulose, straw, and clay, rather than hydrophobic materials such as foam.

Appendix A – Energy Performance of Straw Bale Buildings Research Program Aggregated Results Chart

THERMAL CHARACTERISTICS OF SELECTED STRAW BALE HOMES – as tested between 3/10/11 – 4/5/2011 by Building Performance Services LLC for New Frameworks Natural Building, LLC

TOWN	BUILT	WX	WX temps	BDT (CFM50)	HEATED SqFt	VOLUME CuFt	EXT. SURFACE-SqFt	Stories/ Exposure	ACH-50	ACH-NAT	CFM50/ Ext.SqFt
Brookfield, VT	2009	rainy	68IN 32OUT	557	1272	13360	3748	2/normal	2.50	0.18	0.15
Barnet, VT*	2008	snow/sleet; breezy	58IN 31OUT	2139	2096	27329	5829	2.5/exposed	4.70	0.40	0.37
Barnet, VT*	1998	snow/sleet; breezy	58IN 31OUT	3015	2692	32117	7705	2.5/exposed	5.63	0.49	0.39
Newbury, VT	2011	cloudy	58IN 36OUT	767	1537	13400	4539	1.5/exposed	3.43	0.25	0.17
Middlesex, VT**	2010	cloudy	66IN 34OUT	850	2448	19844	6506	2.5/exposed	2.57	0.20	0.13
Warren, VT	2009	mostly cloudy	62IN 43OUT	552	456	5028	2535	1.5/low	6.59	0.36	0.22
Granville, NY	2010	rainy; breezy	65IN 40OUT	2057	2931	33221	7091	3/exposed	3.72	0.34	0.29
Clinton, NY***	2010	snow/sleet; breezy	68IN 35OUT	1756	1190	8921	2888	1.5/exposed	11.81	1.02	0.61

TOWN	ROOF STYLE	CEILING Style	WALL-Framing	FOUNDATION Type	AIR FIN - Type	AIR FIN - Quality	HEAT SOURCE	VENTILATION
Brookfield, VT	SIPS	Cathedral; drywall finish	Timber Frame	slab on grade; 2" PIC edge insul.	Masonite	High	Masonry Heater w/ in-slab radiant loop	Venmar HRV, concentric in/out
Barnet, VT (addition)*	N/A	Cathedral; drywall/ Paneling finish	Timber Frame	Full basement + SOG****	Paper and Lath	Medium	Wood stove	Exhaust-only fan
Barnet, VT (total)*	N/A	Cathedral; drywall/ paneling finish	Timber Frame	Full basement + SOG**** + crawl	Paper and Lath	Low (cabin) /Medium	Wood stove	Exhaust-only fan
Newbury, VT	16.5" built-up rafters with 1/4" foam thermal break, dense-pack cellulose	Cathedral; drywall finish	Timber Frame	SOG**** + root cellar	1/2" Drywall	High	Wood Stove	Venmar HRV
Middlesex, VT**	Lattice-frame, 16" dense-pack cellulose, 2 dormers (1 shed, 1 gable)	Cathedral; ADA***** finish	Timber Frame	Full basement – R-20/28 Durisol Block	Paper and Lath/ Homosote	High	Propane-fired in-slab radiant, wood fireplace	HRV
Warren, VT	Clerestory, 16" double-rafters and 12" clerestory wall with dense-pack cellulose	Cathedral; ADA***** finish	Timber Frame	slab on grade, 2" foam insulation	Paper and Lath/ Homosote	High	Wood stove, DV propane space heated in-slab radiant	None
Granville, NY	Site-built 12” foam panels; Clerestory salt-box	Cathedral; T&G paneling finish	Timber Frame	Walk-out two-side basement, 2" foam insulation (incomplete)	Paper and Lath/ Masonite	High	Wood and propane-fired (duel-fuel) in-slab radiant	Bath exhaust fan exhausts to basement

Clinton, NY***	Trusses, dense-pack cellulose;	Cathedral, T&G paneling finish	Post-and-Beam Frame	Rubble-trench; earth floor/S.O.G with Durisol stem wall, 2" foam insulation	Paper and Lath/Homosote	High	Wood stove	None

* (Addition) refers to large primary residence and breezeway; (total) includes original small cabin, attached
** Tested by Matt Sargent of Vermont Energy Investment Corporation, Burlington, VT
*** Tested by Richard Robinson, Advanced Energy Systems of New York, Utica, NY
**** Slab-On-Grade
***** Air-tight Drywall Approach serving as ceiling air barrier

NOTES:

- Brookfield: Masonry heater is only heat source
- Barnet (addition): Primary heat loss through cupola with no air barrier, breezeway connections to structure, occasional plaster edge detailing
- Barnet (total): Cabin featured no plaster-edge air barriers
- Newbury: Still in construction, nearing completion; chimney-to-ceiling connection and incidental plaster edge and dormer edge air sealing to be completed before finish
- Middlesex: Primary heat loss through chimney-to-ceiling connection, incidental plaster edge detail; ADA and majority of plaster edges tight
- Warren: Primary heat loss through chimney-to-ceiling connection, salvaged windows, clerestory window-to-frame (not sealed)
- Granville: Primary heat loss through ceiling t&g paneling (runs through wall), eave-end rafter blocking, ceiling-to-frame connection, clerestory wall edges and windows, basement windows and doors (some windows missing, temp. plastic, no weatherstripping); plaster edges very tight
- Clinton: Primary heat loss through ceiling and knee walls (no air barrier), chimney-to-ceiling connection, through-wall ventilation port; plaster edges very tight
- Vermont Energy Star Homes (VESH)-rated 2009 building average value: 3.2 ACH50

Appendix B – Project Infrared Reports

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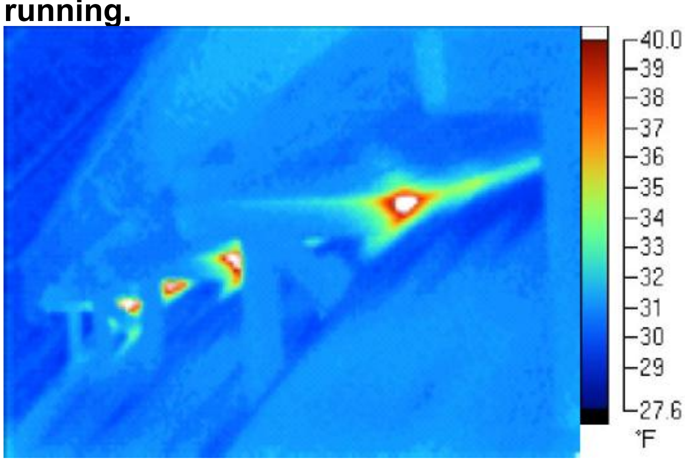
IR Report for Energy Performance of Straw Bale Buildings Research Program

Brookfield Project-11119

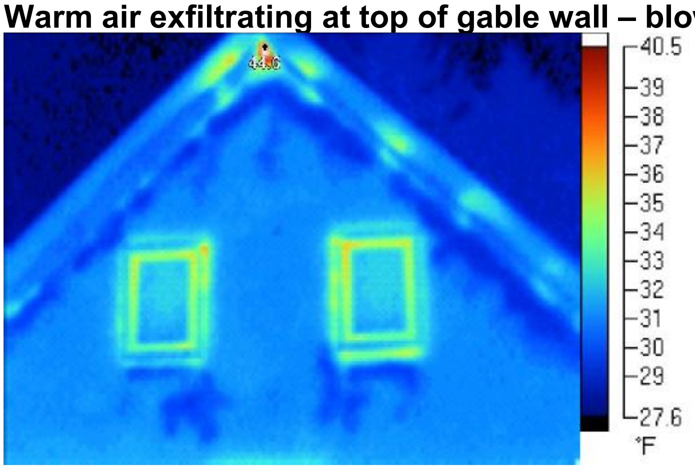
This is looking at the east eaves (at an angle). Warm air is leaking out at each rafter tail, with the warmest spots at about 48 deg.F. The blower door is NOT running.



Visible Light Image

IR20110310_0446.is2
3/10/2011 2:19:32 PM
68 deg.IN/32 deg.OUT; rain/sleet

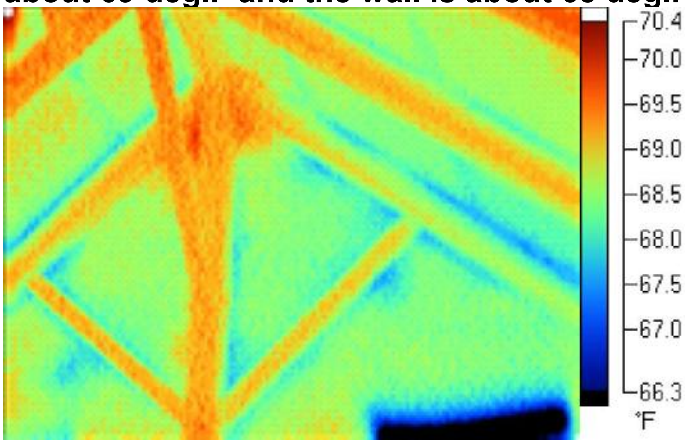
Warm air exfiltrating at top of gable wall – blower door is NOT running



Visible Light Image

IR20110310_0459.is2
3/10/2011 2:38:06 PM
68 deg.IN/32 deg.Out; rain/sleet

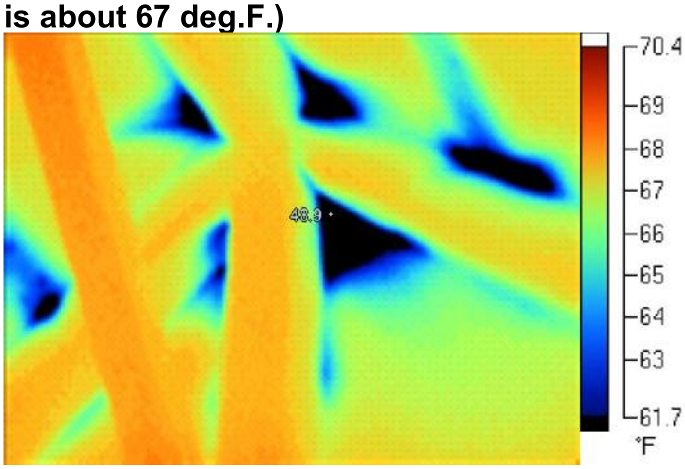
You can't see it with IR from the inside, but warm air is leaking out at the top of the gable wall (blower door NOT running). The top of the wall and posts are at about 69 deg.F and the wall is about 68 deg.F.

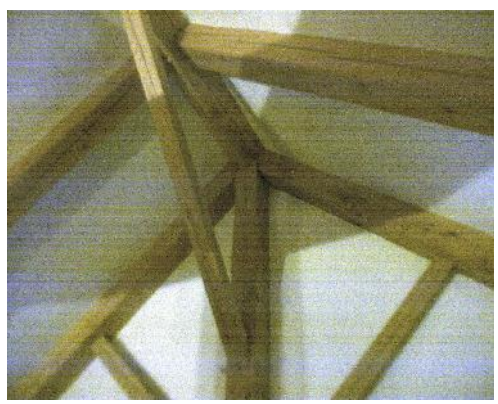


Visible Light Image

IR20110310_0465.is2
3/10/2011 3:24:44 PM
68 deg.IN/32 deg.OUT; rain/sleet

The blower door is now blowing OUT and the cold air is coming back in at the top of the gable wall. The coldest part of the wall is now 49 deg.F (the rest of the wall is about 67 deg.F.)

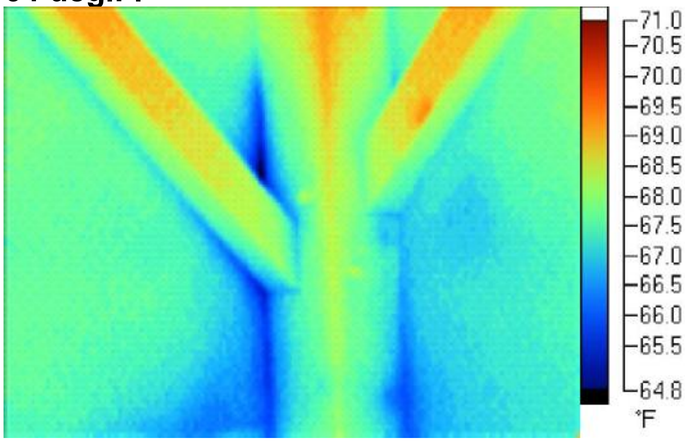




Visible Light Image

IR20110310_0491.is2
3/10/2011 5:48:40 PM
68 deg.IN/32 deg.OUT; rain/sleet

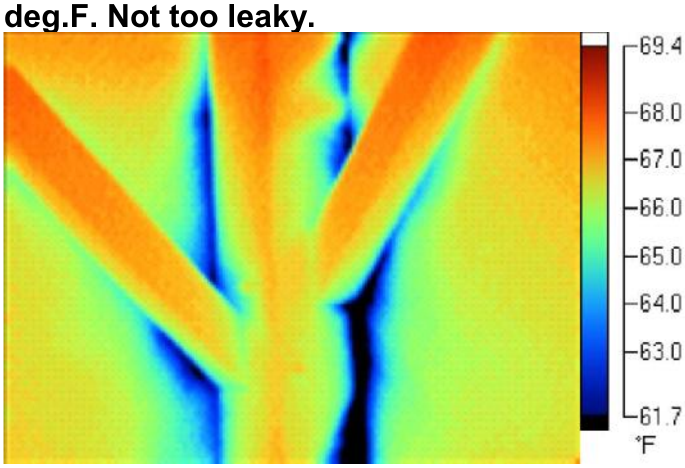
This is a corner post, without the blower door running. The coldest spot is about 64 deg.F.



Visible Light Image

IR20110310_0463.is2
3/10/2011 3:09:53 PM
68 deg.IN/32 deg.OUT; rain/sleet

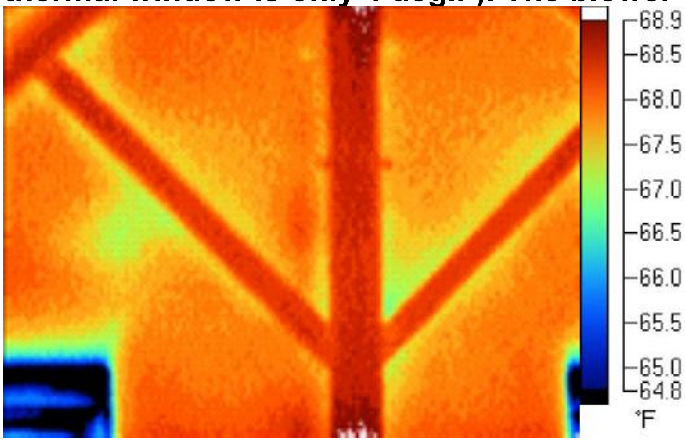
Here is the same corner post with the blower door running. The coldest spot is 57 deg.F. Not too leaky.

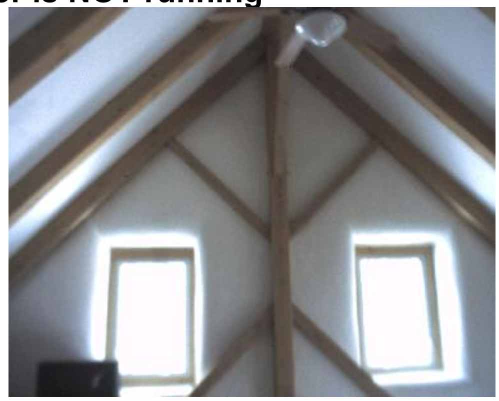


Visible Light Image

IR20110310_0480.is2
3/10/2011 5:26:54 PM
68 deg.IN/32 deg.OUT; rain/sleet

This is a post in the gable end wall. There do not appear to be any leaks here (the thermal window is only 4 deg.F). The blower door is NOT running

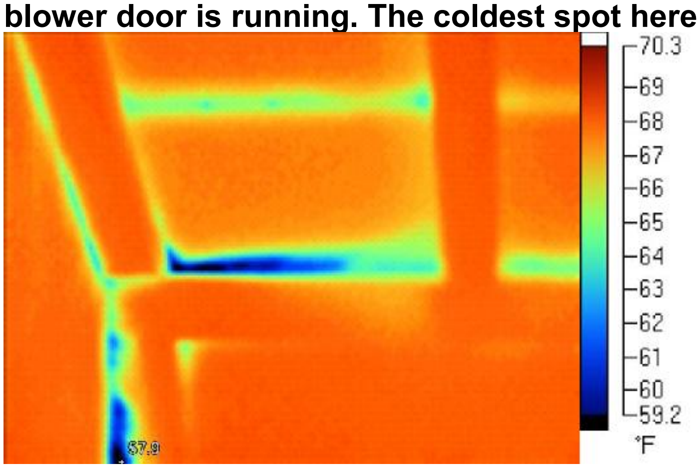




Visible Light Image

IR20110310_0469.is2
3/10/2011 3:37:17 PM
68 deg.IN/32 deg.OUT; rain/sleet

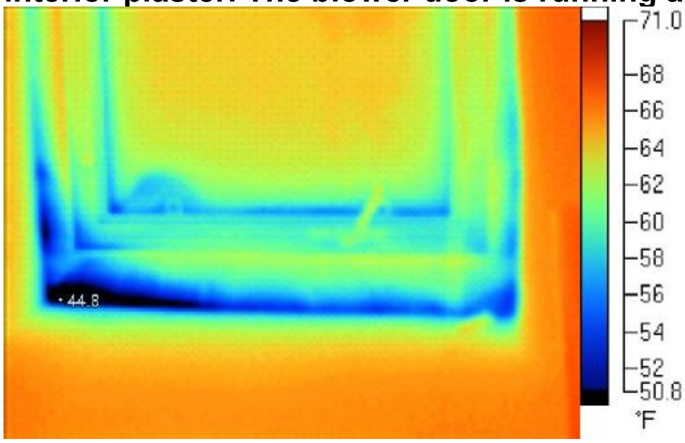
Here is some air leakage at posts and beams at the corner, but not a lot. The blower door is running. The coldest spot here is 58 deg.F.



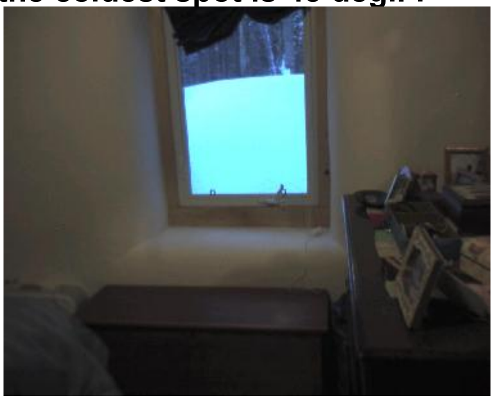
Visible Light Image

IR20110310_0488.is2
3/10/2011 5:42:41 PM
68 deg.IN/32 deg.OUT; rain/sleet

This is a classic IR image of air infiltration. It is between a window jamb and the interior plaster. The blower door is running and the coldest spot is 45 deg.F.



IR20110310_0482.is2
3/10/2011 5:32:53 PM
68 deg.IN/32 deg.OUT; rain/sleet



Visible Light Image

Summary

- Tightest building overall
- At 32 degF, very little temperature difference throughout the house in structure (1 degF difference between peak of cathedral to base of back bedroom)
- Leaks noted at occasional corner posts, gable timber frame transitions (to plaster, ceiling), occasional windows
- Timber joints and bottom- and top-of-wall transitions very tight
- Surface, pin, and probe moisture metering at area of exterior plaster wetting indicated a low transfer of moisture to straw wall within

Notes

IR images are subject to interpretation. Note the temperature range in each. Temperature differences of one or two degrees can appear to be very different in color, but actually be close in temperature. Check the scale in each image.

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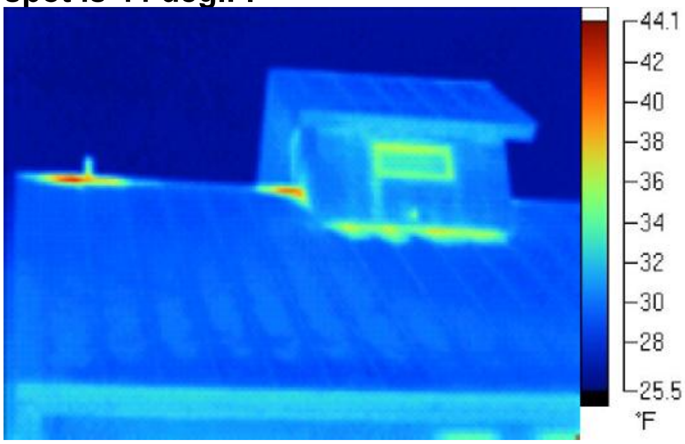
IR Report for Energy Performance of Straw Bale Buildings Research Program

Barnet Project-11120

Heat loss at cupola and vent stack pipe. Blower door is NOT running. Warmest spot is 44 deg.F.

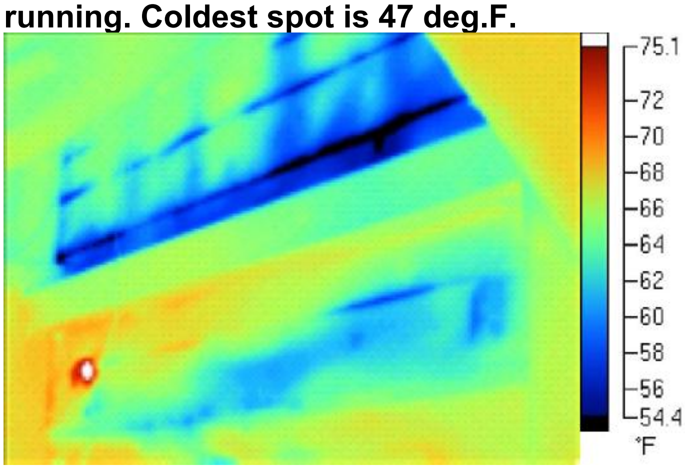


Visible Light Image

IR20110316_0531.is2

3/16/2011 10:00:56 AM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

Air is now leaking IN to the south side of the cupola, with the blower door running. Coldest spot is 47 deg.F.

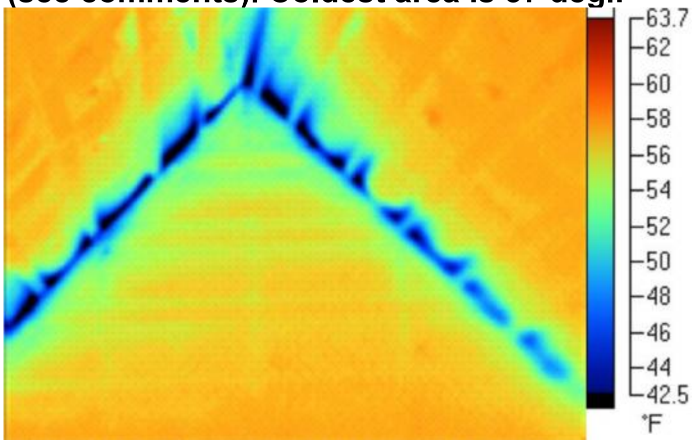


Visible Light Image

IR20110316_0622.is2

3/16/2011 2:45:17 PM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

Cathedral ceiling of large mudroom, with plastic only. With blower door running, there is a lot of leakage at the top of the gable wall, which is why strapping is bad (see comments). Coldest area is 37 deg.F

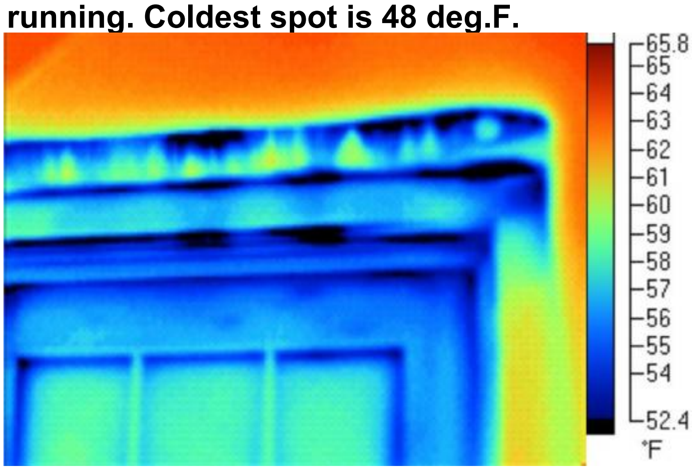


Visible Light Image

IR20110316_0658.is2
3/16/2011 3:18:48 PM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

Strapping on a ceiling (or wall) creates an air space that will allow any air that leaks into that space to travel anywhere else in that plane to continue its journey out (or in).

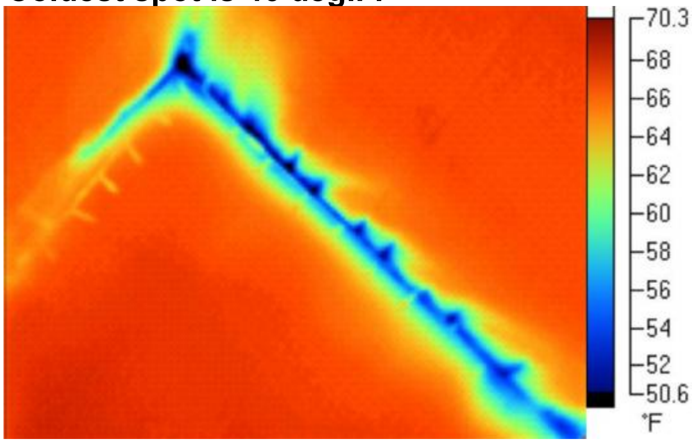
Air infiltration at west entry door, around jamb and lintel, with blower door running. Coldest spot is 48 deg.F.



Visible Light Image

IR20110316_0603.is2
3/16/2011 2:15:36 PM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

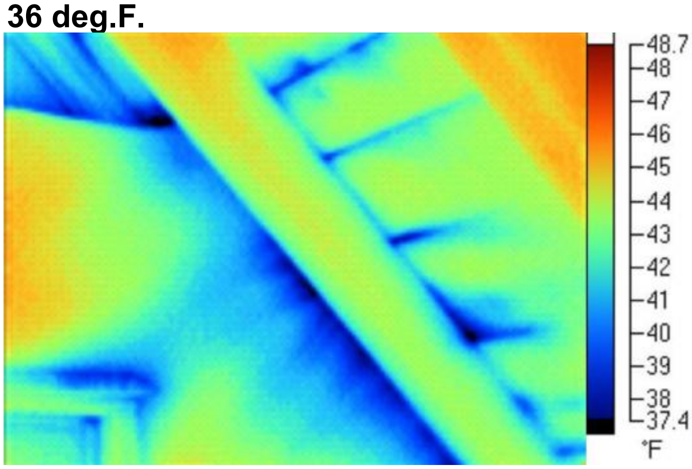
This is the east gable end of the main house, with the blower door running. Coldest spot is 46 deg.F.



Visible Light Image

IR20110316_0620.is2
3/16/2011 2:42:36 PM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

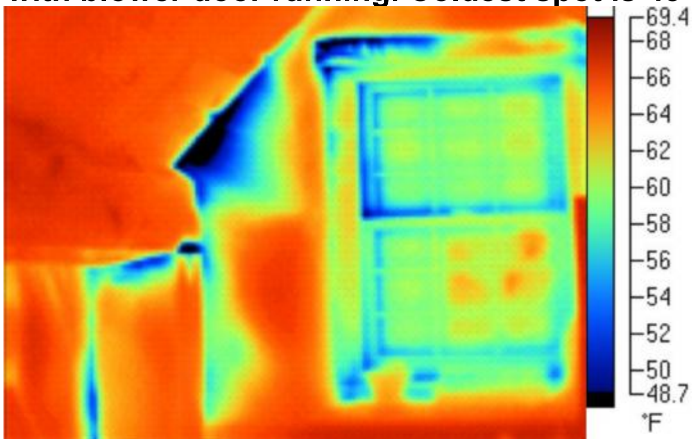
Air leaks at gable end of original house, with blower door running. Cold spot is 36 deg.F.



Visible Light Image

IR20110316_0673.is2
3/16/2011 3:32:10 PM
58 deg.IN/31 deg.OUT; snow/sleet;

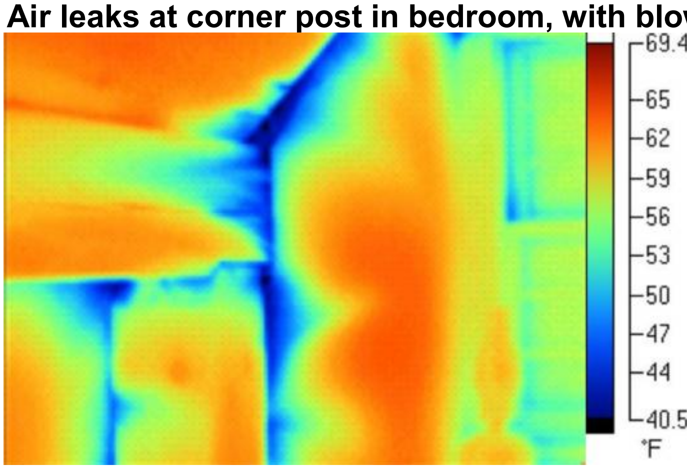
Lots of air leakage at rolled beam in east bathroom, and at top of window at lintel, with blower door running. Coldest spot is 43 deg.F.



Visible Light Image

IR20110316_0615.is2
3/16/2011 2:28:32 PM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

Air leaks at corner post in bedroom, with blower door running.



Visible Light Image

IR20110316_0643.is2
3/16/2011 3:09:47 PM
58 deg.IN/31 deg.OUT; snow/sleet;
upstairs is warmer (68 deg.F)

Summary

- Complete connection from basement through breezeway through building to cupola
- Early air finning - little caulk used, incomplete installations; noted improvement from old cabin to new construction despite moderate installation practices
- Most significant leaks involved with cupola, breezeway (conventional framing and cellulose insulation)
- Additional leaks at corner posts, basement band joist (foam insulation), rolled timber (see IR report), occasional windows and doors, top-of-wall at gables
- There is no ventilation system nor exhaust fans in this building. The dryer vents to the inside, in the basement.

Note

IR images are subject to interpretation. Note the temperature range in each. Temperature differences of one or two degrees can appear to be very different in color, but actually be close in temperature. Check the scale in each image.

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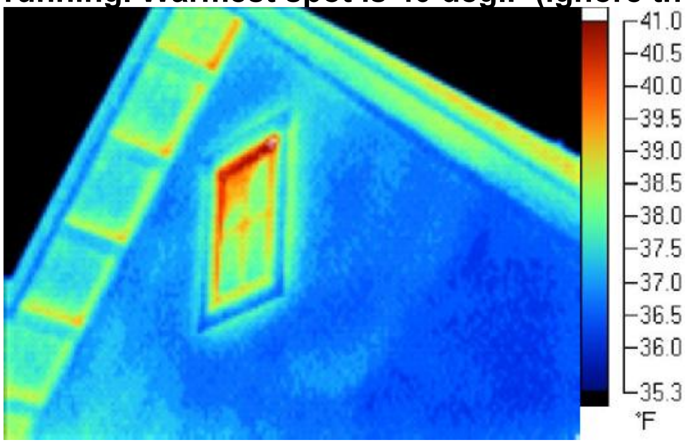
IR Report for Energy Performance of Straw Bale Buildings Research Program

Newbury Project-11121

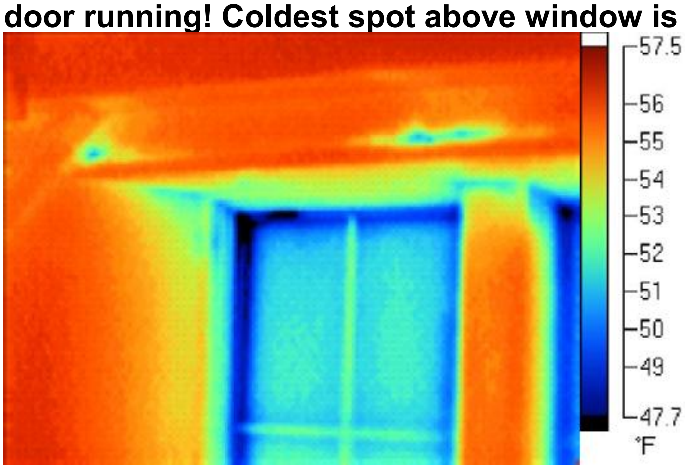
Top of gable wall shows essentially no warm air leaking out. Blower door is NOT running. Warmest spot is 40 deg.F (ignore the window).

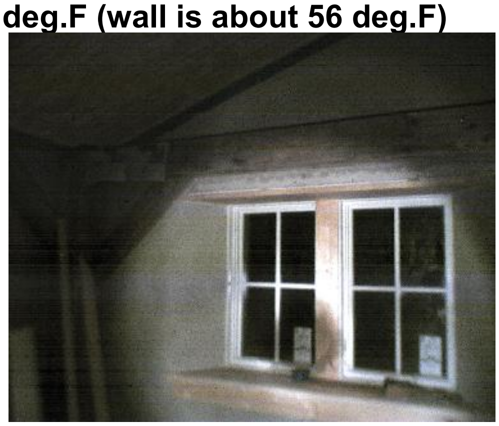


Visible Light Image

IR20110316_0681.is2
3/16/2011 4:58:14 PM
58 deg.IN/36 deg.OUT/ cloudy

Window in NE bedroom (1st floor) shows very little air infiltration with blower door running! Coldest spot above window is 51 deg.F (wall is about 56 deg.F)

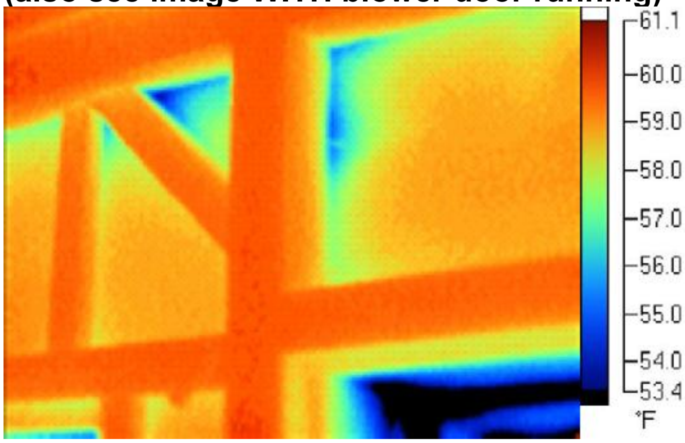




Visible Light Image

IR20110316_0741.is2
3/16/2011 7:53:41 PM
58 deg.IN/36 deg.OUT/ cloudy

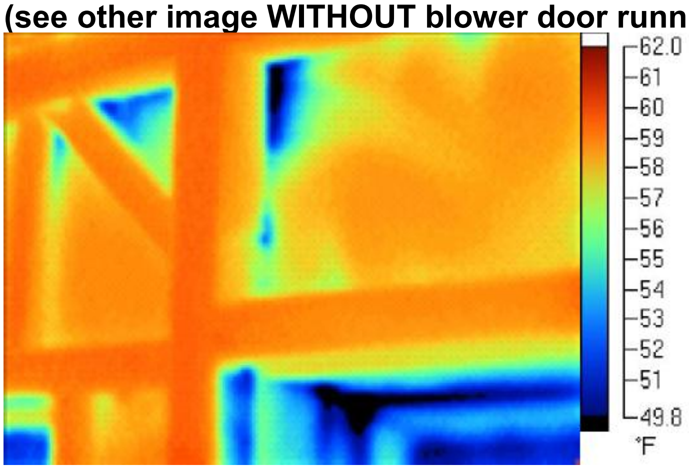
South wall framing above door, with blower door NOT running. Coldest spot is 53 deg.F.
(also see image WITH blower door running)



Visible Light Image

IR20110316_0717.is2
3/16/2011 6:07:31 PM
58 deg.IN/36 deg.OUT/ cloudy

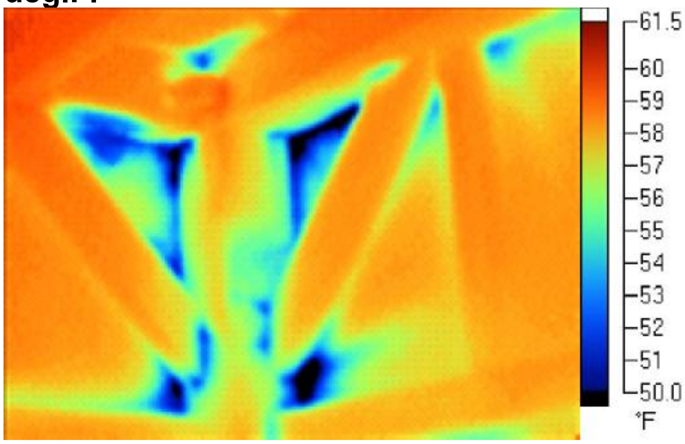
South wall framing above door, blower door is running. Coldest spot is 48 deg.F.
(see other image WITHOUT blower door running)



Visible Light Image

IR20110316_0749.is2
3/16/2011 8:03:00 PM
58 deg.IN/36 deg.OUT/ cloudy

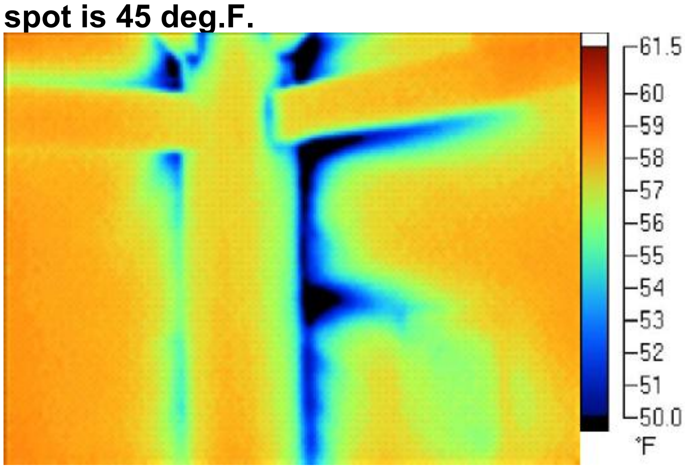
Air infiltration at SE corner posts, with blower door running. Coldest spot is 47 deg.F.



Visible Light Image

IR20110316_0745.is2
3/16/2011 7:59:53 PM
58 deg.IN/36 deg.OUT/ cloudy

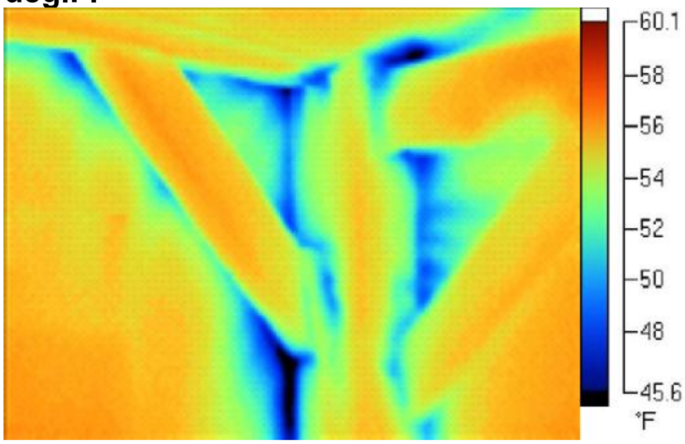
Air infiltration at SE corner posts, lower part, with blower door running. Coldest spot is 45 deg.F.

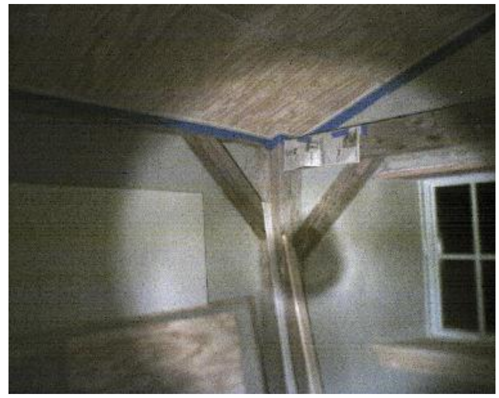


Visible Light Image

IR20110316_0746.is2
3/16/2011 8:00:15 PM
58 deg.IN/36 deg.OUT/ cloudy

Air infiltration at NE corner posts, with blower door running. Coldest spot is 43 deg.F.

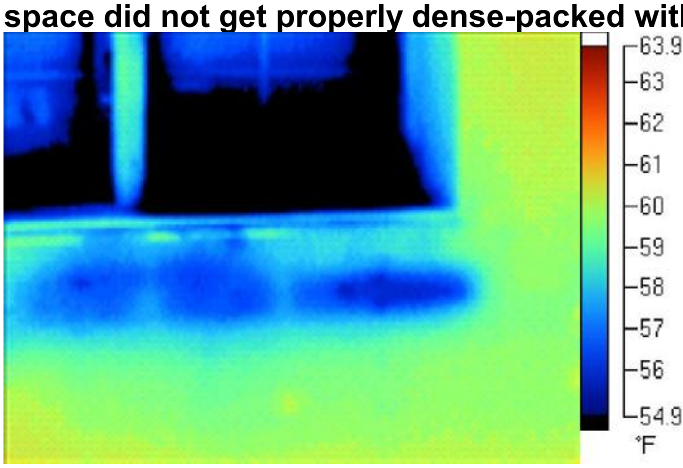


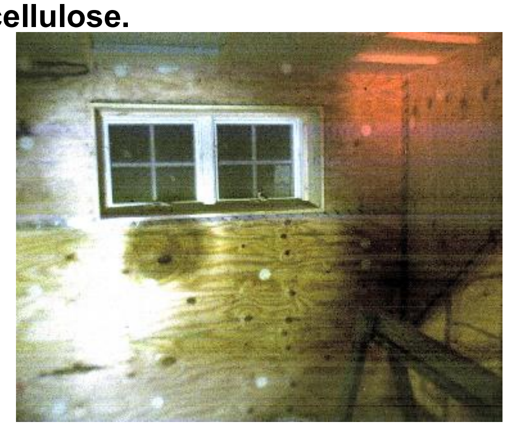


Visible Light Image

IR20110316_0740.is2
3/16/2011 7:52:56 PM
58 deg.IN/36 deg.OUT/ cloudy

This area below an upstairs (north) window is about 5 deg.F below the surrounding wall, with the blower door running. The rough opening for the window had been made smaller. It may be an indication that the small framing space did not get properly dense-packed with cellulose.





Visible Light Image

IR20110316_0761.is2
3/16/2011 8:21:23 PM
58 deg.IN/36 deg.OUT/ cloudy

Summary

- building still under construction, in finishing stages
- Irregular frame made sealing stand-aways to timbers very difficult
- Large leak at chimney perforation
- Incomplete celllulose install below dormer windows (see IR report)
- Leaks at post top and knee transitions, and within framing joints themselves
- Leaks at corner posts between posts and stand-aways
- Despite these leaks, overall this is a very tight house, with the opportunity still available to seal up existing leaks before finishing

Note

IR images are subject to interpretation. Note the temperature range in each. Temperature differences of one or two degrees can appear to be very different in color, but actually be close in temperature. Check the scale in each image.

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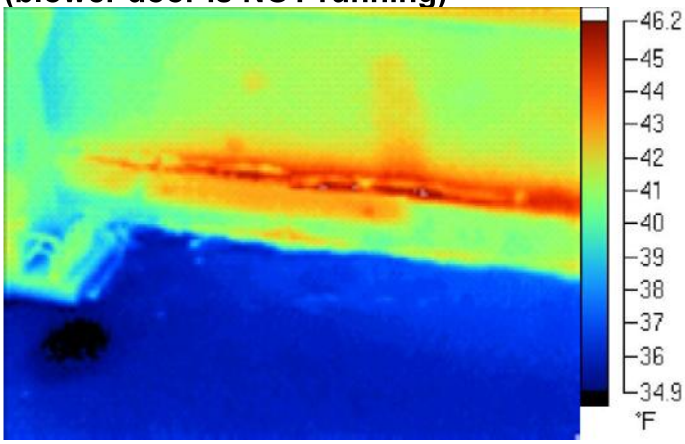
IR Report for Energy Performance of Straw Bale Buildings Research Program

Warren Project-11122

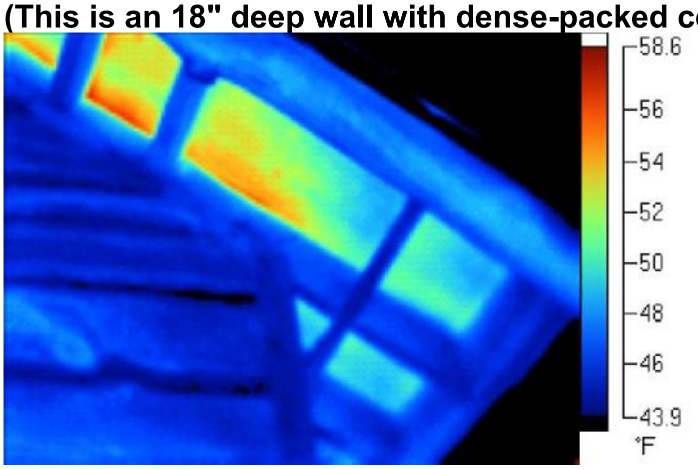
Heat loss at top of stem wall, which is sitting several inches above the concrete slab of carport. Warmest spot is 46 deg.F, while rest of wall is about 41 deg.F (blower door is NOT running)



Visible Light Image

IR20110331_0843.is2
3/31/2011 1:55:34 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

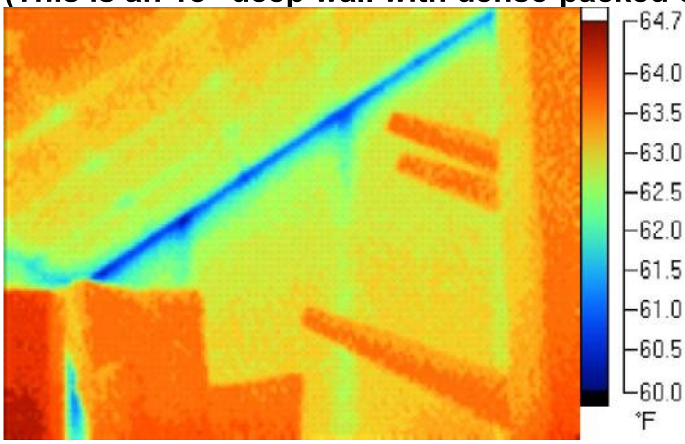
Heat loss at rake, top of east gable wall. Blower door is NOT running. Warmest spot is 57 deg.F, while rest of wall is about 45 deg.F. (This is an 18" deep wall with dense-packed cellulose)



Visible Light Image

IR20110331_0862.is2
3/31/2011 2:17:23 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

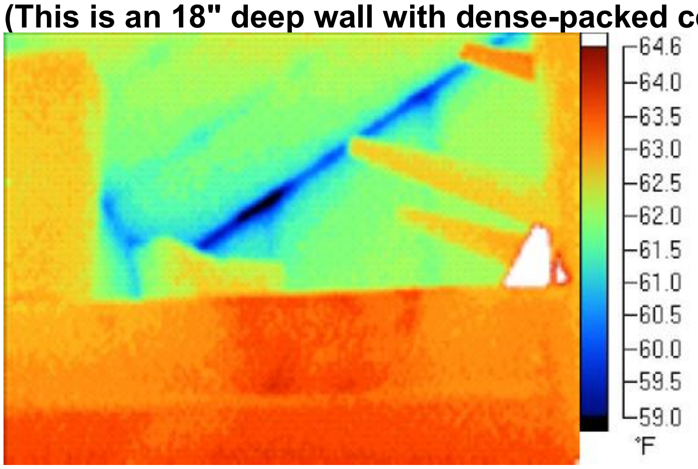
Top of east gable wall (this is the interior view of where heat loss was seen at exterior rake above), with blower door NOT running. Not a lot of temperature difference here. Coldest spot is 60 deg.F, with rest of wall at about 63 deg.F. (This is an 18" deep wall with dense-packed cellulose)



Visible Light Image

IR20110331_0877.is2
3/31/2011 2:55:55 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

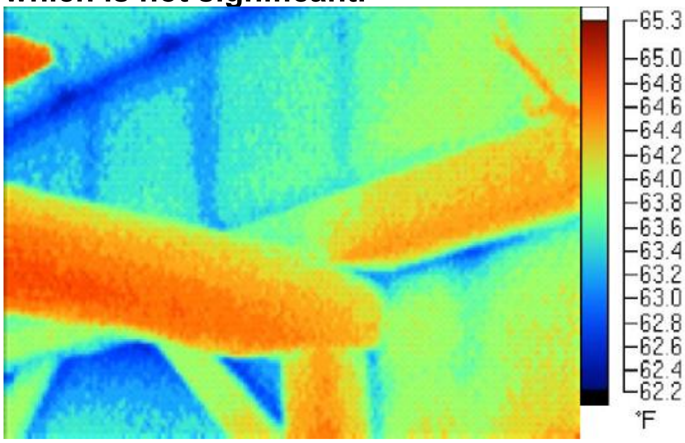
Same east gable end wall, WITH blower door running. Now the coldest spot is 58 deg.F with the rest of the wall at about 62 deg.F. Not a big change with the blower door running.
(This is an 18" deep wall with dense-packed cellulose)



Visible Light Image

IR20110331_0878.is2
3/31/2011 4:01:23 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

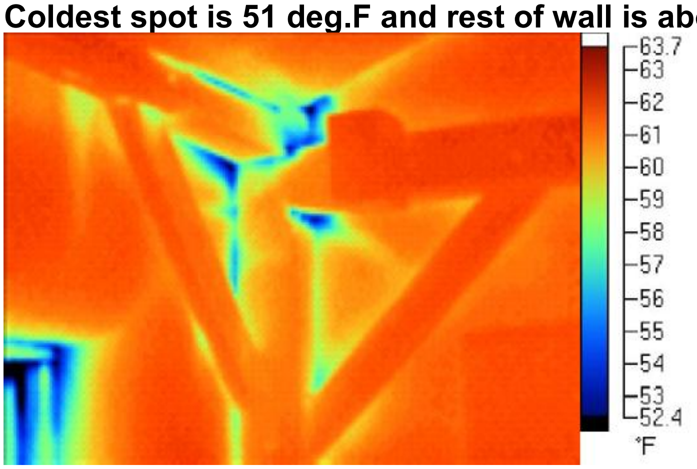
This is the post and beam in the middle of the north wall, with NO blower door running. Maximum temperature difference of wall in this area is only 2 degrees, which is not significant.



Visible Light Image

IR20110331_0868.is2
3/31/2011 2:44:06 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

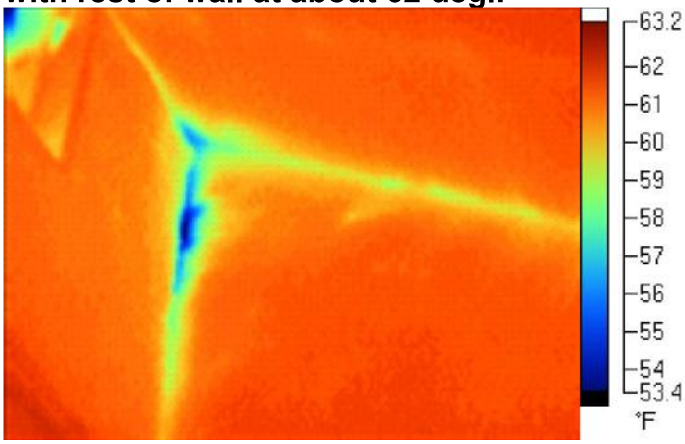
Air leakage at corner post/beams in SW corner, WITH blower door running. Coldest spot is 51 deg.F and rest of wall is about 62 deg.F



Visible Light Image

IR20110331_0879.is2
3/31/2011 4:01:52 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

Top of west clerestory wall. WITH blower door running. Coldest spot is 52 deg.F with rest of wall at about 62 deg.F



IR20110331_0881.is2
3/31/2011 4:03:08 PM
62 deg.IN/ 43 deg.OUT; mostly cloudy

Visible Light Image

Summary

- Knee walls are tight
- Ceiling-to-plate connections throughout roof are good
- Chimney damper very effective!
- Massive window losses, both in windows and sealing to R.0.s
- Windows are salvaged
- Building is student and volunteer-built
- ADA approach for ceiling, moderate detailing
- Large losses around ceiling-to-chimney connection
- Corner post, top of wall, window corner greatest plater edge losses
- Exterior rafter blocking unsealed - heat losses

Note

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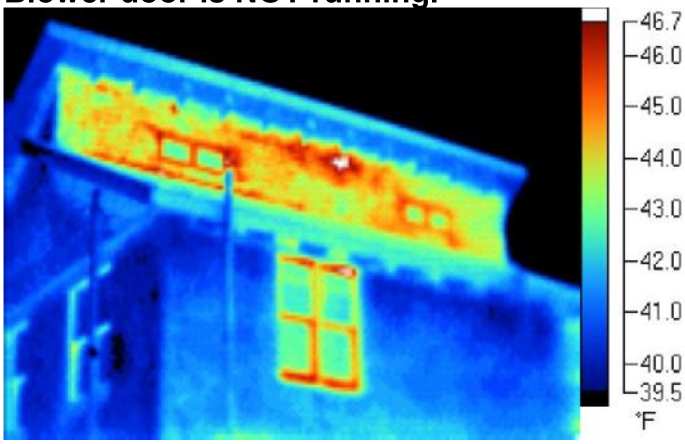
IR Report for Energy Performance of Straw Bale Buildings Research Program

Granville Project-11123

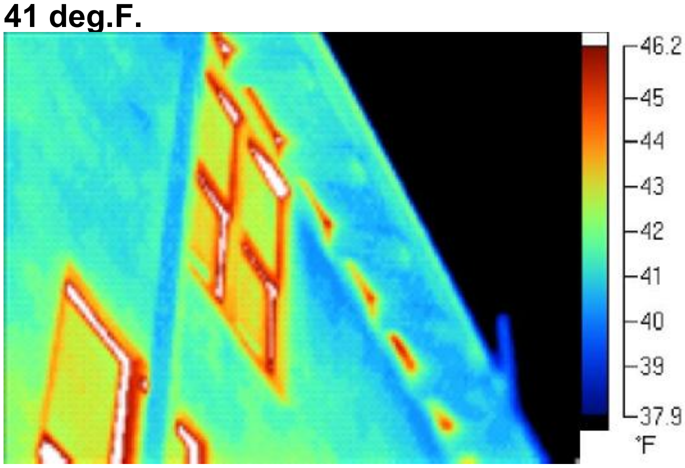
Heat loss at clerestory wall (facing east). Warmest spot is 47 deg.F, at top of wall. Blower door is NOT running.



Visible Light Image

IR20110404_0924.is2
4/4/2011 12:14:54 PM
65 deg.IN/40 deg.OUT; rain and wind

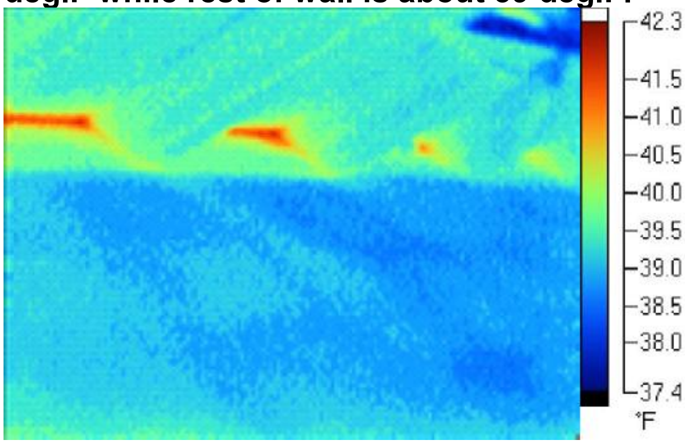
Heat loss at eaves of east facing clerestory. Blower door is NOT running. Warmest spot at eaves is 48 deg.F (ignore windows), while rest of wall is about 41 deg.F.



Visible Light Image

IR20110404_0930.is2
4/4/2011 12:19:23 PM
65 deg.IN/40 deg.OUT; rain and wind

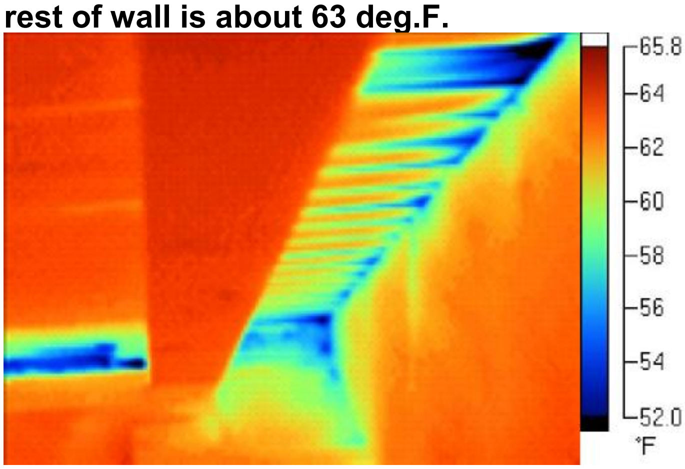
Heat loss at eaves of west wall, with NO blower door running. Warmest spot is 42 deg.F while rest of wall is about 39 deg.F.



Visible Light Image

IR20110404_0905.is2
4/4/2011 11:41:35 AM
65 deg.IN/40 deg.OUT; rain and wind

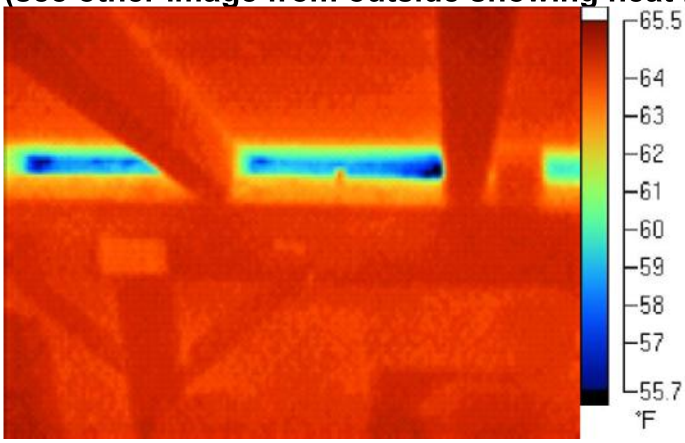
Air infiltration at T&G (joints) in ceiling, looking down on west eaves at north gable end, from inside. Blower door IS running. Coldest spots are 49 deg.F, while rest of wall is about 63 deg.F.



Visible Light Image

IR20110404_0974.is2
4/4/2011 3:20:35 PM
65 deg.IN/40 deg.OUT; rain and wind

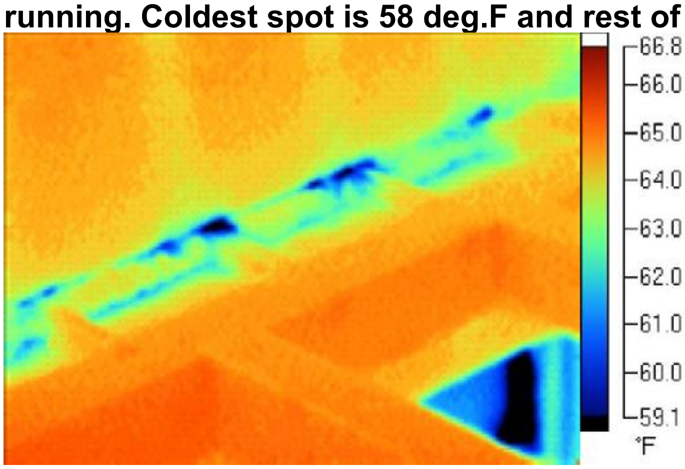
Looking down on west eaves from inside. Blower door is NOT running. Coldest spot is 47 deg.F, while rest of wall is about 64 deg.F.
(see other image from outside showing heat leaking out)



Visible Light Image

IR20110404_0977.is2
4/4/2011 3:28:34 PM
65 deg.IN/40 deg.OUT; rain and wind

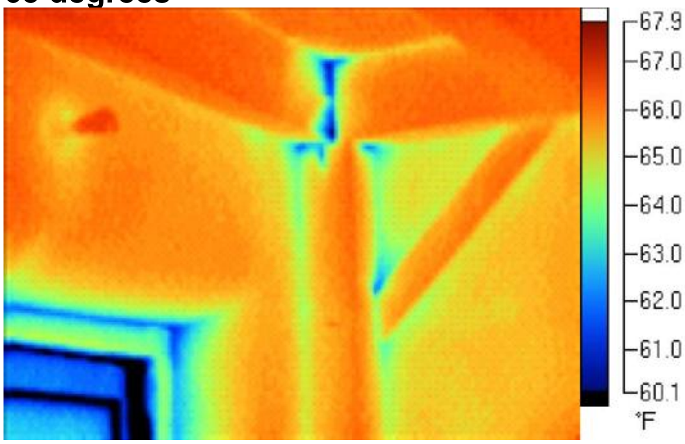
This is the top of the south wall below the clerestory. The gaps here had been foamed with a one-part foam, but several spots were missed. The blower door IS running. Coldest spot is 58 deg.F and rest of wall is at about 64 deg.F.



Visible Light Image

IR20110404_0979.is2
4/4/2011 3:29:09 PM
65 deg.IN/40 deg.OUT; rain and wind

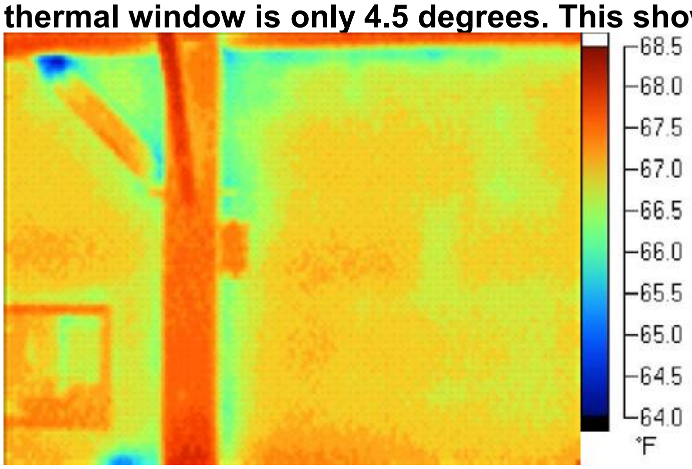
Post and beams at SE corner of 1st floor, WITH blower door running, showing not much air leakage. coldest spot in corner is 59 deg.F and rest of wall is about 65 degrees



Visible Light Image

IR20110404_0989.is2
4/4/2011 4:16:51 PM
65 deg.IN/40 deg.OUT; rain and wind

This is the post and beam in the middle of the west wall of 1st floor. The blower door IS running. Coldest spot is 64 deg.F and rest of wall is about 67 deg.F. The thermal window is only 4.5 degrees. This shows little air infiltration!



Visible Light Image

IR20110404_0990.is2
4/4/2011 4:18:04 PM
65 deg.IN/40 deg.OUT; rain and wind

Summary

- Significant losses in all basement fenestrations
- Significant heat loss through basement walls
- T&G at ceiling/clerestory wall running through envelope - very leaky
- Framed gable wall connection to bale walls/timber frame leaky (at wall, not plaster)
- Eave end walls leaky through blocking between rafters; insulation gap there between bales and roof foam
- Clerestory windows leaky
- Timber joints leaky at corner posts
- Plaster joints uniformly tightest of all buildings- very little evidence of air leakage even under pressure

Note

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