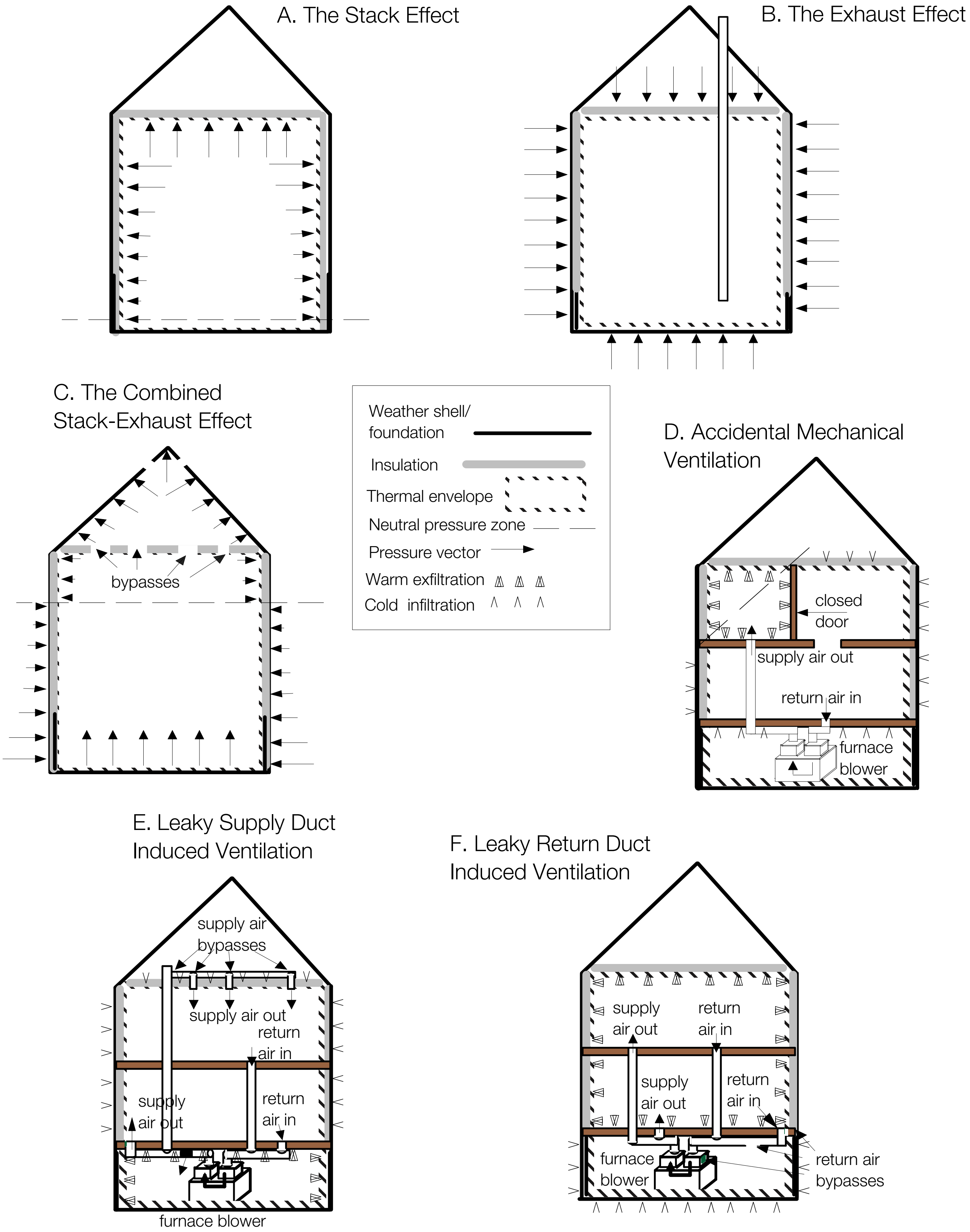

Figure 1: Common problems that reduce the effectiveness of the thermal envelope.

A Passive Approach to Practical Climate Control

Jennifer Baker and Fred Lugano

Introduction

THIS PAPER IS AN INTRODUCTION TO weatherization methods used to improve indoor climates in historic structures using passive methods. Enormous strides have been made in this field in the past twenty years that unfortunately have not been adapted by the conservation or historic preservation fields for use in historic house museums. It is now practical to retrofit historic houses safely to the point where their performance can equal, if not exceed that of new construction.

Passive improvements, by definition, are put in place, and left alone. They can radically improve building performance, stabilize indoor environments and save on energy costs. Passive improvements do not involve any moving parts, machinery, or equipment requiring monitoring, maintenance or upkeep. Most measures will pay for themselves in five years or less.

Air Movement in Buildings

The behavior and performance of any building is profoundly affected by the movement of air within and through that building. Like relative humidity, air movement in buildings is only detectable by humans when it is at its most severe: very drafty or very stuffy. However in between these two extremes is a range of behaviors that have an enormous effect on how well the building performs, and whether it functions as intended. By becoming familiar with the basic principles of air movement, conservators can more accurately assess existing and potential trouble spots in buildings.

The largest components affecting air movement in buildings are the HVAC system and the building shell. While the former gets a great deal of attention by conservators and other consultants in terms of selecting and specifying equipment and performance targets, the latter gets very little beyond routine maintenance. In the past it has been generally considered conventional wisdom that nothing can be done to upgrade a historic building's shell without damaging it. This is no longer true. By focusing on basic principles of air movement in houses, there are many reliable and reversible strategies to improve indoor climate in historic buildings passively.

To manage the climate in any building efficiently, a functional thermal envelope is required. This is a specific continuous layer separating the conditioned from unconditioned space. This is true whether the building is in Vermont or Florida. The thermal envelope does not necessarily follow the weather shell or exterior walls of the building. For example, the attic spaces are usually outside the thermal envelope, while cellars are inside. While most of the discussion that follows focuses on buildings in heating climates, a large portion of this information is also true for buildings that are principally air cooled. The fundamental concept is that any air leaking out of a building is accompanied by an equal quantity of replacement air, usually in the form of a draft. Likewise, any drafts have corresponding leaks elsewhere in the building fabric that may not be nearly as obvious, but may be much larger.

The Stack Effect

This phenomenon is familiar to most conservators. In a heated building, the indoor air is buoyant and applies pressure to the envelope. The pressure increases with the height of the envelope, with the largest amount of pressure on the attic plane. Figure 1A shows a well-sealed house with no leaks, and the entire building is under a slight positive pressure, which is good.

The Exhaust Effect

However, in a building with any sort of exhaust, indoor air is forced out *(Fig. 1B)*. Outdoor air is drawn in to replace it. This applies a uniform negative pressure to the entire envelope, which is bad. An exhaust can be any number of intentional or accidental sources from mechanical blowers such as a range hood, bath fan or clothes dryer, a combustion flue, such as a furnace, hot water heater, fireplace or wood stove, or simply a pressurized hole, such as a plumbing vent, chimney chase, wiring penetration, partition top plate, sloped ceiling, balloon framing, extended framing, stair well, attic hatch or fan grill.

The Combined Stack and Exhaust Effects

Figure 1C represents a leaky building. The house is full of pressurized holes. The holes in the air barrier at the top of the house allow heated air into the attic. If there is any attic insulation, it is now hanging between two heated spaces and is doing nothing. This has several negative effects on the building. First, the neutral-pressure plane, the point at which everything above is under positive pressure and everything below is under negative pressure, has risen so that a large part of the house is now under negative pressure. This part of the building will be drafty, subjected to raw, outdoor air and harder to maintain a stable climate. If the interior air is intended to be filtered at the intake, the infiltration may allow more air in than through the intended mechanical ventilation intake. This will induce a significant air conditioning load (heating or cooling). Meanwhile, large amounts of expensively-heated and possibly humidified air is now pouring into the attic, a very bad place for it. If the attic is vented, the vents act as an exhaust to outdoors, increasing the stack effect. This results in condensation in the attic, and the heated roof deck will cause damage from ice dams. An HVAC system designed to induce positive pressure, a common specification in historic houses, will be in an uphill battle against this building shell. Consequently to be successful, it will have to be oversized, two to four times, which will consume more energy, and over-pressurized, which can drive humid indoor air into wall cavities, causing more damage.

Faulty HVAC Effects

The HVAC system and ductwork itself can increase these problems further *(fig. 1D).* It is quite common in old houses to have far fewer return ducts than supply ducts, or to use building cavities as the return ducts. Without a balanced system, localized pressures can develop, creating spots of damage that are sometimes hard to understand, and building performance will deteriorate.

Leaky ducts or ductwork that is poorly located, is another major problem *(fig. 1E).* In this diagram, the supply ducts are located in the attic, outside the thermal envelope, another common historic house retrofit and a fundamentally bad idea. When these ducts leak, and they always do, they send large amounts of expensive heated air into the attic. Since ducts are pressurized, the effect of even the smallest leak is greatly magnified. Since leakage is a function of both the size of the hole and the velocity of the air passing through it, the heating and cooling loads can double. The attic gets too warm in the winter causing condensation and ice dams, energy costs sky rocket, and the rest of the house will be under negative pressure due to massive infiltration of make up air, regardless of what the HVAC system is designed to do.

One last example: When return ducts leak in the cellar (*Fig 1F*), or if there are not enough of them, bad things can happen throughout the entire house. It can become over pressurized by the heating system, driving warm, moist air into the walls and attic, soaking the sheathing and siding, and causing peeling paint, rotting framing, condensation and ice dams. Mechanically induced negative pressure in the cellar will also contaminate the indoor air with poisonous combustion and soil gases.

Diagnosing the historic house

While some building defects might be difficult to track down, under the right conditions, others can be spotted from a moving car at 50 mph. In cold climates, the appearance of melt patterns on roofs, impressive icicles and ice dams *(fig. 2)* are striking visual manifestations of large air leaks. Ice dams are not an inevitable consequence of having gutters; and are not caused by not enough attic venting. They are caused by large amounts of heated air escaping into the attic through bypasses in the thermal envelope.

While snow and ice are very helpful diagnostic tools at pinpointing thermal defects, there are plenty of other signs as well. Peeling exterior paint, mold, frost or condensation in the attic, rotten framing, ice dam damage, stained interior surfaces, rust stains, and tannic acid stains are all visible symptoms. Dirty fiberglass *(fig. 3)* can identify locations of leaky bypasses from pressurized holes, as the fiberglass acts as filter, much as it does in a furnace as the warm air flows through it. Old repair attempts such as several attic vents, button vents in siding, or lots of added chimneys all indicate a losing battle with a poor thermal envelope.

Just as relative humidity is hard to detect by humans except in its extremes, but is easy to track and monitor with instruments, imperceptible air

Figure 2: When the snow on a roof melts much more quickly than on those of surrounding buildings, it is evidence of large amounts of heat loss.

Figure 3: The dirty, stained fiberglass around this electrical fixture indicates that a large volume of air is moving past this spot. The fiberglass acts as a filter, trapping the dirt, much as fiberglass furnace filters do.

movements that can cause tremendous problems can also be measured with the right tools.

The cornerstone analytical tool used by the weatherization industry is the blower door *(fig. 4).* Blower door studies have been responsible for much of the current emphasis on air movement and away from conduction and diffusion as the principal cause of thermal and moisture building failures. Blower door tests and data should be a fundamental requirement by conservators before proceeding with any HVAC or other climate improvement recommendations.

How it works

The concept is simple. A large variable speed, reversible fan is sealed into a door jamb. Manometers, or pressure gauges, measure the flow through the fan in cubic feet per minute (CFM) and the pressure across the panel in Pascals (Pa).

Since flow = pressure x area, the blower door can be used to impose a known flow through the building and then the pressure can be measured. Or a known pressure can be induced on the building and how much flow it takes to produce that pressure can be measured. In either case, the remaining variable, hole size, can be calculated from these measurements, and some practical insights about the pressure boundary of the building can be gained without ever seeing or putting a hand on the defects. This is important because the key holes in a thermal envelope are often buried behind finished walls that can't be disturbed.

Since the pressure applied using a blower door can be set at any number, weatherization contractors have settled on a standard, 50 Pa, to make meaningful comparisons between buildings. This is roughly equal to a 20 mph wind. The air flow needed to sustain this pressure, CFM50, can be thought of as a unit of effective leakage area. A higher number indicates a bigger aggregate hole in the house. As a rule of thumb, it takes roughly 1 square foot of leakage in the pressure barrier to produce 1000 CFM50. So a house that tests at 4500 has about four and a half square feet of effective leakage area letting air pass through it. The relationship is not precise because some hole shapes leak more easily than others of the same size.

A leakier house will have more or larger bypasses through its pressure boundary. In these cases, the blower door fan must be run faster to push more air out to get the pressure up to 50 Pa. As the pressure barrier is improved or rebuilt, the house shell gets tighter and the pressure boundary is more resistant to air flow. Now fewer CFM are needed to reach 50 Pa. Weatherization contractors depend on the blower door to guide their air sealing efforts to make the holes smaller. This is called pressure-directed air sealing.

Aside from the quantitative analysis, the blower door can be used simply to provide some pressure on the thermal envelope. With the infiltration artificially enhanced, the house can be surveyed room by room to look for leaky areas. By cracking open a bedroom door and feeling for a draft, it is

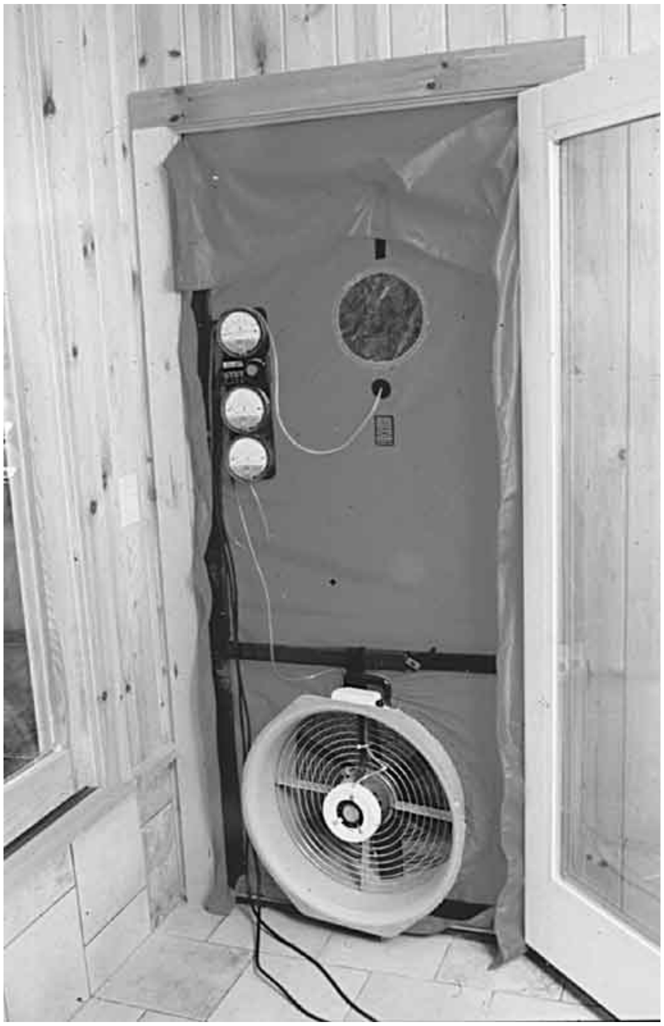

Figure 4: A blower door set up.

possible to tell right away if there is a large bypass anywhere in that room.

It takes some training and experience to interpret blower door results. Like any other exhaust fan, it applies a vacuum evenly to the entire shell. This is generally not how the building behaves naturally. Particularly in ceilings, air will normally flow upward into the attic, but a depressurization test will pull air down and toward the blower door. The blower door treats all holes in the same regard, even if nature does not. The actual pressure on any particular hole (and the resulting flow of air) will vary greatly depending on its position in the shell. So even knowing the size of the holes, it is important to understand which of them are benign and which are the real trouble makers by understanding the adjacent forces that create air pressure.

A rough idea of leakage in any house can be gained with a few simple tests. The location of the neutral pressure plane in a building can be estimated by simply opening a window or door. On a cold, calm day, with the furnace off, open the front door just a crack. Hold a small piece of tissue or a smoky candle up to the crack. Which way does it blow? If the air is coming in, then the building is under negative pressure at that point. If it is blowing out, then it is under positive pressure. If the building is under negative pressure on the first floor, try the second floor. Open the bottom of an upstairs window, and test again. If it still blows in, try the top sash. If it is still blowing in, the building is very leaky , or as some weatherizers put it, the whole building is "sucking air."

Treating the historic building

After diagnosing a building, there are many techniques employed by weatherization contractors to correct thermal defects. Four key elements are: moisture mitigation, air sealing, duct sealing and insulating using the dense-pack cellulose method.

Moisture mitigation

When trying to protect a collection in a historic house, especially in one with year-round use, one of the principal problems in colder climates is too low RH in the winter months. However, in a properly insulated historic structure, the problem no longer is one of too little humidity but that of too much. In fact, weatherizers regard the use of a humidifier as an indicator of major defects in the thermal envelope. In most buildings, the primary source of this moisture is the cellar. An unimproved (dirt) floor cellar can be evaporating tens of gallons of water into the building every day. In an uninsulated house, this moisture goes right through the building's fabric because the shell is thoroughly heated, but once it is insulated, the framing cavities become much colder and moisture levels can build up to unacceptable levels, causing damage from biological action.

Therefore the first step in improving a thermal envelope starts in the cellar. All dirt floor surfaces, including crawl spaces *(fig. 5),* must be covered with a plastic membrane. In most cases, a cross-linked polyethylene sheeting such as Tu-Tuf, is preferred over standard polyethylene sheeting, because it is more durable and compatible with adhesives. In an area that receives regular use, an EDPM (ethylene-propylene-diene monomer, a roofing material) membrane can be used for even more durability. Depending on the building and the moisture load in the cellar, it may be necessary also to cover cement slab floors or the walls. Walls can be covered using a water-based contact or polyurethane adhesive to adhere the plastic.

Foundation vents, found in many old houses, are always bad, regardless of climate or season, and should simply be blocked up. They are naturally under negative pressure with respect to the outdoors and pull in more moisture than they allow to escape. In the heating season, vents flood the cellar and then heated areas with cold air. Cold air flowing through the vents is ineffective at evaporating foundation moisture. During warm weather, the ambient air is loaded with water. When this air is drawn into a cool space, the entrained water vapor condenses and wets all the available surfaces—the foundation, the soil or masonry floor below, and the wooden suspended floor above.

Air sealing

Sealing leaks in the thermal boundary is the single most cost-effective way to stabilize the interior climate of a building while at the same time cutting heating and cooling costs. Large bypasses from the conditioned interior space into the unconditioned attic space can easily cause as much air loss as leaving a window open year-round. These bypasses

Figure 5: Laying Tu-Tuf, a cross-linked polyethylene sheeting, in a crawl space. Tyvek tape works well for taping edges together.

Figure 6: Plumbing chases can be large, problematic holes in the thermal envelope.

are most commonly found around chimneys, plumbing vents, staircases, recessed lights, ductwork and electrical bypasses *(fig. 6).* This is also why the attic door should be the tightest door in the house, not what they usually are, either a thin hatch, a flimsy pull-down attic stairs mounted on 1/4″ plywood, or a standard interior closet door.

The nature of the building's construction can also cause countless bypasses. In a balloon-framed structure, common in Victorian-era construction, it is sometimes possible to stand in the attic and send a tape measure right down to the cellar floor through any of the wall cavities. Every single bay is a chimney connecting the cellar, which is indoors, to the attic, which is outdoors. This is why it costs a small fortune to heat these buildings, and why it is so difficult to achieve a stable interior climate. Other places to suspect are the tops of interior partition walls, places where newer additions meet old, where porches are attached, old stove pipe holes (even if covered) and places where wall plaster is crumbling in the conditioned space.

Air sealing techniques use a variety of materials. Around chimneys, sheet metal is commonly used. In cracks, crevasses and smaller holes, expanding foam works well. Larger holes can be plugged with plastic bags filled with insulation, sheets of extruded styrene insulation, 1/4″ plywood or oriented strandboard (OSB). IC rated (insulation cover) recessed lights can be boxed in before insulating to seal leaks. Non IC rated fixtures ought to be replaced. Attic hatchways should also be boxed and sealed as tightly as possible, using gaskets where the door fits.

Air sealing techniques and materials are neither elaborate nor expensive. As air sealing progresses, repeated use of the blower door can show progress in the reduction of leakage. This is known as pressure-directed air sealing. Air sealing should always be done from the top of the building down for two reasons. First, because the pressure is highest in the top of the house, sealing attic holes will be the most cost-effective. Second, many cellars contain combustion appliances. To tighten up the cellar without addressing attic bypasses can cause dangerous back drafting.

Duct sealing

Duct-sealing is another area where significant improvements can be made to improve indoor climate. If supply ducts run outside the thermal envelope, as in figure 1E, this is especially important, as each hole in the duct represents a pressurized hole in the thermal envelope, losing conditioned air at a rate equal to a much larger unpressurized leak. Warm, moist air forced into the attic heats the roof and causes condensation, rot, mold, ice and excessive energy costs. This air loss has to be made up some how, usually through accidental ventilation, depressurizing the entire structure.

When ducts are accessible in the cellar and attic, they can be sealed using a water-based duct mastic *(fig. 7).* Holes can be covered using mastic and screening. Duct tape should never be used to seal ducts, as it doesn't last. Duct leaks in the attic and cellar are the most important ones to fix. Some times a building just uses the building cavities as return ducts. This is a very poor practice, and if

Figure 7: Sealing a duct with duct mastic.

possible should be corrected with real duct work, or at least sealed up as tightly as possible.

Dense-packing

Insulating walls with dense-pack (DP) cellulose *(fig. 8)* has become the cornerstone of the weatherization industry, and is indispensable to the revitalization of old buildings. In dense-packed walls, the cellulose insulation is blown into the walls at higher densities than the industry standard. Cellulose insulation manufacturers recommend densities of approximately 2.7 pounds per square foot. However, when cellulose is pneumatically installed at high velocity to densities greater than 3.5 pounds per square foot, it acquires a unique air sealing property. In this process, the material behaves as a fluid, flowing into obscure bypasses and solidifying them. Dense-packing solves air movement problems critical to building performance that would be impractical to access or repair in any other way, especially in historically significant buildings, where retaining original interior and exterior wall surfaces is crucial.

Building cavities subjected to wind, stack, or mechanical pressure move enormous amounts of conditioned air. Common insulation methods do little to stop this flow, so the insulation performance is degraded, and the larger convective heat losses continue. Dense-pack forms an injection molded block in these cavities that stops the air movement and delivers real control of conductive heat loss too.

Building cavities are dense-packed by inserting a pipe, tube, or hose down the entire length of the passage. A powerful insulation chopper and blower delivers a lean mixture of cellulose and air at about a hundred feet per second. Initially the cavity is pressurized with a cloud of insulation. The air flows out through every crack and pinhole carrying fine particles of insulation. The holes are clogged with insulation until they stop flowing and the cavity fills with a loose pile. Then the cellulose chunks charging down the tube start to slam into the loose pile and pack it. When it becomes very tight, it plugs the end of tube and stalls the insulation blower. The tube is quickly pulled back until

Figure 8: This demonstration wall was blown full of cellulose and then the interior sheathing was removed to inspect the result.

the tip finds more loose insulation. The flow and packing process starts again and this continues until the entire cavity is solid. In attics, if you have no attic floor to dense-pack, then a process called "open blowing" is necessary *(fig. 9)*. Since this cellulose is not as pressurized as a dense-pack, the previously mentioned air sealing techniques are critical to success.

As an organic material, cellulose is cellular and hygroscopic. Fiberglass, on the other hand, is amorphous and hydrophobic. This simple comparison alone should make it immediately obvious to anyone concerned with controlling relative humidity of a conditioned space which is the more appropriate material. When you fill wall cavities of a structure with several tons of a hygroscopic material, an enormous moisture storage capacity is imparted to the shell and the building's ability to buffer against daily humidity fluctuations radically improves. The entire structure acts as a microclimate case for its contents. Fiberglass insulation has none of these properties or abilities.

DP is an invisible and completely reversible process. With no diffusion barrier to trap moisture, it helps to preserve the shell of the building. The highly-absorbent cellulose fiber wicks moisture content away from framing members. This increased moisture storage capacity stabilizes the interior plaster and exterior paint by buffering the moisture load forced into the shell through the heating season. Another important consideration is that in a well-insulated and sealed building, we can entirely rethink the heating distribution systems. Duct work, which frequently requires chopping lots of large destructive holes into an historic structure, can be greatly reduced and in some cases eliminated as point-source heat solutions more compatible with historic interiors become viable. A 2000 square foot building (not historic) at the Lake Champlain Maritime Museum was recently converted from a dirt-floor boat shed to a fully-finished, winterized exhibit gallery. Because specific emphasis was placed on making a tight thermal envelope, a single Monitor kerosene heater is all that is need to heat the entire space in the winter, and a room air conditioner cools it in the summer. No distribution system was necessary, saving money, and the heating and cooling costs are only a couple hundred dollars a year. When air loss is eliminated, distribution manages to take care of itself.

Figure 9: Blowing an attic crawl space. Cellulose does not have to be sandwiched between two surfaces as in a wall or under a attic floor.

Cellulose can be retrofitted much more easily than other types of insulation because no vapor barrier is needed. Interior plaster walls act as enough of an air barrier. Studies have shown that vapor diffusion is only a small portion of the moisture transfer mechanism of moisture in walls, and that convection carries most of the water vapor. In fact, more water vapor will transfer through a one square inch hole than diffuses through a 100 square foot wall. In a cellulose insulated wall, air movement stops, and along with it the flow of water vapor. Instead, the walls will adsorb and desorb moisture back into the building interior strictly by diffusion. In other words, the walls will wet more slowly, and dry out more quickly without a plastic diffusion barrier. In a building insulated with fiberglass, plastic vapor barriers are common. As fiberglass does not hinder convective air movement, these have the unfortunate effect of often trapping moisture in the wall cavities, causing serious damage. And in an uninsulated building, interior moisture loads travel through the framing, causing exterior paint to peel.

DP insulation is also an important element in fire safety. Typically, fire destroys wood buildings by entering and traveling through the framing bays. Once walls start to act like chimneys, the studs are quickly consumed. Blocking or fire stops are known to be effective in preventing the spread of fire from floor to floor and ultimately into the attic. DP behaves as continuous blocking in walls because the framing is really solid. Buildings with DP walls are difficult to destroy by fire. The fire retardant used in cellulose is typically borate, also used in historic buildings for pest management.

Case Study: The Cornwall Congregational Church

The Cornwall Congregational Church in Cornwall, VT (*fig. 10*), built in 1803, was a huge financial drain on its congregation. Heating the building for just one Sunday service in the winter burned through about 200 gallons of fuel oil. Needless to say, the building was all but useless during the coldest months. When a member of the congregation donated some money for repairs, they decided to do something about it. Most of the contractors called to give estimates focused on the windows, proposing to replace them or block them entirely, solutions that would have adversely affected the appearance of the building, even though studies show that windows are the least cost-effective place to go for energy savings. Usually the payback time is longer than the life of the replacement windows.

Instead, by concentrating on the minimally-insulated attic, leaky ducts and the walls' 14″ deep cavities, the appearance of the building wasn't changed a bit. The building was air-sealed and duct-sealed, and over ten tons of cellulose was blown into the walls from the exterior and open blown into the attic. Air leakage was cut over 70% as measured by the blower door tests, and the heating bill was cut by two-thirds. Now the building is used year-round by its congregation, making it much more useful and vital to the community, rather than a problem white elephant destined to extinction.

Figure 10. The Cornwall Congregational Church. The passive improvements made in this building had no effect on its appearance.

Conclusion

This paper is intended as an introduction to a different approach to evaluating and treating historic structures. We believe that we can do much better than we have done to maintain stable indoor climates in historic structures safely and cost-effectively. By learning some simple diagnostic techniques and using a blower-door specialist to evaluate buildings, conservators can produce far more effective recommendations for climatic improvements. Passive improvements can reduce or eliminate entirely the need for more expensive, mechanical solutions to climate control problems and should therefore be implemented first, and monitored for effectiveness before more intrusive, costly HVAC solutions are explored.

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www.ornl.gov/ORNL/Energy_Eff/Energy_Eff.html – Oak Ridge National Lab Energy Efficiency & Renewable Energy Programs

www.ashrae.org – American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Weatherization materials such as duct mastic, cellulose and Tu-Tuf plastic can be ordered from Energy Federation Incorporated, www.efi.org 1-800-876-0660. 40 Washington St., Suite 3000, Westborough, MA, 01581-1012

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