Building America Special Research Project: High R-Value Enclosures for High Performance Residential Buildings in All Climate Zones

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High R-value Enclosures for High Performance Residential Buildings in All Climate Zones

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TABLE OF CONTENTS

PREFACE

Building America Program and the Purpose of this Report

The objective of the U.S. Department of Energy's Building America Program is to develop innovative system-engineering approaches to advanced housing that will enable the housing industry in the United States to deliver energy-efficient, affordable, and environmentally appropriate housing while maintaining profitability and competitiveness of homebuilders and product suppliers in domestic markets. For innovative building energy technologies to be viable candidates over conventional approaches, it must be demonstrated that they can cost-effectively increase overall product value and quality while significantly reducing energy use and use of raw materials when used in community-scale developments. To make this determination, an extensive, industry-driven, team-based, system-engineering research program is necessary to develop, test, and design advanced-building energy systems for all major climate regions of the United States in conjunction with material suppliers, equipment manufacturers, developers, builders, designers, and state and local stakeholders.[1]

Building America research results are based on use of a team-based systems-research approach, including use of systems-research techniques and cost and performance trade-offs that improve whole-building performance and value while minimizing increases in overall building cost. This report describes the Building America Program research teams' current state of knowledge of High R-value Enclosures.

Task Description

On behalf of the BA program, BSC will lead the development of a white paper on "High R" enclosures for high performance residential buildings. This paper will review and synthesize published research conducted in this area by the Building America Program research teams and the National Laboratories supporting the program. Key gaps that currently limit the broad delivery of high thermal resistance enclosures, including below-grade elements, walls, roofs and windows, will be discussed in the context of a systems approach to high performance building design.

Notice

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[1] More information about the Building America Program, including other research publications, can be found at www.buildingamerica.gov

Definition of terms

The following terms and abbreviations are used in this report.

Term	Definition
BA	Building America Program, a research program of the U.S. Department of Energy. Building America forms research partnerships with all facets of the residential building industry to improve the quality and energy efficiency of homes. The goal is to develop cost effective solutions that reduce the average energy use of housing by 40% to 100%. Ultimately, Building America research will lead to net zero energy homes, which produce as much energy as they use. More information about Building America can be found at www.buildingamerica.gov.
DOE	U.S. Department of Energy
EPS	Expanded polystyrene insulation
IECC	International Energy Conservation Code
R-value	Quantitative measure of resistance to heat flow or conductivity, the reciprocal of U-factor. The units for R-value are ft^2 F hr/Btu (English) or m^2 K hr/W (SI or metric). While many in the building community consider R-value to be the primary or paramount indicator of energy efficiency, it only deals conduction, one of three modes of heat flow, (the other two being convection and radiation). As an example of the context in to which R-value should be placed, 25% to 40% of a typical home's energy use can be attributed to air infiltration.
SHGC	Solar heat gain coefficient
SIPS	Structural insulated panel system
UL	Underwriter's Laboratory
U-factor	Quantitative measure of heat flow or conductivity, the reciprocal of R-value. While building scientists will use R-values for measures of the resistance to heat flow for individual building materials, U-factor is usually used as a summary metric for the ease of heat transfer through building assemblies.
XPS	Extruded polystyrene insulation

CHAPTER I: Introduction to High R-value Enclosures

Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. Building codes and green building codes are being changed to require higher levels of thermal insulation both for residential and commercial construction. This report will review, and summarize the current state of understanding and research into enclosures with higher thermal resistance, so-called "High R Enclosures".

High R enclosures will reduce energy consumption for space heating in all climate zones. Their impact is largest in climates with cold temperatures for many hours, and smallest in climates with few hours per year at cold temperatures. However, High R enclosures are still important for enclosures exposed to the direct solar radiation in hot climates: the roof is the obvious example, especially if finished in dark colors that absorb solar radiation.

The introduction will present some definitions and background information. The balance of the paper is a review of current research by Building America research teams and other groups. Challenges remaining to be solved and recommendations for further research are addressed in the conclusion.

Why Control Heat Flow

Good thermal control is fundamental to good housing in all climate zones: achieving low-energy and ultimately net zero energy homes in a cost- and resource-efficient manner will require exceptional thermal control. Space heating and cooling remain the largest components of the energy use of typical new and existing houses. For the current stock of housing (see the Residential Energy Consumption Survey 2005, Table US14, excerpts below) space heating/cooling consumes more than half of the total site energy. In new construction, better thermal control has resulted in lower fractions (about 45%), but thermal control remains one of the lowest cost, most durable, easiest to predict, best developed means of reducing household energy use.

Table 1: RECS 2005 Energy Consumption Data

	U.S. Households (millions)	Energy End Uses (million Btu of consumption per household)					
		All End Uses	Space Heating (Major Fuels)[4]	Air-Conditioning[5]	Water Heating[6]	Refrigerators	Other Appliances and Lighting
Type of Housing Unit							
Single-Family Detached	72.1	108.4	44.2	11.0	21.7	5.2	29.3
Single-Family Attached	7.6	89.3	41.7	6.7	19.0	4.0	20.9
Apartments in 2-4 Unit Buildings	7.8	85.0	48.5	6.3	15.6	3.5	16.3
Apartments in 5 or More Unit Buildings	16.7	54.4	25.0	6.6	12.2	3.0	11.8
Mobile Homes	6.9	70.4	26.1	9.2	13.3	4.2	21.4
Total	111.1	94.9	40.5	9.6	19.2	4.6	24.7

The control of heat flow is important for more than just saving energy: by controlling interior surface temperatures, heat flow control helps ensure human comfort and avoid cold-weather condensation. As described later, controlling the temperature of various elements and layers within an enclosure assembly can be used to avoid condensation or enhance drying, both of which influence durability.

Thermal control is typically seen as being provided by insulation. However, air barrier systems, radiant barriers, solar control coatings, and thermal breaks are also part of any enclosures thermal control system.

Defining the High R-value Enclosure

The term "High R" enclosures attempts to bring together what is known about delivering exceptionally good control of heat flow through walls, roofs, windows, and foundations. High-R enclosures are more than just assemblies with a lot of insulation, they are systems that are airtight, have little thermal bridging, are buildable, manage solar heat gain, ensure human comfort, and provide moisture control to ensure durability and health expectations are met.

There are no widely accepted definitions of the term "High R", but we will use the term here to describe much higher thermal control than the code mandates, usually offering around twice as much resistance to energy flow as more common approaches, but also meeting high standards of buildability, durability, health, and comfort.

R-value is commonly used to measure the thermal control of insulation products. However, this metric does not account for the impacts of thermal bridging, air leakage, installation quality, or thermal mass. It this multitude of factors that working together deliver good thermal control.

ORNL conducted work over a decade ago [ORNL 1994, 1995] in which they defined a number of useful terms:

- Center-of-Cavity R-value: R-value at a point in the wall's cross-section containing the most insulation.
- Clear-wall R-value: R-value of the wall area containing only insulation and necessary framing materials (i.e., for a clear section with no fenestrations, corners, or connections between other envelope elements such as roofs, foundations, and other walls).
- Interface details: A set of common structural connections between the exterior wall and other envelope components, such as wall/wall (corners), wall /roof, wall/floor, window header, window sill, door jam, door header, and window jamb, that make up a representative residential whole-wall elevation.
- Whole-wall R-value: R-value for the whole opaque wall including the thermal performance of not only the "clear wall" area, but also all typical envelope interface details (e.g., wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections).

High R enclosures must of course be measured by whole-wall R-values. But at the same time, higher levels of airtightness, good durability, and comfort must be added. True R-value is what is actually required to measure performance, but this is not yet developed as a scientific measure.

Thermal continuity / Thermal Bridging

Continuity of the thermal control layer is important. Heat flow deviates from one-dimensional at corners, parapets, intersections between different assemblies, etc. When heat flows at a much higher rate through one part of an assembly than another, the term thermal bridge is used to reflect the fact that the heat has bridged over / around the thermal insulation. Thermal bridges become important when:

- they cause cold spots within an assembly that might cause performance (e.g., surface condensation), durability or comfort problems
- they are either large enough or intense enough (highly conductive) that they affect the total heat loss through the enclosure

Thermal bridging through insulation by wood framing causes significant heat loss. Reductions in R-value of 25% are typical for wood framed walls, and 40% reductions regularly occur. The trend to increasing complexity in building plans results in an increasing fraction of wood framing relative to studspace insulation. This phenomenon is well understood in the scientific literature, and excellent tools have been developed to predict this impact with reasonable accuracy (for example, the DOE-sponsored THERM software package is widely used for this purpose by researchers and advanced practitioners). Unfortunately, thermal bridging is poorly understood by the design and construction industry, and residential building codes do not address it directly. Techniques to address dramatically reduce thermal bridging are available and reasonably well proven, but face many challenges in reaching widespread acceptable. Advanced framing (see BSC 2010 Advanced Framing fro details) and insulating sheathing can make significant reductions in thermal bridging and thus increase thermal resistance without increasing "installed" R-value. True R-values (e.g., including thermal bridging of realistic enclosure framing details) for more wall assemblies are needed and should be disseminated more widely.

Some new enclosure systems attempt to increase the thermal resistance by increasing the thickness of framed walls (e.g., by increasing from 2x6 to 2x8, or 10, 12, or 14" deep TJI roof rafters, or by the use of double-stud framed walls). These systems continue to suffer from thermal bridging, and hence their true R-value is constrained. Double stud walls (enclosure walls with two disconnected framed walls with voids filled with insulation) notionally reduce thermal bridging, but the extent of the reduction is highly dependent on the details at floor joists, basement interfaces, window frames, etc.

It is practically acceptable to have some small local interruptions and reductions in the efficacy of the heat flow control. Penetrations such as nails and screws rarely affect the energy, durability, or comfort-related performance of the enclosure. Even a rather small amount of thermal control, e.g. R2 to R4 (the thermal resistance of double-glazed windows) is tolerated over significant areas of many enclosures, although the energy and comfort penalty can be significant if the area covered is large. The trend to greater window area without commensurate improvements in window thermal performance leads to both increased energy consumption and reduced comfort at the same time that such practices increase construction costs.

Airtightness

As homes become better insulated, unplanned air leakage can consume a greater proportion of heating and cooling energy. Hence, as insulation values are increased, airtightness should also be increased. At the same time, air leakage can result in damaging condensation, moisture damage, and poor Indoor Air Quality, in all climate zones, but especially hot-humid and cold climate zones. The airtightness of American homes has improved significantly over the last several decades [LBNL study], but still lags behind that of some other countries such as Canada, Sweden, etc. Perhaps more significantly, although most of the homes built in the US require specific minimum insulation values, there is no minimum airtightness level required, or even airtightness measurement.

Part of the challenge is that the effectiveness of air barrier systems are largely a result of careful design and workmanship. Products can be specified, but it is difficult to enforce robust details and inspect the many small, and often hidden, details that can cause leaks. Testing, usually via a blower door, has been shown to be a very effective means of testing the airtightness of a home, and assisting a builder in achieving specific targets. The challenge remains that too few homes are tested for airtightness. Even those new homes and retrofits tested for airtightness are often tested when most of the construction is complete: if targets are not met, it is difficult and expensive to find and repair hidden leaks. It would be useful to develop airtightness approaches, technologies, and testing protocols that allow for early airtightness characterization easily and less expensively.

Durability

Reducing the control of heat flow across an enclosure can either increase its durability or decrease it relative to standard construction depending on how that heat flow reduction is achieved. High R walls are no different. By adding insulation inside of wood sheathing / cladding, the moisture content of the sheathing / cladding will rise in cold weather, the risk of condensation increases significantly, and outward drying potential is reduced. Adding insulation also increases the risk of condensation in the summer time, but on the interior finish, especially if vapor impermeable (vapor barriers, cabinets, mirrors, etc).

Solutions exist for these and other durability risks: use insulation exterior to the sheathing, using lower permeance insulating exterior sheathing, building a ventilation space outside of the sheathing/behind the cladding, build a more airtight enclosure, provide better rainwater management (e.g. drained sub-sill flashing), etc.

Different enclosure assemblies will have different requirements to meet or exceed current durability expectations. In general, drained and ventilated claddings, exterior insulating sheathing, and high airtightness combine to provide an enclosure that is more durable even when insulated to high levels.

Quality of Construction

The quality of construction can negatively impact thermal control. Some insulation systems are more prone to worker error than others although this has not been well characterized. Progress has been made in encouraging the proper installation of insulation via inspection and the HERS rating scale. However, this approach must be more widely deployed to ensure expected performance matches actual performance.

The actual energy impact of poor insulation installation has not been measured using standard ASTM hot-box enclosure tests at either very cold and very warm temperatures (when flaws have the most impact). Without this information it is difficult to quantify the impact of defects.

Comfort

Delivering thermal comfort is primarily about maintaining interior air temperature and the Mean Radiant Temperature (MRT): the former is delivered by typical mechanical systems, measured and controlled by the thermostat, whereas the MRT is controlled by the thermal control of the enclosure. ASHRAE 55 provides the tools to assess comfort.

Current building code requirements for opaque walls and roofs generally control the surface temperatures well enough for comfort. Poor thermal control, especially at windows, slab edges, and areas of framing congestion, can result in low enough or high enough interior surface temperatures as to compromise comfort. In climates with lower heating needs, enclosure thermal control is often seen as being less important. However, we have had reports of thermal comfort problems in these climates because of solar gains heating the interior pane of solar control glazing, exposed slab edges, and even dark-colored walls with low, but Code-approved, thermal resistance. Finally, air leaks can cause local jets of cold air that compromise comfort. High levels of airtightness can solve most of these problems.

Economic Aspects

To conduct proper cost-benefit of life-cycle costing one needs to know, among other things, the future price of energy, the cost of interest (discount rate), the cost of materials and labor, the replacement intervals and maintenance costs for equipment and assemblies. Given this wide range of unknowns, High R enclosures can either by shown to be highly favorable (assuming 7% per annum increases in energy costs, low labor costs, and low discount rates) or very expensive (assuming no energy cost increase, high discount rates, and expensive materials and labor). In short, without an agreed upon set of assumptions of what the future will hold, it is difficult to make decisions on current investments using life-cycle cost analysis.

A recent analysis by PNNL [Taylor an Lucas 2010] analyzed the savings achievable by increasing R-values in new residential construction. Energy cost savings of 30% were shown across many different climate zones. The analysis, like many similar studies, assumed current energy costs even though homes built today will likely last 75 years. Similarly, the savings are based on the first years operation, which ignores the significant cost of replacing mechanical equipment over the life of the building.

Most analysis of "payback" in Building America are conducted using simple payback: savings per year/cost of upgrade = years to payback. Other more sophisticated approaches use a fuel escalation rate, but this rate is often chosen to be 2-3%/yr: rarely is the 30 year average rate of 6%+ per year used. According to the DOE Energy Information Agency 2009 Annual Energy Review, residential energy costs have increased at an annual compound rate of 6.5% per year since 1970. Hence, if detailed analyses are conducted, a rate considerably higher than 2-3% should be selected without evidence that future energy costs will rise more slowly than costs have risen in the past.

Analyses that ignore realistic fuel escalation rates, do not consider the replacement costs of HVAC equipment and appliances (e.g., typically on 15 yr cycles) relative to insulation lifespan (likely over 75 years) inherently result in significantly lower recommended R-values than the likely optimum. NREL's BEopt tool is capable of accounting for some of these factors, and, not surprisingly, recommends higher R-values for building enclosures than code on a monthly total ownership cost basis.

Life cycle cost analysis rarely account for the environmental cost of energy production and consumption. These externalities are difficult to price, and hence difficult to include in an analysis. However, this is an area of on-going research and will become more important as homes become more energy efficient.

Another approach used by BSC (and also reported on by Proskiw & Parekh 2010) to making investment decisions revolves around the idea of energy targets. Given an energy target (such as a code minimum, the Building America Benchmark, Net Zero, Architecture 2030, Energy Star, etc.), a designer list incremental design choices required to save progressively more energy, and ranks these based on a cost per Btu/yr saved. This approach avoids the need to know about future costs of any sort, but does demand a good understanding of construction costs and energy saving potential. The advantage of this approach is that it more fairly compares the cost of High-R walls to the use of efficient equipment (e.g., a ground-source heat pump in lieu of a gas furnace) or the cost of renewable energy production (e.g. photovoltaics). One disadvantage of this approach is that it does not favor choices that have a very long service life (such as insulations) over choices with a short service life (such as a condensing hotwater heater). This approach has the decided advantage that it demonstrates very different cost-optimized solutions for different regions and different builders.

High R-value Enclosure Recommendations

Recommendations for high R performance targets must, necessarily, include factors such as climate, available enclosure and space-conditioning technologies, desired lifespan, comfort expectations, lifestyle, as well as the costs of construction, energy, environmental damage, and borrowed money. Some of these factors can be well defined, but many cannot. However, based on currently available technology, experience with costs and expectations with production and custom builders from coast to coast, and the desire to provide new homes that will be ready to be powered by renewable energy sources immediately or in the future, BSC has developed a set of recommendations (Table 0.2). These recommendations will therefore vary for locations with high construction costs, or low energy costs, or clients who value environmental impact highly.

Climate Zone	Wall	Vented Attic	Compact Roof	Basement Wall	Exposed floor	Slab edge[1]	Windows (U/SHGC)	Sub-slab[2]
1	10	40	35	5	10	none	yes	none
2	15	50	40	10	20	5	0.35/<.25	none
3	20	50	45	10	20	7.5	0.30/<.3	5
4	25	60	45	15	30	7.5	0.30/<.35	7.5
5	30	65	50	15	30	10	0.24/<.50	7.5
6	35	75	60	20	40	10	0.18/--	10
7	40	90	65	25	45	15	0.15/--	15
8	50	100	75	35	50	20	0.15/--	20

Table 2: Current Recommended "True" Minimum R-value (+/-)[3] including thermal bridging

1. Slab edge insulation includes all of stem wall or monolithic slab edge
2. Full area coverage of slabs
3. these are recommended values based on experience - see economics section

From a practical point of view, high-R enclosure performance can be specified, albeit imprecisely, by using whole-wall R-values and superimposing requirements for air tightness, moisture control, etc. Higher R-values may be justified, especially in the colder climate zones, if energy costs increase markedly (i.e., more than double) but in many cases the table below is still twice that of code requirements.

Walls

The recommended R-values of walls is based primarily on the exterior air temperatures experienced over the years, the cost to increase insulation above the current baseline wall (assumed to be a 2x6 advanced framed wall in all climate zones but climate zone 1), and the cost and difficulty of applying cladding and installing windows.

To achieve an R-value over and above an approximately true R14 baseline (that is, a 2x6 wood-framed wall with R19 batt and normal framing practices results in a true R-value of 14) it is recommended that a continuous layer of exterior insulation be used. This approach has the benefit that as the climate becomes colder, a greater proportion of the total insulation is provided by the exterior insulation layer: to improve durability, this is exactly the strategy suggested by building physics to reduce the chance of condensation and to encourage inward drying. This approach also dramatically reduces thermal bridging, particularly at locally congested framing.

Roofs

The optimal true R-value of roofs is often more complex to define than that for walls because of the impact of solar heating. Roofs in warm and hot climates experience high temperatures due to solar exposure for many months of the year: dark shingle roofs experience surface temperatures of 140 to over 160°F on every sunny day. This generates temperature difference of 60 °F or more, which is similar to winter night-time temperature differences experienced in a Zone 7 climate. Light-colored / reflective roofs will experience much lower temperatures and may allow lower R-values. The actual impact of low-solar roofs on the choice of R-values in high-R roofs has not been conducted, although there has been considerable work investigating the performance of cool roofs by ORNL and LBNL and on the choice of R-values of compact roofs (commercial) [Bianchi et al, 2007].

Unvented attics / cathedral ceilings are always significantly more expensive to build in a durable manner than ventilated attics. This additional expense is the reason for lower target values for these roofs. Research has shown [BSC and others] that a significant energy penalty is incurred if a builder locates ductwork and equipment within a vented attic. Therefore, some may choose to use an unvented cathedralized attic or ceiling to allow HVAC equipment to be located within the space. Locating the ducts in conditioned space saves more energy than the reduction in recommended R-value and increased surface area increases energy use.

Basements

Temperature differences across basement walls are always more modest and hence lower R-values are recommended. In many climates, the temperature difference between the interior and the exterior soil over the height of a full basement wall is about half that of above grade enclosures. Hence, R-values in basements are recommended at about half that of above-grade walls. However, basement insulation can sometimes be significantly less expensive and less disruptive to design and common working practices than increasing R-values in some above-grade components. For these reasons it may be economically justified to increase the basement wall R-values well

Slabs

Slabs experience smaller temperature differences than differences across basement walls, and hence the recommended slab true R-values are about half that of basement walls. A minimum insulation level of R5 is recommended to provide better thermal comfort and to avoid condensation on slabs (especially slabs with carpets, furniture, millwork etc) during warm humid weather. If a slab is radiantly heated, its temperature will be much higher, and hence higher insulation levels are justified. Although little research has been conducted to date (Beaver Plastics 2000), R-values of around double that of unheated slabs is recommended.

Windows

The heat flux allowed to occur through windows, during both warm sunny weather and cold dark nights has long been much larger, often an order of magnitude larger than through roofs and walls. A window with a U-value of 0.35 and SHGC of 0.35 will allow almost ten times as much heat flow on a cold winter night than a true R20 enclosure, and much more than ten times as much heat during a sunny day. The primary restraint on higher performance has been the cost-effectiveness of the technology to achieve more. Recent market and technologies changes are rapidly breaking down this barrier.

The recommended R-values and SHGC are based on available performance, and this means triple-glazed windows in cold climates. In very cold climate zones 7 and 8, high-performance foam-filled frames with exceptional glazing package will be needed to meet the recommended values, but these are now available.

Enclosure Air Flow Control

Airtightness must also be specified in conjunction with True R-value requirements. In Zones 1-3, an enclosure air permeance of less than 0.25 cfm/sf of enclosure area at 50 Pa pressure difference measured by blower door testing is currently recommended. Builders who focus on airtightness and regularly conduct testing to verify performance can consistently achieve this airtightness target. For Zones 4-6, and Zones 7-8 an air permeance of less than 0.20 and 0.15 cfm50/sf respectively is recommended for High R assemblies. Airtightness levels of under 0.10 cfm/sf @ 50Pa are achievable in prototype housing and by custom builders. As experience is gained with delivering air barriers, it is likely that these values can be practically and cost-effectively decreased over the long term.

Whole-house Ventilation

As building airtightness improves, the number of annual hours during which ventilation through accidental openings driven by highly variable natural forces increases to the point that indoor air quality begins to suffer. For these reasons it is assumed that a home with High-R enclosures will require mechanical ventilation. A Canadian study [Reardon, 2007] showed that as the air leakiness drops below about 3 to 6 ACH@50Pa (depending on climate), mechanical ventilation has become mandated. New Scandinavian houses are now all required to have mechanical ventilation that provides controlled air exchange. Given the above, it is expected by almost all researchers that low-energy housing will require controlled ventilation and that this will typically be provided by a mechanical ventilation system. The ASHRAE 62.2 committee continues to work towards defining acceptable ventilation strategies and rates.

CHAPTER II: Materials for Thermal Control in Buildings

Technologies Currently Deployed

Insulation is a well-developed industry. Significant progress is being made in deploying spray foam insulations, spray fibrous insulation products are become increasingly popular, and there is a nascent awareness that airtightness is both important and a separate function from that of stopping heat by conduction.

A very brief review of established insulation materials will be presented below, followed by a deeper investigation into emerging technologies.

Light Cavity Fill Insulation Materials

The vast majority of residential insulation is fibrous, low-density cavity fill: preformed, friction fit batt of fiberglass, rockwool, or even cotton and blown (requiring netting or an interior finish to support the insulation) or sprayed-in ((where insulation is held in using an adhesive and/or water) cellulose, fiberglass, or rockwool.

To ensure all spaces and voids in framing cavities are properly filled (to minimize the potential of convective looping), spray or blown fibrous insulation is preferred. Whenever air and vapor-permeable insulation is added to a cavity, extra care is required for selecting the location and permeance of the vapor control layer and the location of the air control layer.

Air-impermeable Cavity Fill Insulation Materials

Air-impermeable insulation in the form of spray foam has recently become more popular, especially as some of these foams also have higher R-values.

Enclosure systems that use board foam, machined or molded to fit between studs, are produced by several manufacturers of wall and roof panels. Primarily because of coordination costs, this approach is not widely used or as economical a means of producing High R walls, but it has been successfully deployed by several small manufacturers.

Insulating Sheathing Materials

Adding continuous layers of rigid and semi-rigid insulating materials is one of the preferred methods of increasing enclosure thermal performance. However, locating insulation as a continuous layer on the exterior of the structure requires insulations with more mechanical resistance, lower air permeance (to reduce wind washing impacts), and higher moisture tolerance (since the insulation is more likely to get wet during construction and in service) than traditional lower-cost fibrous batt and loose-fill insulations. Low-density fibrous insulations are important to fill interior studspaces and supplement the exterior insulation layer, especially when affordable high thermal resistance enclosures are desired.

Cellular foam plastics are used when air impermeable and/or water tolerant materials are required. Products such as expanded polystyrene (EPS), extruded polystyrene (XPS), and faced polyisocyanurate (“polyiso” or PIR) have long been used behind claddings and outboard of the water control layer. Polyiso should not be used in applications where it can be immersed for long periods of time: this is not a concern for above-grade walls, but does limit its use below grade. Expanded polystyrene, especially at higher densities, can be used very effectively below grade. Medium-density closed-cell spray polyurethane (ccSPF) is an increasingly common product that is spray applied to appropriate substrates. This product can act as part of the rain, air, vapor, and heat flow control of an assembly.

Most rigid foam board products, especially those with facers (e.g. the aluminum facer on polyiso intended for walls, faced EPS board), can act as part of the water and/or vapor, and/or air flow control so long as other requirements, such as structural support, and durability and continuity at joints, are met.

A new breed of products, those which combine significant insulation value with good racking resistance, are now available. Termed Structural Insulating Sheathing, they are currently available in a maximum thickness of 1", and thus only add R5.5: hence they are not yet sufficient for High R walls in most climates.

Semi-rigid fibrous insulation boards can only act as heat flow control layers, although they can provide a drainage path (i.e., they provide a drainage gap) for rain water, either by design or in actuality. In many applications, air- and vapor-permeable mineral-fiber semi-rigid insulations (MFI) such as fiberglass and rockwool can be used as exterior continuous insulation and have a very long track record of performance in these applications for commercial buildings. To perform in unsupported applications, fiberglass products generally require a minimum density in the range 2.5-4 pounds per cubic foot (40-70 kg/m3) whereas rockwool should have a density of over about 3 pcf (50 kg/m3). Such MFI products tend to be less expensive and are always more fire resistant than foamed plastics: hence they may be an important product category for zero lot line housing.

Non-insulating sheathing is often installed over framing for structural reasons. The addition of insulating sheathing over structural sheathing has no impact on the structural performance. In many cases, sheathing may not be needed for structural purposes, or may be needed only at corners, or can be replaced with a range of well-developed and emerging bracing solutions.

Radiant Barriers

Radiant barrier systems (RBS) are products that control thermal radiation. As such, they must have a significantly lower emissivity than normal materials in the infrared range. There is no widely agreed definition, but an emissivity of less than 0.30 and less than 0.05 have been proposed.

As an RBS only control radiant energy it cannot work without an airspace. Although the radiation physics are very well understood, and relatively simple for the temperature ranges in buildings, there is still widespread confusion about how RBS work, and how well. Unlike solid body insulation, the DOE or FTC have not provided definitive and widely promulgated definitions or performance requirements. As a consequence, the industry is rife with confusion, overblown claims, and bad design decisions.

RBS are complex in that their performance varies with temperature, air gap width, and direction of flow. An RBS with a 3.5" gap has a performance that varies significantly between operating at a temperature of 140 °F (i.e., a solar heated roof sheathing) with an R-value of about 10 and a temperature of 0°F (a cold winter night) with an R-value of only 2.5. Add additional variables such as dirt accumulation on the barrier and a wide range of performance values can be quoted. In most cases, the annual benefit of an RBS relative to an inch of insulation is small or non-existent: however, research is needed to quantify the true annual energy and peak cooling load reductions for roofs and crawlspaces in modern homes. Previous research [ORNL] considers specific points in time, not hourly data, and often investigated the performance improvement compared to very poor insulation layers (e.g., R11 or R19 ceiling insulation) rather than airtight R30-R50 assemblies.

Research and Development of New Materials

Research in many insulation materials has slowed to focus on specific issues such as process improvements, and reduced environmental impacts. These improvements have relatively small impacts on actual performance or cost. Insulation is already rather inexpensive on a per pound or per cubic foot basis.

The most rapid change in established insulations has been the development of a wider range of spray foam products. Until recently, products were either open-cell with about ½ pound per cubic foot density, or closed-cell with 2 pcf density. There are now closed-cell 1.2 pcf, open-cell 2 pcf products, and the boundaries of what is possible are constantly being moved. Some of these products offer advantages in that they can provide desirable vapor permeance properties with good R-values/inch. Changing part of the feedstock to plant based (the maximum content of plant-based raw materials is still only about 25% by weight) has also been implement by some manufacturers.

Research and development continues on nanoporous materials and vacuum panels, which offer the possibilities of very high R-values per inch (very low thermal conductivity). This characteristic is most important for applications in which volume is very expensive (such as aircraft, shipping containers, train cars, pipelines, etc), but high R/inch products also enable high-R enclosures in walls of modest thickness.

Phase Change Materials (PCM)

Phase Change Materials were first used in passive solar residential building applications in the 70's and early 80's, mostly based on paraffins, fatty acids, or Glauber's salt. These products where available encapsulated on tiles, sealed containers located in ceilings, or impregnated into gypsum board (Rudd 1993). Problems with separation, combustibility, have resulted in a second generation of compounds and new micro-encapsulation technology (Schossig 2005). Salt-hydrate PCMs, packaged in slim capsules, were used below the floor of the North House Solar Decathalon house to increase its solar-savings fraction.

ORNL [Kosny 2007] and others [Zhang 2005] have conducted significant research into the impacts of PCM on walls and roofs, and have shown that they can reduce heat flow little, but reduce daily peaks more noticeably: however, it is currently often less expensive and much easier to reduce the heat flow and peaks by increasing insulation thickness.

Vacuum Insulated Panels

Numerous Vacuum Insulated Panel (VIP) products are now on the European market, a result of developments over the last 25 years [IEA 2001]. VIPs have been investigated with cores of aerogel, silica fume, glass fiber, and open cell foams. In all cases, these cores are wrapped with a vacuum-tight wrapper, usually of metal or metalized plastic film to maintain the vacuum. These products achieve R-values of 15 to over 30 per inch depending on the core and the level of the vacuum. Edge effects can results in significant reductions below this potential [Ghazi et al, 2004].

Other than cost, two challenges remain: the risk of puncturing the seal (the almost instantaneous loss of 80% or more of the R-value) and the slow loss of vacuum over many years. The former is being solved using thoughtful applications (such as including VIPs in concrete, or protecting the with heavy sheet metal), and the latter is the current subject of research.

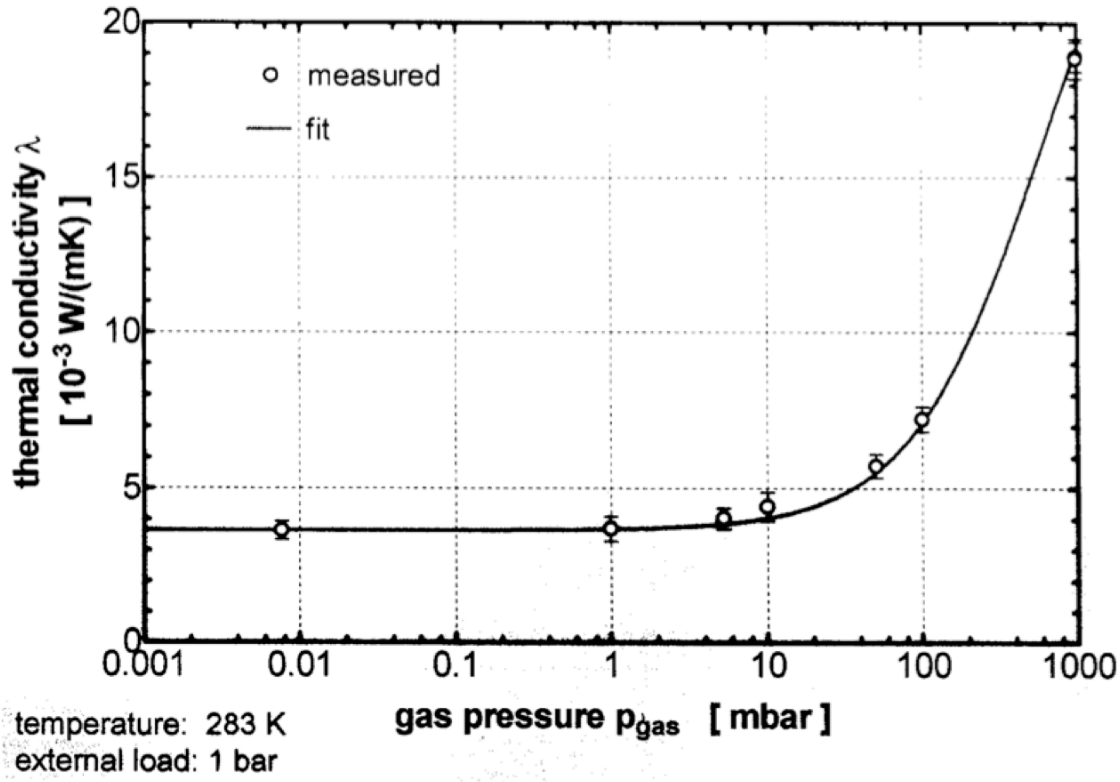

Figure 1: Plot of thermal conductivity vs gas pressure of a fumed silica board insulation [IEA 2001]

Recent work in Scandinavia has focused on integrating VIP into wood frame construction. Testing [Haavi et al 2010] has shown that walls with R-values of nearly 60 can be constructed of 2x8's (actually slightly smaller: 36 mm x 170 mm). The practical issues of inserting VIPS tightly between studs in the field has not yet been solved of course.

Other European work has considered the use of VIP as thin exterior retrofits to existing buildings: the high performance of the VIP at relatively small thicknesses can allow for modest changes (e.g. 3" or so) in depth and [Nussbaum et al 2006].

Aerogel

Aerogels are a broad range of materials that were developed decades ago. Although these materials can produce products with a range of physical and thermal properties, there use has been investigated for building applications because of their high R-value per inch [Kosny et al 2007].

Aerogel research should focus on reducing production costs and indentifing applications, perhaps in retrofit, that justify its current high cost.

Dark-colored Cool Roofs

Many owners of homes with pitched roofs would like to have or maintain a darker palette of colors. Unfortunately this typically means that more solar radiation would be absorbed than if a light-colored roof were used.

Several manufacturers are developing a new breed of coatings that can reflect light in the visible range to meet the color expectations, but which still reduce solar heating by reflecting other portions of the spectrum. The products are not as reflective as a bright white roof, but meaningful reductions can be made. LBNL [Levinson et al 2007] and ORNL [Miller et al 2004] has conducted some measurements and modeling of the impacts. Like all cool roof technologies, when such roofs are placed over well-insulated airtight ceilings (i.e, high R systems) the benefits are much smaller. Hence, this technology is likely beneficial for retrofits, in which a mixture of upgraded insulation and cool roof technology could be combined.

Environmental Issues

Insulation, like all materials used in construction, has some negative environmental implications in its production. Unlike almost all other materials used to build homes, however, the use of insulation increases R-value, reduces operational energy consumption and thereby reduces the environmental impact of a home over its lifecycle.

The *embodied energy*, that is, the energy required to produce a product, of all common insulations has been studied (Harvey 2009) and found to be small relative to the energy saved by their use. The embodied energy of common insulation products is small relative to the energy saved even for thicknesses of up to twice most building code requirements. Within classess of insulation the spread of embodied energy is small: most air and vapor permeable non-structural insulations (like fiberglass, cellulose and rockwool) have embodied energy in a narrow range, as do air- and vapor-permeable insulations with some structural characteristics (e.g., plastic foams). In many assemblies, a low-embodied energy product, like cellulose, cannot simply be substituted for a higher embodied energy product, such as polystyrene foam, and result ion the same performance. This renders simple material specific comparisons somewhat limited.

A more complex issue is the net impact on global warming potential (GWP). Some foam plastic products (e.g., closed cell polyurethane, and extruded polystyrene) use blowing agents with high Global Warming Potential. Little definitive research has been conducted to confirm the amount of gas that will leak out over the life of most foam products. However, making what is believed to be reasonable assumptions calculations show that if moderate thicknesses of such insulations are used, the net impact on GWP is positive even for the most efficient heating sources (Harvey 2007). For very thick layers (high R-values), it is possible if sufficient blowing agent leaks out for the benefit of energy saving to be overwhelmed. However, new blowing agents are currently be investigated in Europe to replace the current generation. This change will require a considerable amount of retooling and reformulation, new fire testing, and new concerns re: dimensional stability, insulating value, etc.

A third issue is the end of life of the product. Mineral fiber insulation is usually assumed to be inert and hence easily land filled. Natural fiber products like cellulose and cotton can be composted. Foam plastics can be burnt in an incinerator and some of the energy recovered and all of the blowing agent gases consuming, a process already demonstrated in Europe (ISOPA 2001).

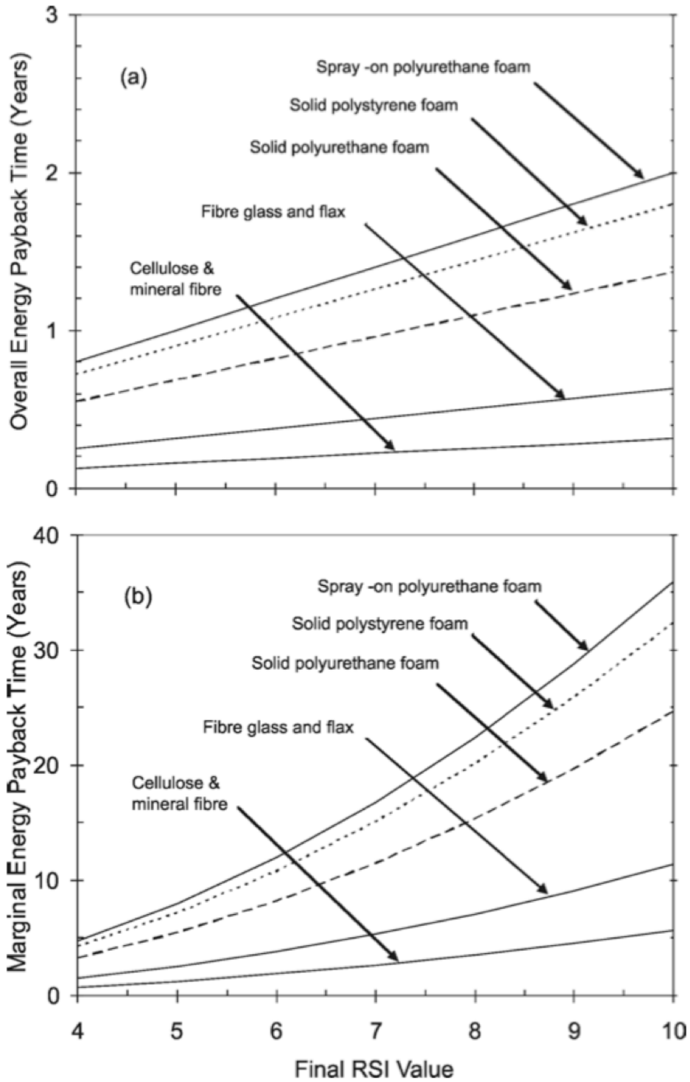

Figure 2: Embodied energy for an assembly of up to RSI10 (R56) is saved within two years for even energy intensive products in the a 7000 HDD climate (Harvey 2009)

CHAPTER III: High R-value Enclosure Systems for New Buildings

The following sections discuss approaches to High R-value enclosures for new building, examining walls (including windows and doors), roofs, and foundation assemblies in turn.

Walls

There are several difference conceptual approaches to thermal control in wall assemblies:

- interior insulation (i.e., thermal control to the inside of the wall structure),
- cavity insulation (i.e., line of thermal control within the wall),
- exterior insulation (i.e., thermal control to the outside of the wall structure), and
- integrated insulation (i.e., insulation material integrated with the structure of the building)

As has been explained in sections above, thermal control in building enclosures depends on more than just the nominal R-value of the selected insulation material. Enclosure air tightness, thermal bridging and other factors, such as wind-washing and convective looping, play a major role in the creation of High R-value walls. For these reasons, of the four approaches listed above, only cavity, exterior and integrated insulation techniques will be considered in this report.

Cavity Insulation

Cavity (studspace) insulation approaches are the traditional approach that developed historically from uninsulated studspaces to partially insulated, to fully-insulated.

The current widely-accepted approach to insulation involves filling the cavity between framing members with insulation. The International Residential code only requires R2 more insulation in Fairbanks Alaska (14 000 HDD) than in a Zone 5, 5500 HDD climate! Clearly, the code is not basing its R-value recommendations on heat loss, or it assumes High-R walls are very expensive.

The code limit of R21 for the stud cavity is artificial, as it is limited to specific types of insulation: closed-cell spray foams with R30 are widely available. The limitations of the cavity insulation approach, however, are broader than “installed R-value”, and can be listed as:

> • Maximum cavity size. Typical wood or steel frame residential buildings use either 2x4 or 2x6 wall framing members, providing a stud cavity of 3.5” and 5.5” respectively. Walls framed with conventional materials, therefore, will have a maximum R-value (using values for the traditional materials listed above) of approximately R12-14 and R19-21.
>
> • Thermal bridging of framing members. The Clear-wall R-value (i.e., the R-value of the wall area containing only insulation and necessary framing materials) is significantly less than the nominal R-value of the insulation used to fill the stud cavity. Research has shown that with typical framing factors, the true R-value of a 2x4 or 2x6 wall is reduced by about 25%. The reductions are far more severe for steel stud construction, exceeding 50%.
>
> Limiting insulation to only the stud cavity however seriously constrains the amount of insulation that can be installed, even with high-R insulations like spray foam. Thermal bridging and wood-wood joints seriously compromise a wood frame walls ability to control conductive heat flow and air leakage respectively. Using typical wood framing factors (about 25% of opaque walls are wood, 75% are insulated cavities), true R-values of just over R20 are possible with the highest R/inch (and most expensive) insulations when installed between framing members.
>
> • Poor whole building air tightness. Infiltration/exfiltration heat gain and loss has been shown to be a significant source of energy loss in both Hot and Cold climate building enclosures. Research has shown that air leakage is a source of moisture in the building

enclosure and contributes to durability and health issues. Traditional cavity-fill insulation is highly air permeable and can do little to contribute to overall enclosure airtightness. This limitation can be overcome by ensuring a quality continuous air barrier elsewhere in the assembly.

• Convective looping within the stud cavity. Even with a perfect air barrier system, high permeance cavity fills, especially those installed less than perfectly, can allow convective looping. Spray fills with almost zero air permeance solve these problems. High density fibrous products, spray applied products, and careful installation and inspection go a long way to reducing and potentially eliminating this issue.

• Cold-climate condensation on inboard surface of exterior sheathing.

• Warm-climate condensation on outboard surface of interior sheathing/finish.

To increase insulation values, the first obvious step is to use larger studs to increase the cavity size: 2x8 framed walls are however expensive in terms of wood, but do allow about R28 of fibrous insulation to be installed, thermal bridging limits the true R-value. This approach is taken to the extreme by building walls with wood I-joists of 12 to 14" thickness. Such I-joists are quite expensive, and require expensive top and bottom plates. The increased cost of the framing will often offset the cost reductions provided by allowing the use of blown-in insulation rather than more expensive foams. The heat loss through thermal bridging is less for deep stud walls than that through a 2x4 or 2x6 stud (because of the larger thickness of wood) but is far from negligible, especially at floor joists, roof-wall intersections, etc. However, the bigger concern with deeper stud cavities is the increased moisture risk that comes with making the sheathing colder and colder for longer.

Double-stud walls were developed in the 1970's to allow builders to install thicker insulation: typical depths are 10-14". There are many variations, but the easiest to build, and hence most common design, tends to use an exterior load-bearing 2x4 wall with a second non-loadbearing 2x4 wall (perhaps at 24" o.c.) built on the inside (Figure 3). This solution is popular with builders because it allows for familiar cladding attachment and window installation details. However, this design suffers from significant thermal bridging at the floor penetrations. More seriously, it places the exterior sheathing at a greater moisture risk by reducing the temperature of the sheathing (thereby increasing condensation risk and drying rate potential), reducing the flow of internal heat to the sheathing (thereby reducing available drying energy), and does this for more months of the year. Hence, double stud walls need to have very good airtightness, must control interior humidity to lower levels during cold periods, and should increase the drying capacity of the exterior sheathing layer (by using ventilated cladding, highly permeable housewraps, and high-permeance sheathing).

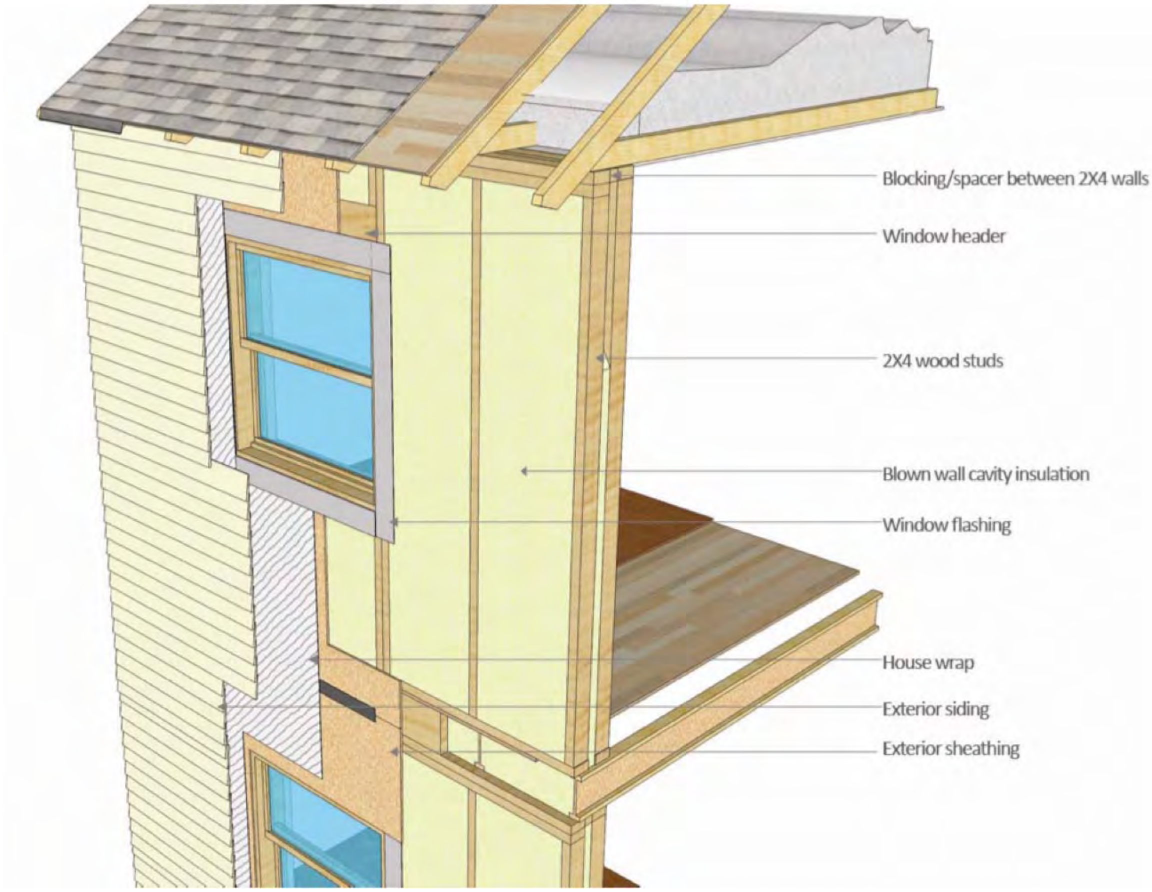

Figure 3: A common design of double stud wall. The thermal bridging at the floor and top plate can be seen in this Building America prototype design (Aldrich et al, 2010).

Another approach attempted is to increase the R-value/inch of cavity insulation (Figure 4). This approach will return higher true R-values, but because of thermal bridging, the increase in cavity R-value will not directly relate to an increase in true R-values, but the cost increases dramatically. Even with spray foam of R6/inch, a true R-value of R20 is barely achieved. The use of spray foams, open- or closed-cell, has the major advantage of providing good airtightness, filling all voids, even if irregular, and thus practically eliminating convective loops. However, while a significant improvement in performance is practically achievable, the improvement over standard practice is limited, perhaps 25-30%, while the cost increase is significant (usually three times or more the cost of installed insulation).

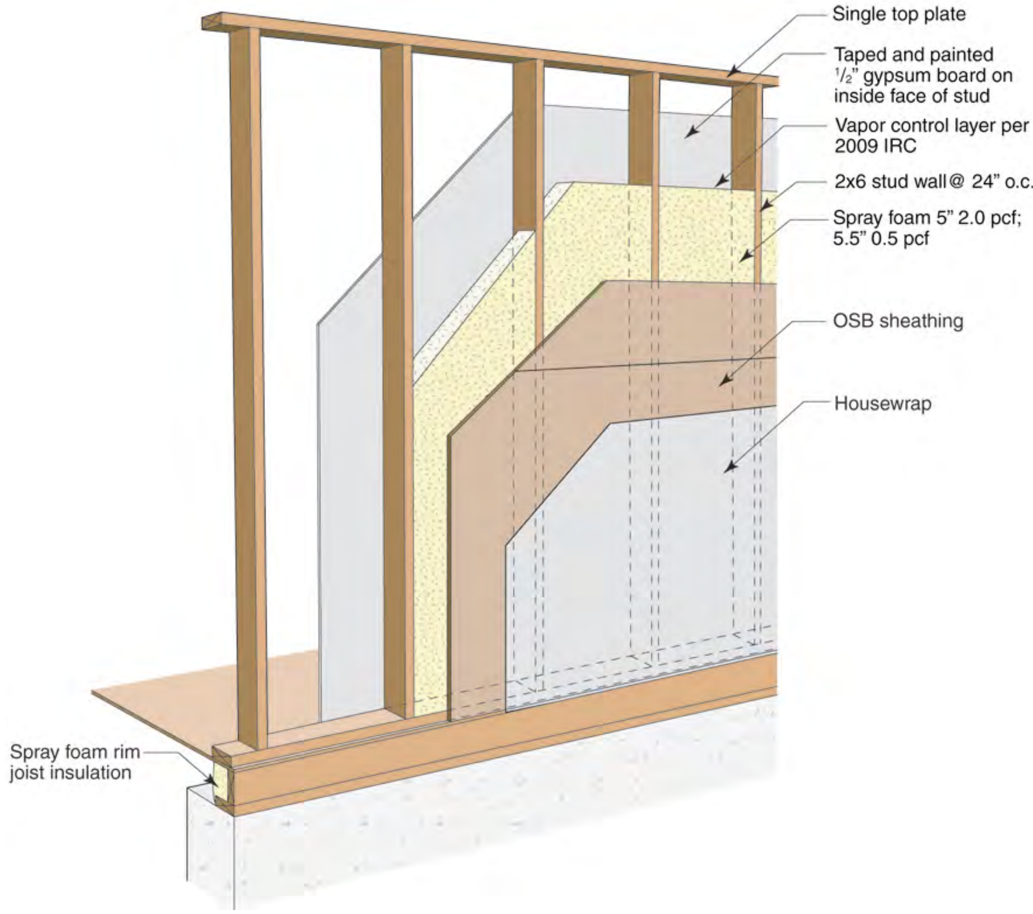

Figure 4: Standard 2x6 wood-frame wall with high-R, air impermeable, spray-applied cavity fill

Current research is being conducted in several other areas that relate to high R-value walls with a cavity insulation approach:

- Measuring whole-wall thermal resistance (needed to better characterize the performance of wall systems and allow for fair comparisons)

- Characterization of air flow pathways and the role of air semi-permeable insulations such as dense pack cellulose, high-density spray fiberglass, etc.

- Water management details – because high r-value walls lack the drying potential of inefficient older ways, this is a fundamental research concern.

Research is these areas should be considered advanced and has already yielded deployable technologies that are compatible with conventional construction methods. However, all cavity insulation approaches that meet the High R-value criteria can only minimize the effect of thermal bridging and the risk of interstitial condensation and bulk water penetration. On both issues, exterior insulation strategies are fundamentally superior and are discussed in the following section.

Exterior Insulation

Insulating sheathing has been applied to the outside of wood-framed residential structures for more than 30 years. Given the growing awareness of thermal bridging and condensation issues in the 1970's some early adopters chose to use rigid board foam on the exterior as a path to higher performance.

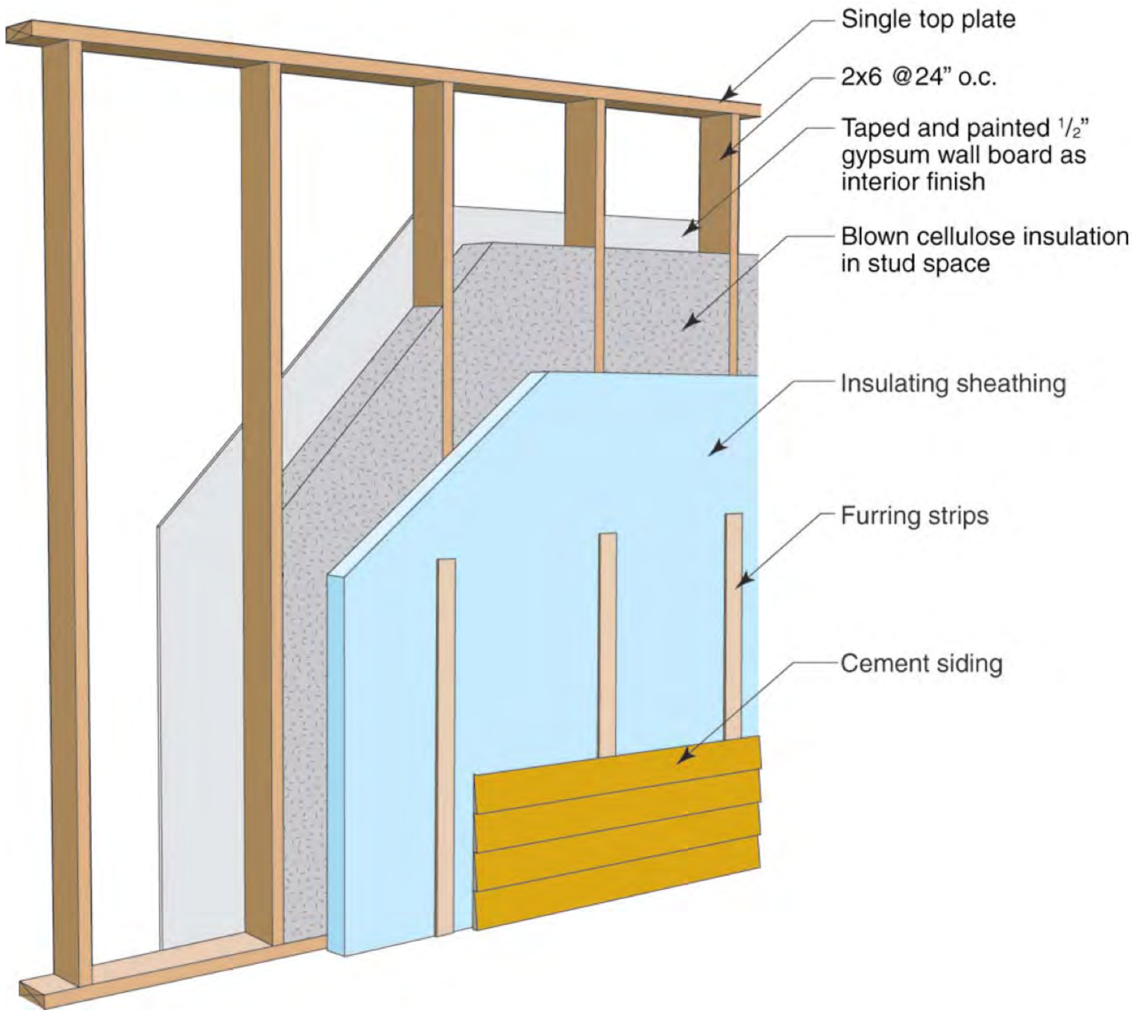

Figure 5 : Advanced framing combined with insulating sheathing (of 1 to many inches) controls thermal bridging, reduces the risk of condensation, and improves the R-value

All enclosures should be designed with a continuous thermal control layer (i.e., insulation layer that is not bypassed by thermal bridges) and a continuous air barrier/control layer. The exterior side of wall assemblies typically have fewer penetrations, transitions, and instances of structural interruptions than the interior side of the wall. For example, electrical penetrations on the interior side of the wall are typically more numerous than on the exterior side. The interior sides of exterior walls are interrupted by intersecting partition walls and floor framing. The exterior side of the wall, in contrast, typically presents a better opportunity for continuous insulation and airflow control layers.

The most common impediment to widespread deployment of thick layers of exterior insulating layers is the practical challenge of attaching cladding and trimming door and window openings. Although many builders have overcome these practical challenges in individual cases, there is essentially no code support for the techniques developed, and no scientifically-based method or test result to support the use of over about 2" of insulation. Many concerns, including the rising cost of energy, climate change concerns, and demands for increased comfort, have lead to the desire for increased insulation levels in many new and existing buildings. Building codes and green building codes are being changed to require higher levels of thermal insulation both for residential and commercial construction. This report will review, and summarize the current state of understanding and research into enclosures with higher thermal resistance, so-called "High R Enclosures". Rigid foam has been used the most in the field, but there is much less information available for semi-rigid mineral fiber insulations of rockwool or glass fiber, or for irregular surfaces such as spray foam.

A specific widely-deployed solution is Exterior Insulation Finish Systems (EIFS). EIFS are typically seen as a finish, chosen based on the desire for certain aesthetic. As such, the exterior layer of foam is typically applied with an R-value of only 4 to 6. However, most EIFS manufacturers have approvals for products with R12 to as much as R40 (!) that can be applied over 2x4 and 2x6 walls. This approach limits the owner to a specific aesthetic, but sidesteps the issue of cladding attachment, and hence can be more easily specified and installed. The challenge with EIFS over wood-framed enclosures in the past has been durability problems caused by poor rain control. Research and product development in the last decade has essentially solved this issue, and most products are now available as drained systems. The airtightness can often be exceptional, given the full exterior-to-the-sheathing liquid-applied membrane, but more emphasis of this is required in the field.

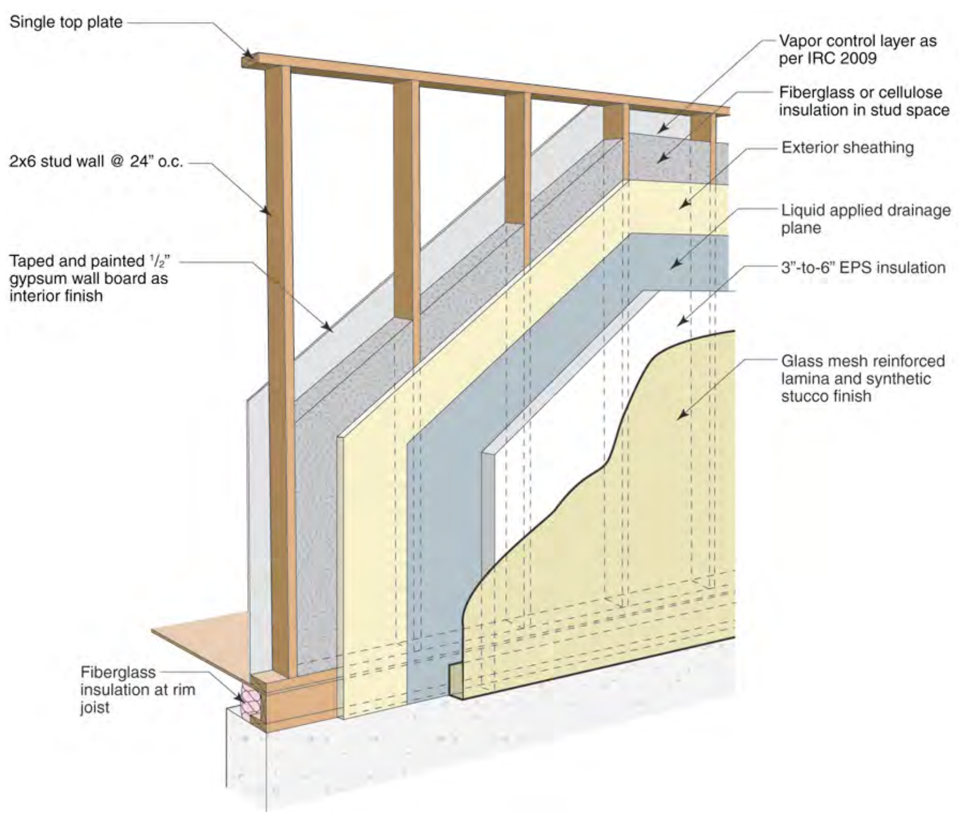

Figure 6: EIFS are an exterior insulated wall system that can reach very high R-values, airtightness, and durability targets.

Integrated Insulation Techniques

Numerous systems have been developed in the last decades that are not based on a wood-framed structure. Structural Insulated Panel Systems (SIPS) (Figure 8), Insulated Concrete Forms (ICF) (Figure 7), and numerous proprietary combinations have been developed. It is worth noting that both ICF and SIPS provide the potential for good airtightness, and inherently solve the challenge of cladding attachment while reducing or nearly eliminating thermal bridging.

SIPS solve many of the thermal bridging issues by employed a stressed core of EPS, XPS, or PIC insulation to replace most studs. However, most systems use solid wood elements between panels as stiffeners and fastening points: these 2x wood members act as thermal bridged. More significantly, to be cost effective, most SIPS walls are designed with 3.5" or 5.5" cores, limited the true R-value to around R20. ORNL [2005] built several prototype houses with SIPS that delivered a maximum of R27 panels by sandwiching polyisocyanurate insulation in a 5.5” panel: the impact of thermal bridges was not reported. Thicker panels are available and can easily be specified (the panel strength and stiffness increases with panel depth) to generate a High R enclosure. The airtightness of SIPS are dependent on details of how the joints and penetrations are detailed: very low leakage is possible, but rather high air leakage is not uncommon.   Efforts to maximize the panel size and improve joint sealing are needed. The durability of the exterior OSB sheathing is a concern, as there is little inward drying capacity, and the OSB is kept very cold, thereby reducing its drying capacity. Hence, to deliver good durability, it is recommended that all siding should be placed over furring strips or other form of ventilated gap.

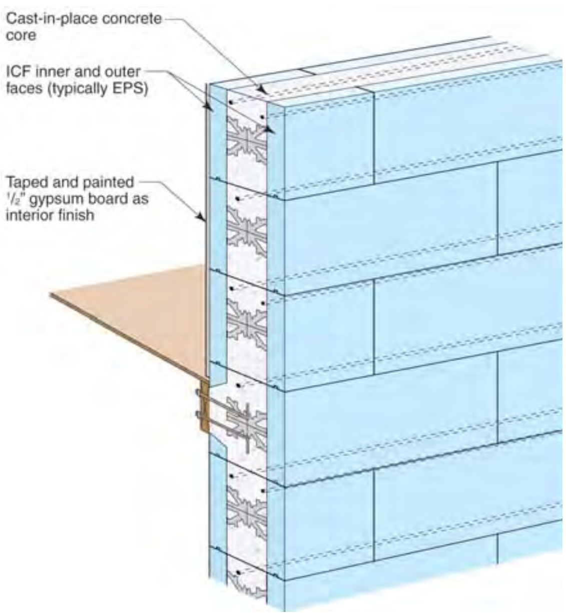

Figure 7: ICF wall system

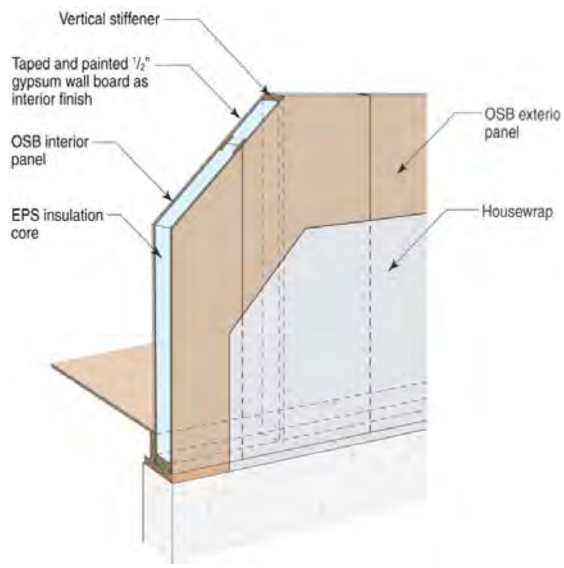

Figure 8: SIPS wall system

ICF walls provide the structure in the form of a concrete core, which also provides a relatively high-performance continuous air barrier. As for all systems, joints and penetrations require attention to achieve exceptional performance. Although most thermal bridging is avoided (as the exterior skin of foam covers almost all penetrations from the interior), the true R-value of most products are limited to about R20. There is at least one ICF product that provides a range of R-values, up to R80, but this is very much the exception. For above-grade applications, the cost of ICF systems is usually significantly more than wood-framed walls with the same R-value, but they do simplify some attachment details. The lack of wood-based sheathing results in very good durability, and fastening strips embedded in the foam skins simplified interior and exterior finish attachments.

Windows and Doors

Modern windows often have thermally efficient frames, solar control and low-emissivity coatings on the glass, gas fills such as argon in the glazing space, and increasingly use insulating spacers. A combination of all of these technologies allows the U-value of the glazing to reach a value of only around 0.3 to 0.4 (R-values of 2.5 to 3.0). It is difficult to achieve a whole-window R-value of even 4. This is only 10 to 20% the R-value targeted for other parts of the High-R enclosures. Similarly, the solar gain through windows, the largest component of the cooling load in many buildings,

The benefit of high performance windows and curtainwalls are becoming more widely known: significant improvements to comfort by improving the Mean Radiant Temperature (MRT) avoidance of cold films falling off the glass and wide temperature swings, major reductions in peak sizing of air conditioning, and major reductions in annual space conditioning and lighting energy (Carmody et al, 2004). Increasing the R-value and airtightness of walls and roofs to R20, 40, and even 60 is now well developed and can be deployed in almost all projects if desired (Straube & Smegal, 2009). High performance windows technology is more expensive and has not been as widely adopted. Changes are occurring however, with a range of new products being released, both from established firms and new technology firms.

Double-glazing has reached the limits of what is practical, with coating emissivity values of as low as 0.03 and cavity fills of krypton or even xenon, the R-value at the center of glass cannot reach even R5. Hence, other approaches are used. The most obvious approach is to add another layer of glazing. This is a time-tested and reliable method, which, when combined with noble gas fills and low-e coatings can deliver center of glass R-values of 6 to 9. Quadruple glazing takes this approach another step further to deliver center-of-glass R-values of R10 to 12 and higher.

The technical drawbacks to adding sheets of glass include increased thickness and weight. If this is a problem, there are solutions to both: the interior glazing can be replaced with a thin and lightweight sheet of plastic or film, and narrower cavities can be used if the argon gas fill is replaced with krypton. Center of glass R-values of over 9 are achievable with current technology in a 1" (25 mm) glazing package, and R20 in a 1 3/8" (35 mm) quintuple-layered system.

Vacuum glazing is another approach to increasing the R-value (decreasing U-value) of glazing. By drawing a vacuum on the space between two sheets of low-e coated glass, and using closely spaced small glass "posts" to support the glass, the conduction and convection heat transfer can be virtually eliminated, much like a thermos. There are only a few such products available, with center of glass R-values less than 5. However, products are improving, and relatively thin (3/4") triple glazing with 4 low-e coatings theoretically has the potential to deliver well over R20.

The limitation with all of the high R-value glazing technologies is heat lost through the spacers and the framing systems. Warm-edge spacers have become quite affordable and widely available, but most insulated glazing units (IGU) still have more heat lost through the spacers than center of glass.

Much more significant is the heat loss through the frame. As high-performance glazing units deliver higher R-values, the heat loss of poor frames begin to dominate. In residential construction, a normal wood or vinyl frame may have an R-value of just 2 to 3. Hence, the energy-saving potential provided by multiple glazings, coatings and gas fills are bypassed by low-performance frames. This is a very significant penalty in practice: an R9 3'x5' triple-glazed glazing unit in a standard vinyl aluminum frame can have a whole window thermal resistance of only R5.

Frames of high-performance composite materials, commercially available as fiberglass frames, offer most of the strength, stiffness, and durability of aluminum with the thermal performance of wood. Composite frames have been demonstrated in the lab, and are becoming commercially available: foam-filled vinyl frames with aluminum exterior claddings, wood frames with polyurethane foam thermal breaks, and slender foam-filled fiberglass extrusions with wood interior finish and aluminum outer weathered components all offer the possibilities of R6 to R8 frames that are commercially available or nearly so. These frames still have more heat flow through them than very-high performance glazing, but can reduce heat flow by 2 to 3 times when compared to standard window frames.

The maximum rate of heat flow through a window does not occur on the coldest night of the year, but during sunny days. Of course, this heat flow is due to solar heat gain. The ratio of solar energy that becomes heat inside a building to that which falls on a window is defined as the Solar Heat Gain Coefficient (SHGC). Dark tinted windows and reflective coatings were used in the past to reduce the solar gain. However, these approaches significantly reduce the view and daylight. Modern windows use spectrally selective coatings, which reduce solar gain with only a small effect on daylight.

As impressive as spectrally selective coatings are, large windows will still allow very large amounts of heat to enter a building when exposed to direct sun. Windows in full shade can allow nearly half as much heat to enter as windows directly exposed to the sun. For well-insulated, airtight, low-energy buildings, even limited areas of low SHGC (e.g., 20% window to wall ratio SHGC=0.33) can define the peak air conditioning load. At the same time, solar gain can be useful in cold weather, and daylight is usually welcome if it is not too intense.

To allow solar heat and daylight through a window when needed (a high SHGC), and reject it more effectively when not (e.g., a SHGC below 0.1) advanced technology is required (Selkowitz & Lee, 2004). Exterior shading, operated by automatic controls, can deliver this kind level of performance: as the light intensity in the building reaches a predetermined threshold, the shades either deploy to fix the light level. If solar gain can be usefully harvested, the shades remain fully open, or pivot to bounce the light off the ceiling, thereby collecting the heat without glare.

The same high-performance can be delivered without any visible shades through the use of electrochromic glazings. Several technologies are available, but ultra-thin thin coatings that change their tint when a small voltage is applied are now available. One product silently changes its SHGC from 0.48 to 0.09 in a few minutes with no moving parts.

Roofs

Roofs are constructed in many different forms: vented, unvented, cathedralized, attics, with dormers, etc. The different approaches taken to provide insulation and airtightness for this diverse set of assemblies has profound implications for cost, durability and performance.

Vented Attics with Insulation at Ceiling Level

As is now well understood by the research community, but not always by the code or construction community, fully-vented pitched attic assemblies are the lowest cost, highest-R, and most durable roofs in all climates zones (except perhaps Zone 1 and Zone 2 coastal high humidity*) if and only if* no ductwork or major air leakage (e.g. can lights) are present in the ceiling plane. Given the low-cost of ventilated attic insulation, rather high R-values are justified even in climates with moderate air temperatures, such as Zone 2, and very high levels (R60 to R100) are affordable and economically justified in Zones 5 through 8.

The additional cost of reaching R-values of 60 to 100 are very small given that blown fibrous insulation has the least marginal cost per R-value of all products (e.g. the cost for an additional R10 given R30 or 40 is to be installed is very small), and thermal bridging does not have much impact, if any, as the ceiling joists are all covered. Other than requiring an airtight ceiling, the only changes required to achieve twice current code levels of R-value are the provision of “high heel” trusses or rafter designs to accommodate the increased amount of insulation.

Providing a truly airtight ceiling plane is very important and the most difficult task as it requires changes to how designers design and builders build. As the installed R-value of insulation increases to R50, 60 or 80, the influence of even very small airleaks takes on great importance. Thus ductwork elimination must be the first step, as well as sealing around all lights, partitions, hatches, etc.

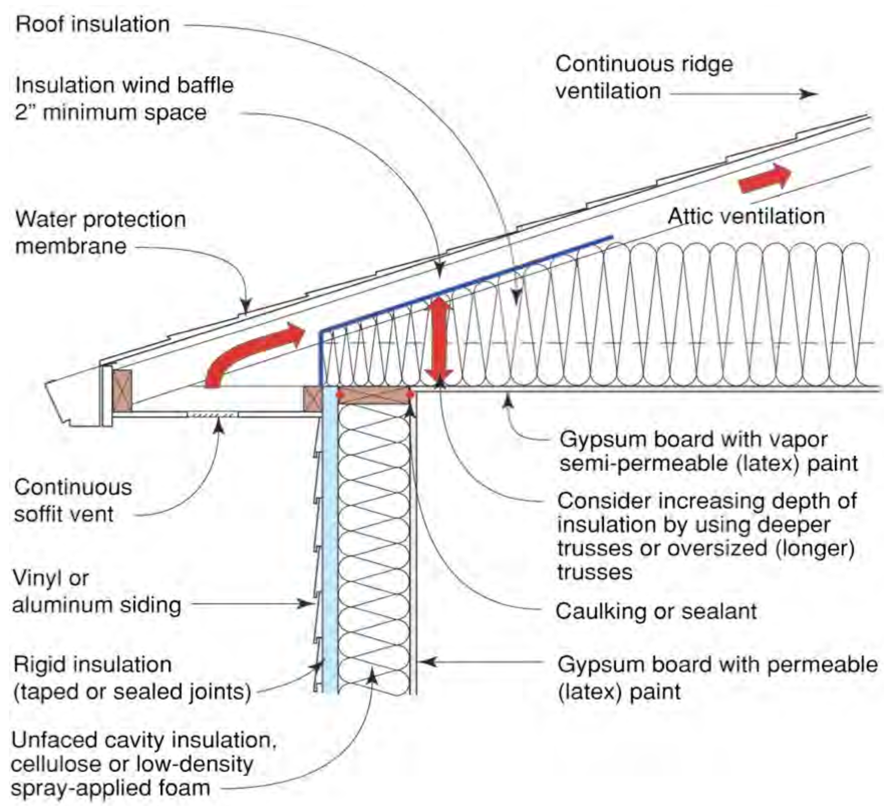

Figure 9: The lowest-cost, highest thermal performance roof system with good durability

Good venting is necessary to remove whatever moisture may leak into the attic space. The roof sheathing will drop below air temperature, by 5 – 20 °F, every clear night, making condensation of any water vapor in the airspace almost inevitable. Solar heating by the sun during the day can drive this moisture from the sheathing, but ventilation is required to remove it.

Vented Cathedral Ceiling Assemblies

Vented cathedral ceiling assemblies have long been used in housing. In principal the performance in the same as vented attics. However, choosing a cathedral ceiling reduces the performance in a number of ways

- the depth of the structural framing members limit the depth of insulation that can be applied: more expensive spray foams must be used to achieve higher R-values
- because the ventilation space is constrained ventilation flow encounters more resistance, and hence the flow rate is less, increasing the risk of moisture accumulating in the sheathing
- Ventilation requires a direct path from the soffit to the ridge: this only happens in simple gable roofs over rectangular plans with no dormers.
- thermal bridging reduces the true R-value

The limitation on ventilation is the most severe. Very few plans are pure rectangles, not all roofs are gable roofs, and many roofs have dormers, hips, valleys etc. Typical ventilated roof designs are not ventilated, and hence cannot recover well from small air leaks.

The roof shown in Figure 10 would be appropriate for a High R roof in a warmer climate as its R-value would be limited to about R40 with a 12" TJI. However, by using a 16" TJI almost R60 can be achieved and the assembly could be used in colder climate: the foam layer is used in this assembly as a baffle to support the fibrous insulation and provide a deep clear ventilation space, and so higher R-values are provided by thicker fibrous fill. The use of more than 12" TJI is rarely justified on the basis of structural need, so the cost of the thicker TJI is part of the cost of increasing the R-value to 60. Airtightness as the ceiling plane is still critical to achieve, and the levels of airtightness required for a high R assembly are difficult to achieve in practice. Install interior partition walls after the ceiling drywall is installed, banning the use of any ceiling fixtures, and similar measures could be used.

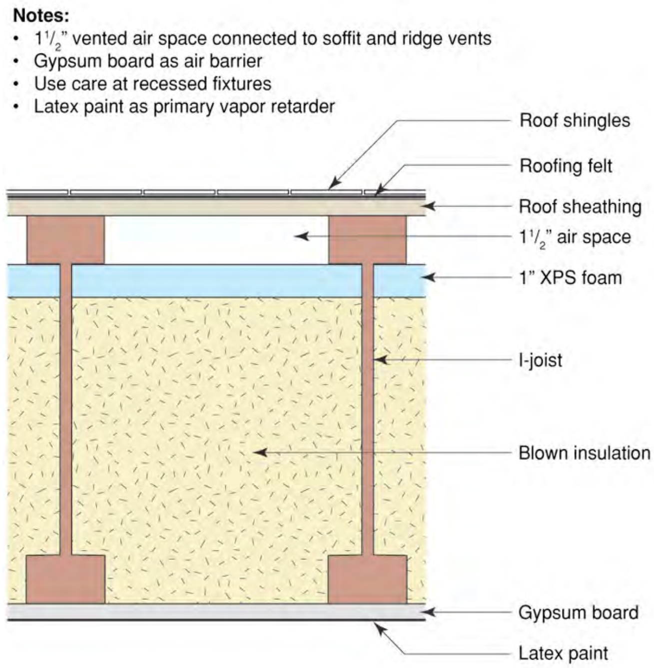

Figure 10: Ventilated cathedral ceiling.

Another approach is to apply interior layers of insulation. This increases the R-value and decreases thermal bridging. The risk of this approach is air leakage. Again, building partitions after the interior layer of insulation has been installed, and the avoidance of any ceiling fixtures is required for this approach to be successful.

Again, it is important to not that both of these compact vented roof systems can only be vented if the roof is a simple gable with no dormers, valleys, hips, or other obstructions.

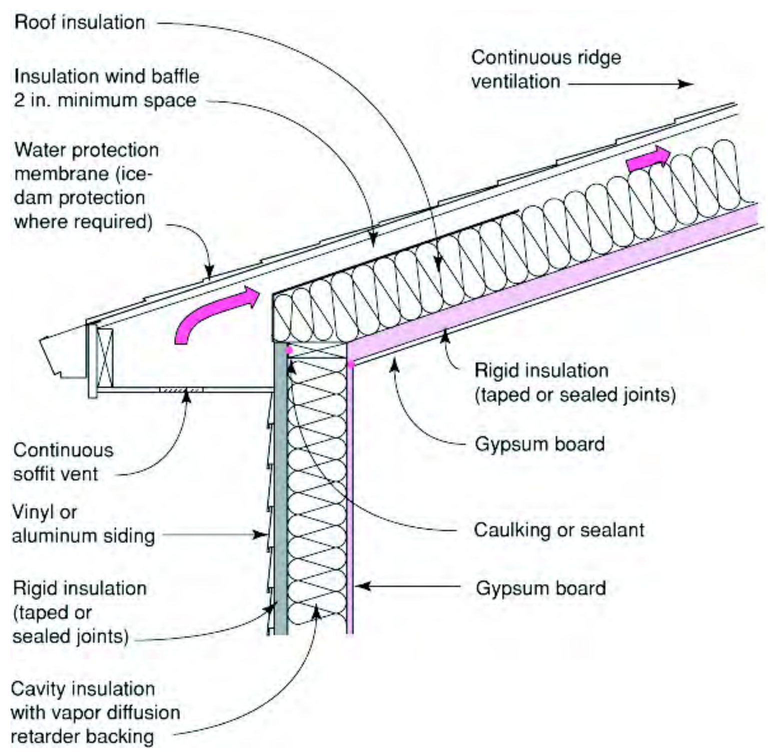

Figure 11: Vented cathedral ceiling

Unvented Attic Assemblies

Unvented attic assemblies, or cathedralized attics, which move the insulation and airtightness planes to the slope, have been developed to overcome two major problems with vented attics (Figure 12). These problems are:

1. locating ducts/air handling units in the attic space causes major air leaks of conditioned air, and heat/loss gain through the ductwork
2. designs with complex coffered ceiling planes, numerous penetrations by lights, speakers, vents, etc. make it practically difficult to achieve the excellent airtightness required just below the insulation layer.

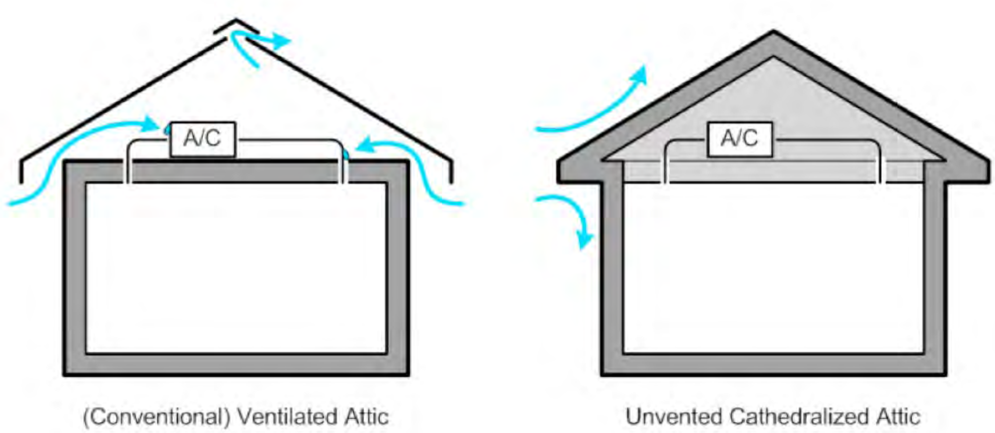

Figure 12: Cathedralized or Unvented Attics

Because high R roofs can be seriously negatively impacted by even small air leaks (wether that leak is through the ceiling air barrier or via ducts), even ducts with 5% leakage are unacceptable and it is difficult to imagine a reasonable scenario with a High R roof and ducts in unconditioned space. It may be possible with spray products (like foam) to reduce duct leakage to tolerable levels (e.g., perhaps 1% or less) but this has not been demonstrated or documented. It is possible to achieve airtightness of the ceiling (#2) by careful workmanship (especially at lights and penetrations) or by the use of more expensive spray foam insulation applied from above. The spray foam need only be about 2" of closed cell foam or 3" of open-cell foam to achieve a good air seal and allow for a vented attic.

However, if the ducts are to be installed in the attic (problem #1) then an unvented cathedralized attic is a recommended solution. Alternate solutions to problem #1 include covering all ductwork, and the ceiling plane with an uninterrupted layer of spray foam, after which this foam is covered with thick layers of fibrous insulation. This is expensive, difficult (because of the geometry), creates equipment servicing difficulties and may not be allowed by equipment manufacturers.

Unvented attics can be comprised of any unvented cathedral ceiling assembly (see below) but do not require a finish. However, the lack of a finish means that gypsum wallboard (GWB) cannot be used as a fire control layer. Code requirements for finishing cathedralized attics vary significantly across the country. In some jurisdictions certain open-cell spray foam or glass-fibre over foam solutions may meet local fire requirements.

Unvented Cathedral Ceiling Assemblies

Ventilated cathedral ceiling assemblies have the significant restriction that they cannot be used for complex roofs because of the blocked ventilation caused by roof obstructions.

All unvented attic and cathedral ceiling designs must provide for either a very high degree of tightness or avoid condensation by warming sensitive surfaces. To meet durability goals in most applications the airtightness must be provided by a continuous membrane, preferably adhered or sandwiched, on the exterior of the framing. In designs where the air tightness is provided between framing elements, spray foam has been found to be a practical solution to the challenge of providing this airtightness: all wood to wood joints in the framing must still be solved with sealants, or other means.

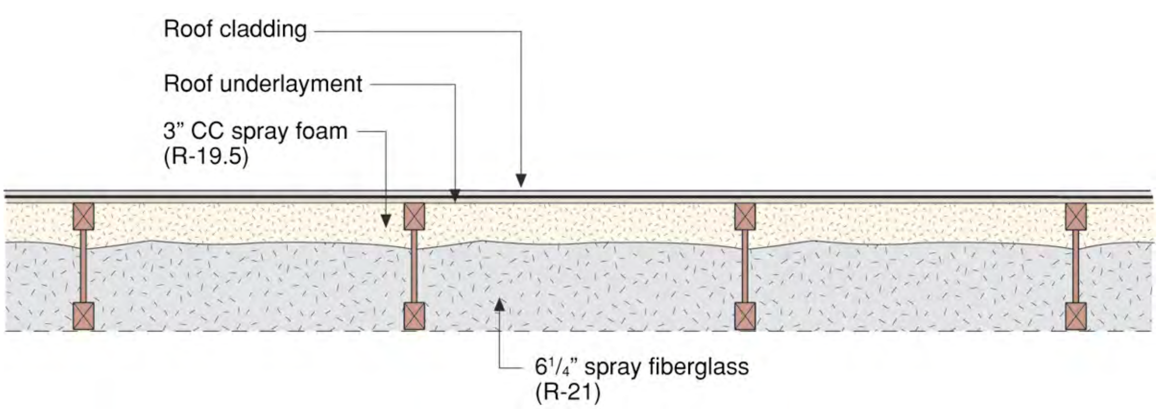

Figure 13: Example High R hybrid unvented cathedralized ceiling/attic

As an alternate design applicable to both retrofit and new construction an often more economical solution for increasing R-value in an unvented roof is to use a hybrid approach of exterior board foam over the structure and air barrier membrane, and fibrous fill between the framing. The IRC provides the ratios of air impermeable to air permeable insulation required in each climate zone.

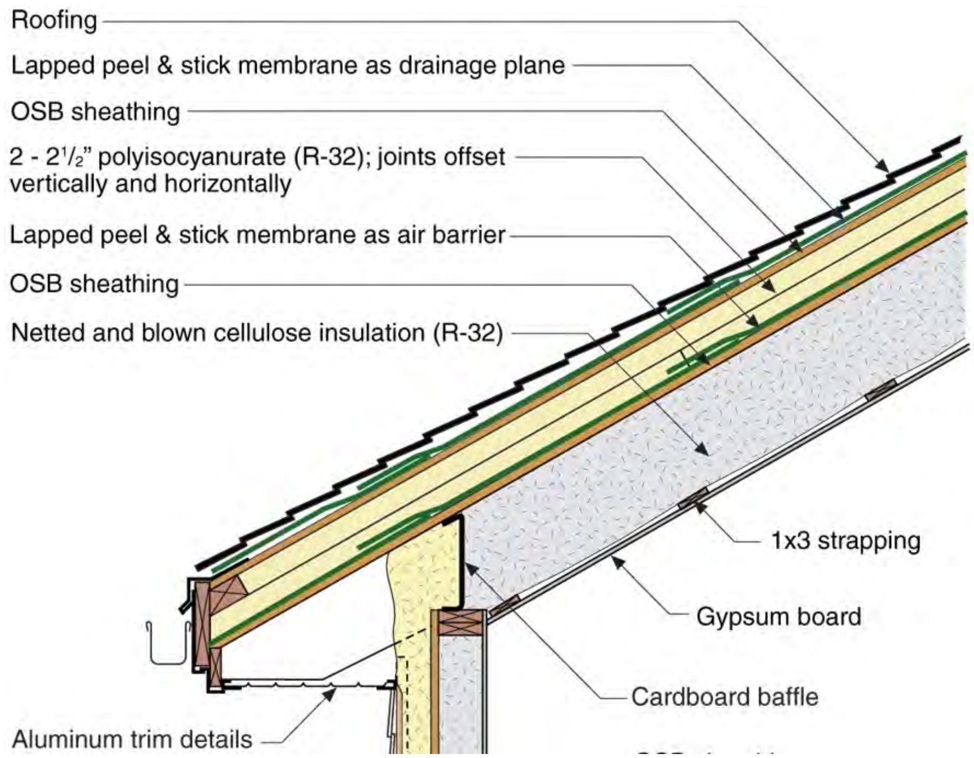

Figure 14: True R60 cold climate unvented cathedral ceiling

Foundation Assemblies

Basement Walls

Basement foundation heat losses have been estimated in the range of 10-30% of a house's total heat loss (BETT 1985, Beausoleil-Morrison 1997, Swinton & Kesik 2005): controlling this heat loss can significantly reduce overall space conditioning energy use.

However, the installation of interior basement wall insulation—in retrofit or new construction—has been associated with moisture problems (Swinton and Kesik 2005, Cheple and Huelman 2001). There are certain assemblies that have historically demonstrated an unacceptably high failure rate in practice; they typically involve some type of fibrous insulation (e.g., fiberglass batt) and a vapor impermeable interior facing (e.g., polyethylene film). Some examples would include a wood stud frame with fiberglass batt and interior polyethylene, and "roll blanket" insulation (4 foot wide fiberglass insulation bonded to an interior polyethylene facer, installed horizontally).

These assemblies lack drying capacity in the only direction available, inward. When coupled with either the built-in moisture of the concrete wall, capillary or vapor-phase moisture from the surrounding soils, and/or bulk water intrusion, the result can be moisture accumulation within the assembly. If there are moisture-sensitive components within the assembly (such as wood framing or fiberglass insulation binders), mold and IAQ problems can (and have often) occurred.

The lowest risk approaches for interior insulation of basement walls use non-moisture sensitive semi-vapor permeable materials at the interface between the concrete and the insulation (Lstiburek 2006, Building Science Corporation 2010). The insulation materials normally used are plastic foam insulations, such as extruded polystyrene, expanded polystyrene, polyisocyanurate, or two-component urethane spray foam.

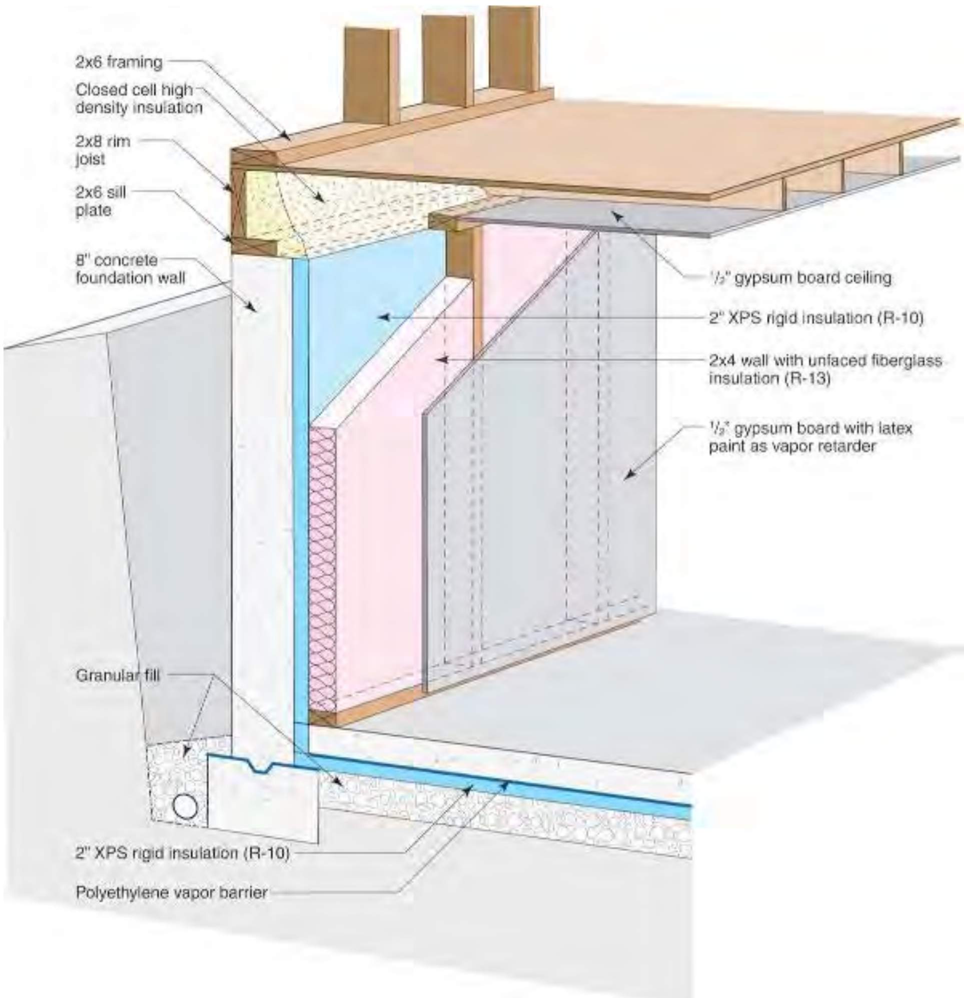

Figure 15: Plastic foam insulation and fiberglass batt high R-value basement wall (BSC 2010)

However, one weakness of all of these materials is compliance with fire ratings; many of them require some type of ignition barrier or coating, in order to be left exposed in a basement space. Dow THERMAX (foil-faced polyisocyanurate with fiberglass reinforcement) meets the combustibility requirement and can be left exposed. However, this leaves a potential gap; the development of additional products or assemblies that can meet thermal barrier requirement would widen the field of available solutions. A synergistic solution would be an insulation material that meets fire code (ignition barrier) requirements. When applied to the interior of the plastic foam insulation, it would provide additional R value (to attain high R value targets), and eliminate the need for a separate ignition barrier.

Another common basement wall insulation failure is due to condensation on the cold concrete surface due to leakage of interior air. This would occur on the upper portions (above grade) parts of the wall in wintertime, and the lowest parts of the wall in springtime. Note that all of the plastic foam insulations above are also air impermeable insulations (ICC 2006); the foam is detailed as an air barrier, preventing air leakage from the interior to the concrete, thus reducing condensation risks. Previous research has shown that air leakage can clearly be more dominant than vapor diffusion resistance alone (Zuluaga et al. 2004, Ueno and Townsend 2006).

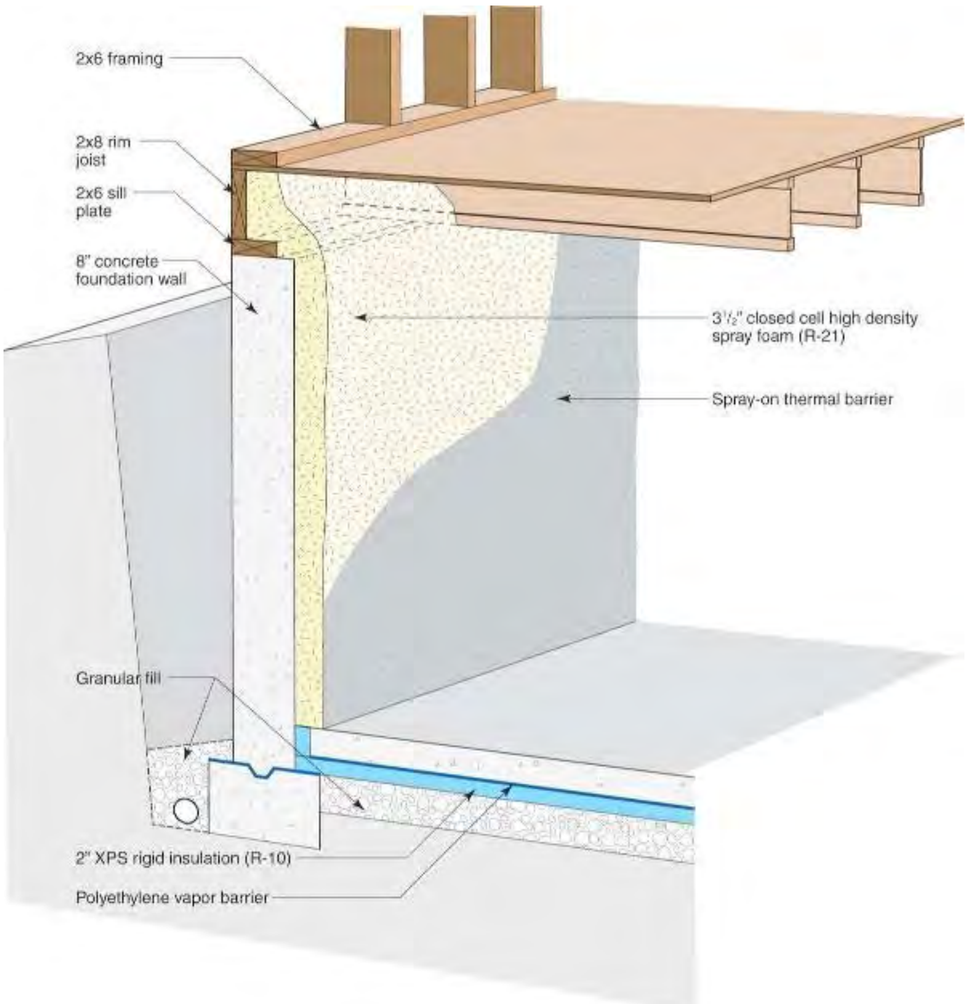

Figure 16: 2.0 PCF spray urethane foam high R-value basement wall (BSC 2010)

The assemblies described above provide a robust, moisture-insensitive, high durability solution to foundation walls that are substantially dry (i.e., minor water leaks can be handled), and have flat surfaces (concrete block or cast concrete walls). High R values in foundation walls would be on the order of R-20 (continuous insulation), compared to code levels of R-10 (continuous insulation) in Zones 4 and 5, and R-15 in Zones 6, 7, and 8 (ICC 2009). These target R values can be achieved with either plastic foam insulation alone, or a combination of plastic foam insulations with fibrous insulation added on the inboard side. Therefore, in these cases, the problem of high-R value insulation assemblies can be considered to be substantially solved although the solutions deserve to be better known and disseminated.

For walls which have more than minor leaks, that is, sufficient water forms to run down the wall and pool in the floor, a drainage layer should be provided, either on the exterior (if excavation is practical) or on the interior (leading to an interior drain).

Floor Slabs on Soil

Floor slabs are currently the only major part of the building enclosure that do not require insulation. Because of the relatively stable and mild temperatures below a slab, especially after several years of heat provided to the soil through the slab, the annual and peak heat loss is modest. However, as High R enclosures are implemented, the heat loss through the slab can become much more significant than typically thought. BSC [2010] conducted a Building America literature review and simulations of the impact on energy use of sub-slab insulation.

In short, some sub-slab insulation is recommended in all heating climates, although the optimal level of insulation is difficult to define. There is little data of careful field measurements of below-slab temperatures for insulated slabs. Although there is a growing consensus in methods for below-grade heat loss, there are still large variations in heat loss predictions, which make choosing the appropriate insulation level difficult.

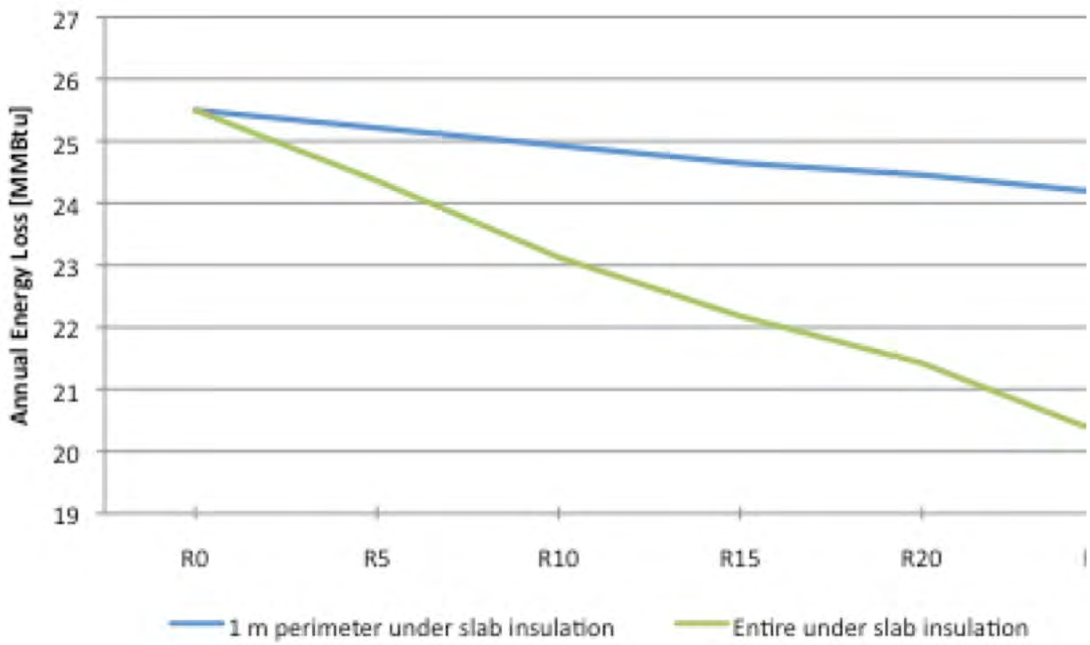

Figure 17: Heat loss through slabs in Minneapolis MN climate using BASECALC [BSC 2010]

Perhaps the most important factor, however, are the comfort and moisture benefits of sub-slab insulation. The temperature of an uninsulated slab will be significantly below the air temperature. Because this depresses the mean radiant temperature of a finished basement space, comfort is compromised or the air temperature in the basement must be increased above the typical set point, thereby increasing energy loss further. Secondly, cool temperatures in the summer result in high surface relative humidities (and the attendant mold growth) or condensation. It is believed that this second factor is the primary cause of the "musty basement" smell in new buildings.

Insulation for floor slabs on earth in new construction should be placed under the slab, and the slab placed on poly sheet. It is recommended that the concrete be poured over a vapor barrier, such as polyethylene sheet, but this is not important if the insulation below is vapor resistant. Although builders traditionally do not like to pour concrete over poly (because it does not allow excess mix water to drain away during the casting process), as concrete quality improves and drier concrete is placed using plastisicers, this practical disadvantage recedes. In no case should a membrane be placed below the insulation as this can allows ground water, flood water, or mix water to be trapped between the concrete slab and membrane.

The use of a membrane such as polyethylene sheet allows the concrete-poly sandwich to act as an effective air barrier. Concrete, even reinforced concrete, cracks during curing and in service, and the use of poly spans these inevitable gaps. Hence, the combination of a poly sheet and concrete provides an excellent air barrier. The polyethylene is also a vapor barrier, preventing moisture in the wet soil from diffusing inward. This function is not always needed, as the insulation may have sufficient vapor resistance (most foam insulations do), and the concrete itself may provide vapor resistance.

However, the poly is important as an air barrier, and its vapor resistance rarely results in undesirable performance.

The insulation can be placed directly on soil as the insulations used are not capillary active, and hence will not wick moisture into the material. However, it is strongly recommended that a layer of stones (no-fines gravel) be placed over the soil to provide an interconnected series of air gaps that allow air and water to flow. This layer can then be used as part of a sub-slab depressurization strategy to control soil gases and radon. The drainage capacity is used to connect the perimeter drains to the center of the slab and thereby intercept and remove any rising ground water. Stones are also a convenient leveling course (it is easy to rake stones flat and level).

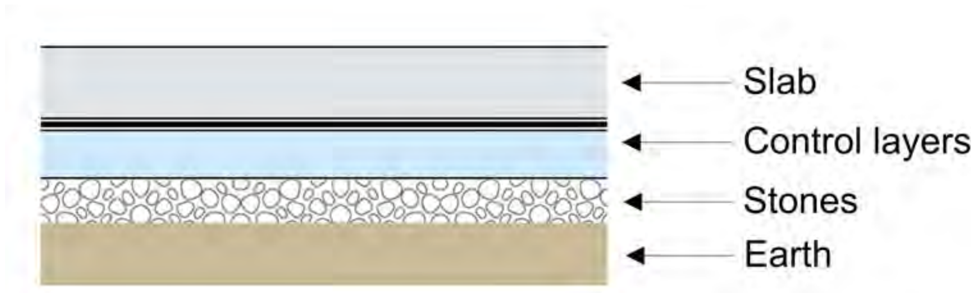

Figure 18: The optimal slab on earth design is both well established and affordable.

The choices for floor slab insulation are limited to moisture-tolerant, stiff insulation materials. The common choices are polymeric foams, such as EPS and XPS. Spray-applied 2 pcf polyurethane foam has been used, and even high-density rockwool has been used to a limited extent in Scandinavia. These other choices have not been studied in any depth.

Crawlspaces

Typical ventilated crawlspaces have serious performance limitations and increasing durability problems. The thermal bridging at the framing and the stem walls, the countless penetrations through the insulated floor that leak air, and the propensity to use ductwork and air handlers (that both leak air) all conspire to make traditional ventilated crawlspaces energy intensive, uncomfortable, unhealthy and non-durable.

Unvented conditioned crawlspaces have become more commonly accepted (including by the code) over the last decade (see also *BSI New Light on Crawlspaces*). They are recommended as they solve the major air leakage and durability problems, allow ductwork, air-handling equipment, and uninsulated plumbing to be installed, and provide an upgrade path for improving the control of conductive heatflow.

Several problems remain that deserve research: heat loss through the earthen floor, and termites. Although earth insulation is likely not justified in warmer climates, it is likely justified in colder (Zone 5+) zones. Practical methods for doing this at low cost include laying down semi-rigid rockwool or rigid foam insulation and coating with a thin layer of concrete (rat slab) on poly to allow for easy access, or spray foam direct to the soil and leave exposed (where fire codes and limited access allow). Lower cost solutions and more demonstrations are a research gap worthy of investigation.

Secondary issues that remain are developing more insulation products that can be installed without requiring additional fire control. Rockwool with air impermeable and vapor semi-permeable skins is one product that might be developed. Currently, certain foil-faced polyiso products with the appropriate fire rating are being used.

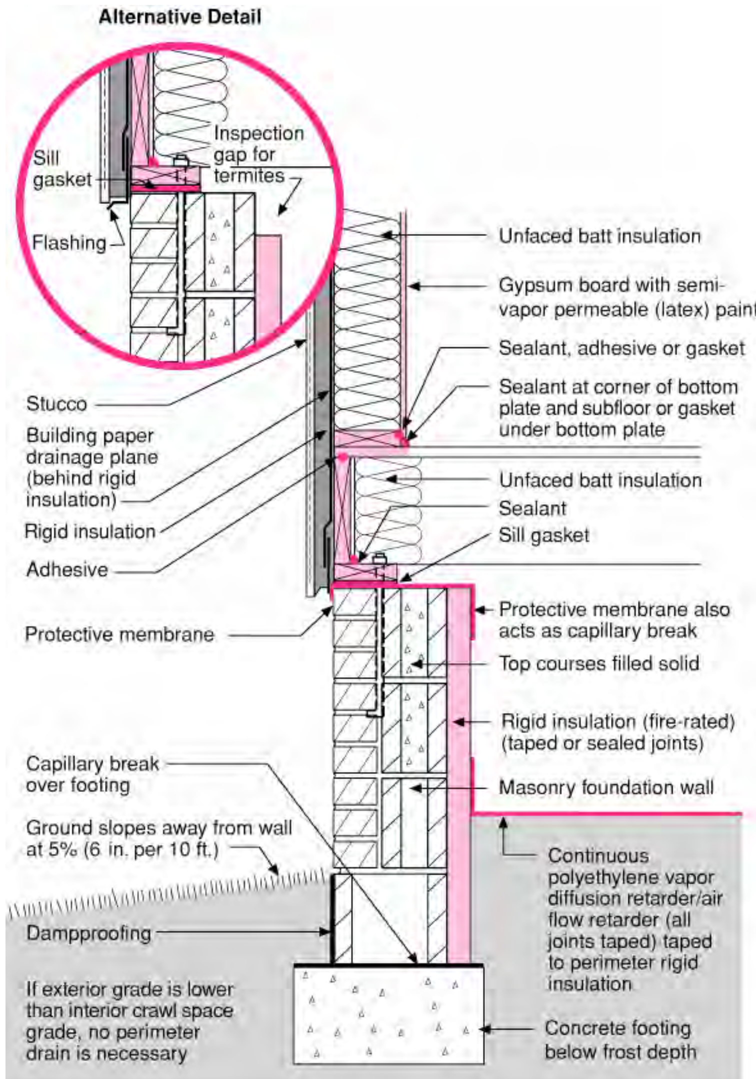

Figure 19: Recommended Unvented and Conditioned Crawlspace

Insulating Vented Crawlspaces or Basements at Floor Level

In some situations (particularly flood zones and steeply sloping sites), unvented crawlspaces are impractical. In such conditions, vented crawlspaces with insulating sheathing are recommended as High R solutions. Although airtightness and thermal bridging is partially solved in this design by the use of rigid, airtight exterior insulation, thermal bridging still occurs are the intersection with stem walls, central supporting beams and posts, etc. Air leakage a major challenge around any exposed plumbing the inevitably projects through the floor. Hence, this approach to crawlspaces is far from perfect and better designs continue to be sought.

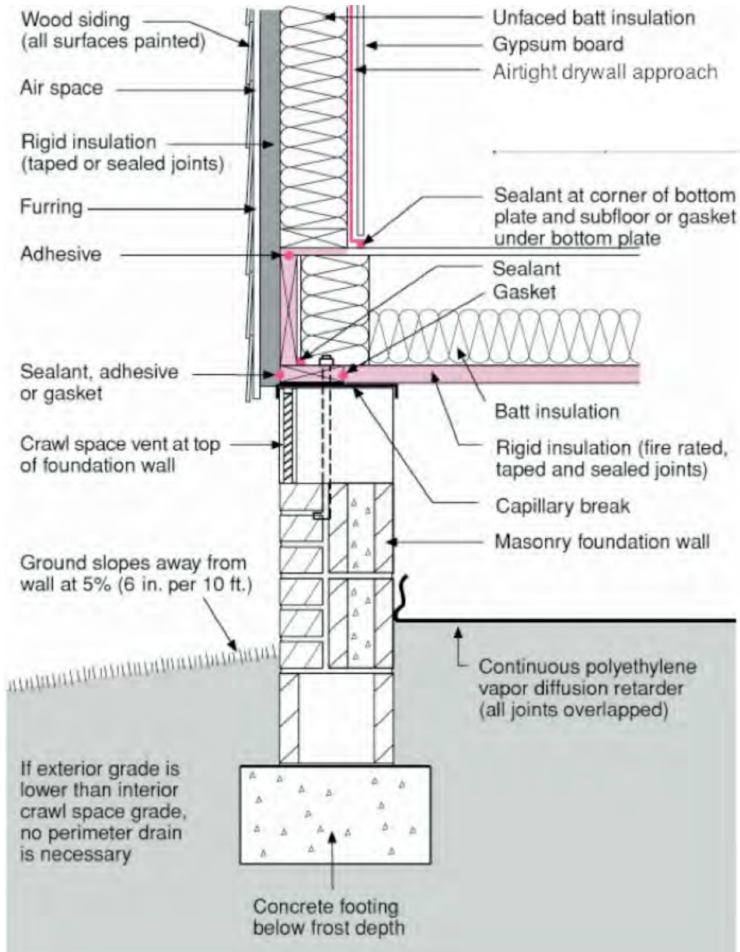

Figure 20: Ventilated High R Crawlspace

Airtightness

Controlling airflow is critical for high-R enclosure systems but specific performance targets for enclosure assemblies or the whole house have not been required by code. This should be pursued in the medium term, and both target-setting and testing required for projects with High R enclosures.

Residential air tightness has traditionally been measured using blower doors (ASTM E779-10). This standard approach is now widely used because of its ease, speed, and cost-effectiveness. Measurements in terms of ACH are fundamentally limited by two aspects: one, it measures the total air leakage through the enclosure (in Air Changes per Hour, or ACH) and thus does not provide information about which components of the enclosure are leaking (i.e., wall, windows, roof) and two, enclosure performance is related to the area of the enclosure (i.e, square feet) not by the volume enclosed (i.e., the volume used in ACH). To address these limitations, most research into enclosure performance uses the metric of cfm/sf or liters/second/m^2 at a given pressure. A blower door test can provide an average value of air leakage in the form of cfm/sf@50 Pa by dividing the cfm@50 result by the total enclosure area (rather than dividing by the enclosed volume in cubic feet).

Many building product standards apply to materials or components, such as windows or walls, and do not apply to the whole enclosure. Although it is common to assume an increase in air leakage from materials to components to enclosures of ten times per step, this has not been well documented in buildings in the field due to the difficulty of measuring in-situ component air leakage.

Source	Requirement	Application
IRC	"Substantially air tight"	Enclosure and assembly
GSA	0.04 cfm75/ft^2	Opaque assembly
GSA	0.40 cfm75/ft^2	Whole Enclosure
ASTM1677	0.045 cfm50/ft^2	Opaque assembly
Bldg. America	0.25 cfm50/ft^2	Whole enclosure
EnergyStar	0.20 cfm50/ft^2	Whole enclosure

Table 3: Different programs and standards apply different air tightness requirements on different parts of the enclosure

Even small amounts of air leakage through an insulated assembly can significantly impact heat transfer, especially if the enclosure is highly insulated (Figure 21). The ASHRAE Handbook of Fundamentals provides estimates of the amount of total air leakage that passes through various components of the enclosure: For example, enclosure walls comprise between 18-50 (35)% of total leakage, roofs 3-30 (18)%, windows and doors 6-22 (15)%. The values in parentheses are the most likely values, and ducts, fireplaces, crawlspaces, and basements comprise the remainder. Airflow through opaque enclosures is not often a large portion of enclosure leakage: most air leakage occurs at joints, penetrations, and transitions between components of the enclosure such as wall to floor (rim joists), floor to basement (mudsill), penetrations, (electrical outlets), and joints (windows).

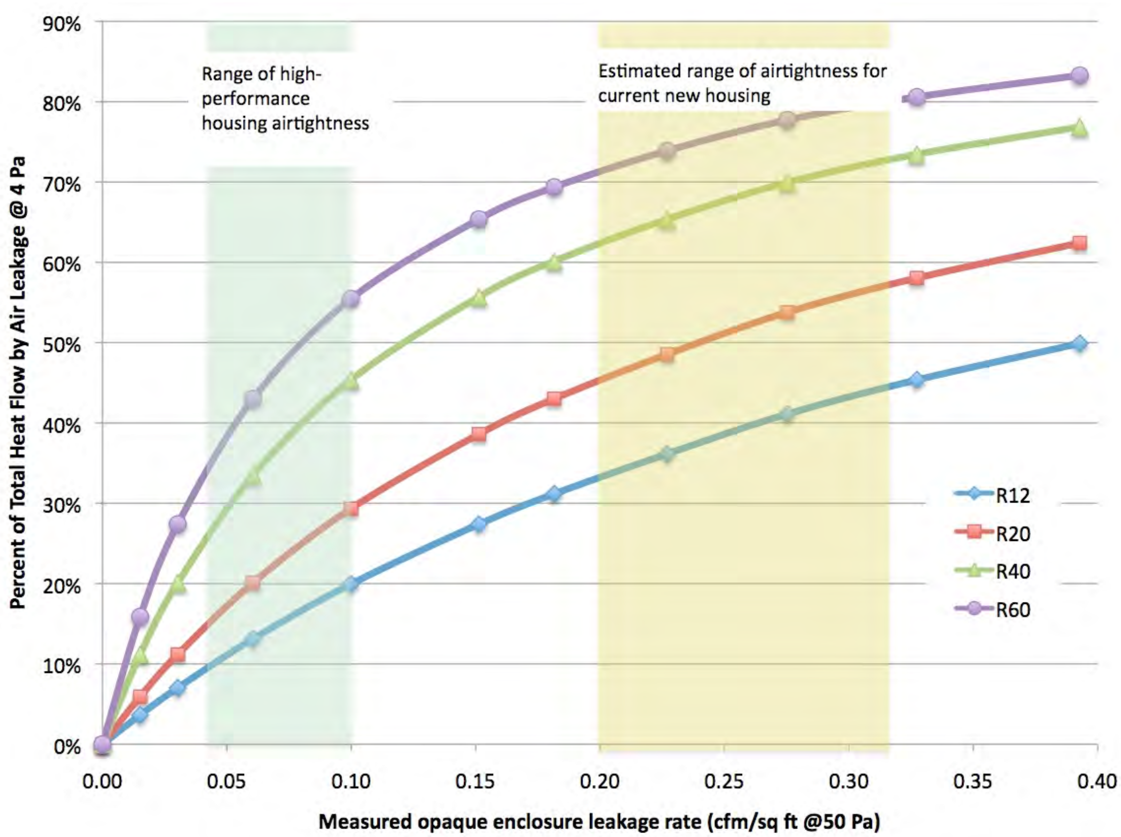

Figure 21: Even modest airflow rates through highly-insulated enclosures can result in significant (20-40%) increases in heat flow.

The blower door test measures this airflow across the entire enclosure. Air can also flow *within* an assembly, from outdoor through an assembly and back outdoors, or from indoors through an assembly and back indoors.

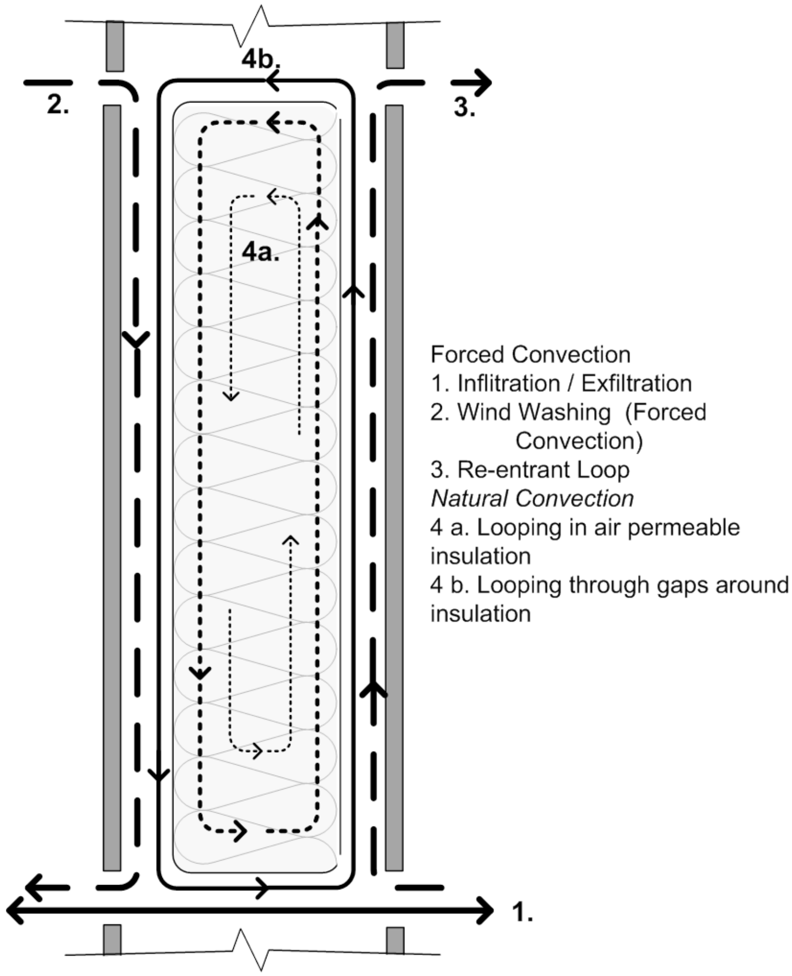

Figure 22: Possible airflow paths within and through an insulated enclosure

Both thermal buoyancy (i.e., natural convection or stack effect) and differential wind pressures cause natural and forced convective air flows within building enclosures. These internal airflows can short-circuit thermal insulation and bypass air barriers with the attendant increase in heat transfer and risk of moisture deposition. Providing an excellent air barrier system will not necessarily control these problems, since no air flow need occur through an ABS for either of these phenomena to cause performance problems.

These other types of airflow can play an important role in thermal performance. For enclosure assemblies with lower R-values, e.g. true R-value of 10, these secondary airflow effects play a small role. As the R-value of an assembly increases (to R-20 or R-40) even small flows can begin to comprise a significant proportion of total heat loss.

Research into the impact of these alternative airflow paths conducted by Uvslokk et al (1988, 1996), Besant (1982), Silberstein et al (1990), Lecompte (1991), Trethowen (1991), Timusk (1991) Brown et al (1993), Ober et al (1995), and Ojanen and Kohonen (1995) was reviewed in 2009 (BSC 2009).

The growing importance of these flow paths has lead to improvements in materials and enclosure systems: blown insulation helps avoid small air gaps and voids that allow for convection, better air barriers and exterior housewraps have reduced the influence of windwashing, and multiple layers (i.e, exterior insulating sheathing) reduce the temperature difference across the insulating layers. All of these strategies deserve more research, and more importantly, wider deployment to gain their benefits.

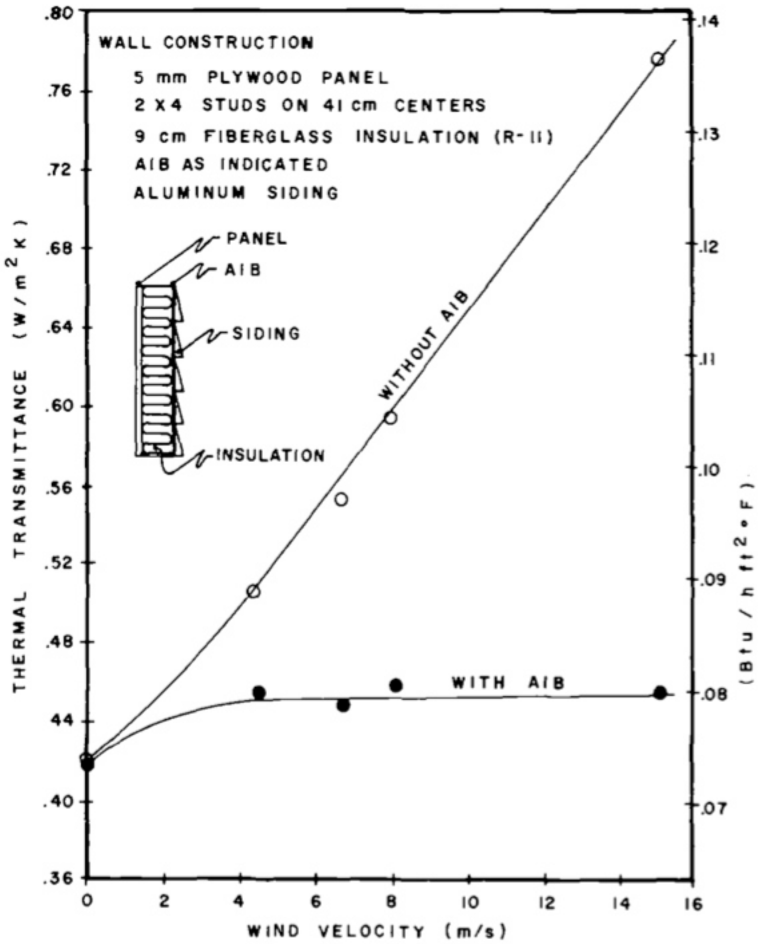

Figure 23: Influence of wind speed on heat loss for a wall with no wind washing (Henning ASTM STP 779)

Chapter IV: High R-value Enclosure Systems for Existing Buildings

High R-value enclosures for existing buildings are in some ways similar to enclosures for new construction. All enclosures have the same functional requirements: the enclosure is the environmental separator and must control rain, air, moisture, and heat, as well as, sound, fire, physical entry and other factors; and the enclosure is the aesthetic surface to in the inside and outside of the building. Enclosures for existing buildings, however, face an additional level of constraints relative to new construction.

A key point to understand is that the retrofit of existing building enclosures requires careful consideration of the thermal and moisture dynamics of enclosure assemblies. Design of high R-value enclosure retrofit must ensure that the retrofit of insulation does not result in a greater accumulation of moisture in vulnerable assemblies. In an existing building, a balance of wetting and drying might have no accumulation, but the retrofit of insulation might upset this balance. In masonry wall assemblies in colder climates, the retrofit of insulation must also account for added risk of freeze-thaw damage.

The retrofit of enclosures may also uncover latent problems in the building assemblies. Damage to building assemblies may be concealed by finishes if it has not progressed to the point of causing failure or of being evident. A best practice for retrofit will be to anticipate most likely instances of latent damage and plan the retrofit in a way that incorporates a survey for damage at likely locations.

A major, and perhaps the most significant challenge, is the financing of deep energy retrofits and the potential lost opportunity of doing small retrofits that payback quickly, but compromise subsequent work. Financing deep energy retrofits over the life of 25 to 30 yr mortgage should likely become normal, as the benefits of new siding, roofing, windows, insulation, and airtightness should all exceed this time frame.

The optimal sequencing of retrofits requires more study. Owners may not have the funds to do a complete retrofit and hence will often conduct only pieces. It is critical to investigate the best sequence of retrofits for the many different conditions that may occur, and minimize lost opportunities, increased costs, or increased risks of failure. For example, HVAC retrofits are often first considered because of equipment age or failure, subsidy programs and the perception that these will address comfort as well as operating cost issues. Later retrofit of the enclosure results in HVAC systems that are often oversized. Given fixed upgrade budgets this is unlikely to change.

Wall Retrofits

Given the goal of high R value wall assemblies, it can be assumed that typical weatherization methods (i.e., retrofit insulation in the existing wood frame stud bays) will not meet R value or airtightness targets. Therefore, more significant and invasive retrofits will be required.

The two types of approaches available are to insulate to the exterior of the existing building enclosure or to the interior of the existing enclosure. In either case, the resulting wall will be thicker than the existing wall and this change must be accommodated during the planning phases (i.e., loss of interior square footage or larger footprint of the exterior enclosure). This increase in wall thickness is particularly important in detailing (e.g., window or service penetrations). Either the interior finish must be replaced/covered or the exterior cladding must be replaced/covered. Another challenge that may be met are the restrictions on side yard setback and historical committees. These non-technical barriers can block even the best-funded and well-designed retrofit.

Exterior Enclosure Retrofits

Thermal enclosure retrofits from the exterior involve addition of insulation to the exterior of the existing structure. Retrofit of insulation to the exterior of wall systems is well suited to the cyclical replacement of sacrificial wall claddings (e.g. wood clapboard, wood shingles, vinyl siding, cement siding) of wood or metal-framed assemblies. Replacement of cladding that has reached end of its service life presents an opportunity to add insulation to the exterior. In addition, this type of overcladding/insulation retrofit can be done for aesthetic reasons. The desire to change building aesthetics, address durability concerns, conduct necessary upgrades of components can all provide complementary – even primary – motivations for thermal enclosure retrofits from the exterior.

As described in the previous chapter on new construction, exterior enclosure retrofit strategies offer some inherent advantages in terms of thermal performance and moisture management. The exterior airtighting and insulation approach has additional benefits in retrofits for several practical reasons:

1. The home or apartment can usually be occupied while an exterior retrofit is performed
2. No interior floor space is lost.
3. Techniques for sealing electrical outlets, partition wall intersections, and floor intersections from the interior that are available for new construction are usually not practical in retrofit.

Exterior enclosure retrofit strategies can provide moisture management benefits in both warm and cold climates.

As for new enclosures, in cold climates, the addition of exterior insulation raises temperature of the assembly interior to the insulation. Therefore, any vulnerable structures (e.g., wood framing) are kept at more seasonally stable conditions, thus improving durability (as described by Hutcheon and Handegord 1995). In cold climates, this will lower the wintertime relative humidity in interstitial cavities, thus reducing risks of condensation (and thus the chances of mold growth or decay due to air transported moisture or water vapor diffusion). Therefore, adding insulation to the exterior can help to preserve existing structures.

It must be noted that exterior insulation can have positive or negative effects on the overall moisture balance in the wall depending on design. Some of these exterior assemblies reduce the water vapor permeability of the structure to the exterior, thus reducing (or even mostly eliminating it in the case of foil- or plastic-faced insulation) drying to the exterior. This can be partially counterbalanced by a significant increase in wood framing /sheathing temperatures which results in a reduced or eliminated risk of interstitial condensation and a significant increase of inward drying potential. However, it is possible to have bulk rainwater leakage issues that did not accumulate in the pre-retrofit wall, which, after the retrofit of exterior insulation cause moisture accumulation and damage.

The relative magnitude of these risks (and the required steps to mitigate this risk) has had some preliminary study (Ueno 2010), but substantial work remains to be done, including hygrothermal modeling and field testing. The relative effects will be a function of interior operating conditions, climate conditions, thermal resistance values of the assembly layers, vapor permeability of the assembly layers, and convective air flow through the assembly. This type of analysis is beyond capabilities or time resources of designers and builders. Therefore, additional research could benefit the successful implementation of high R-value wall retrofits in cold climates by providing guidelines identify bounding conditions for managing moisture risk in the balance of R-value and drying potential.

In warm climates, exterior enclosure retrofit strategies that provide air flow control reduce the risk of condensation due to warm humid ambient air contacting cold potential condensing surfaces within the assembly (i.e., exterior face of interior gypsum in air conditioned buildings). Exterior enclosure retrofit strategies that incorporate vapor diffusion retarders reduce diffusion of moisture through the wall assembly. However, in general, colder climates show the greater benefits from increases in opaque structure insulation upgrades; most case studies seen to date are in heating-dominated climates.

In all climates, exterior retrofits provide an important opportunity to improve bulk water management, and such an improvement may be a requirement of insulating without reducing the risk of damage. Existing wall systems may possess flaws in water management that result in ongoing or concealed damage to the structure or poor indoor air quality. Ensuring the performance of the rain water control system is also essential in cold climates when a thermal enclosure retrofit will reduce the drying potential of the wall assembly. The re-cladding or over cladding of the structure provides the best opportunity to improve the bulk water management system.

Finally, there are advantages to exterior retrofits beyond the hygrothermal benefits. For one, the interior is still habitable during this retrofit. Exterior retrofits often simplify access, and speed construction, allowing for greater worker productivity and hence lower cost. Exterior insulation avoids the problem of the loss of habitable square footage, as with interior retrofits. In addition, applying insulation on the exterior can successfully handle details such as stairwells on exterior walls, which face minimum code width issues when insulating from the interior.

Approaches for exterior thermal enclosure retrofit can be described in four basic categories as shown in Figure 24 through Figure 26:

1. Rigid insulation/insulating sheathing and a replacement cladding,

2. Rigid insulation/insulating sheathing with integral finish system,

3. Spray polyurethane foam (with provision for exterior cladding attachment)

Each of these categories entails a unique set of options for bulk water management, air flow control, cladding attachment, and water vapor control.

Figure 24: Examplel of rigid insulation and replacement cladding. Although 4» of polyisocyanurate is shown, the approach is similar for any thickness over about 2» for all types of rigid insulation.

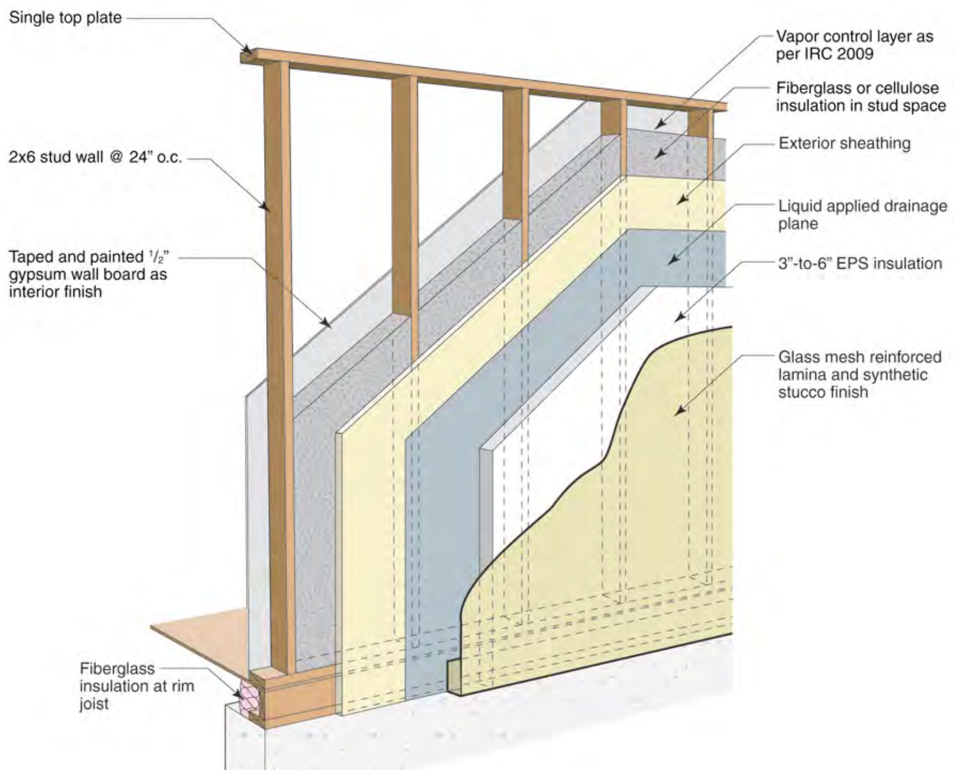

Figure 25: Exterior Insulation Finish System (EIFS) with drainage gap and plane

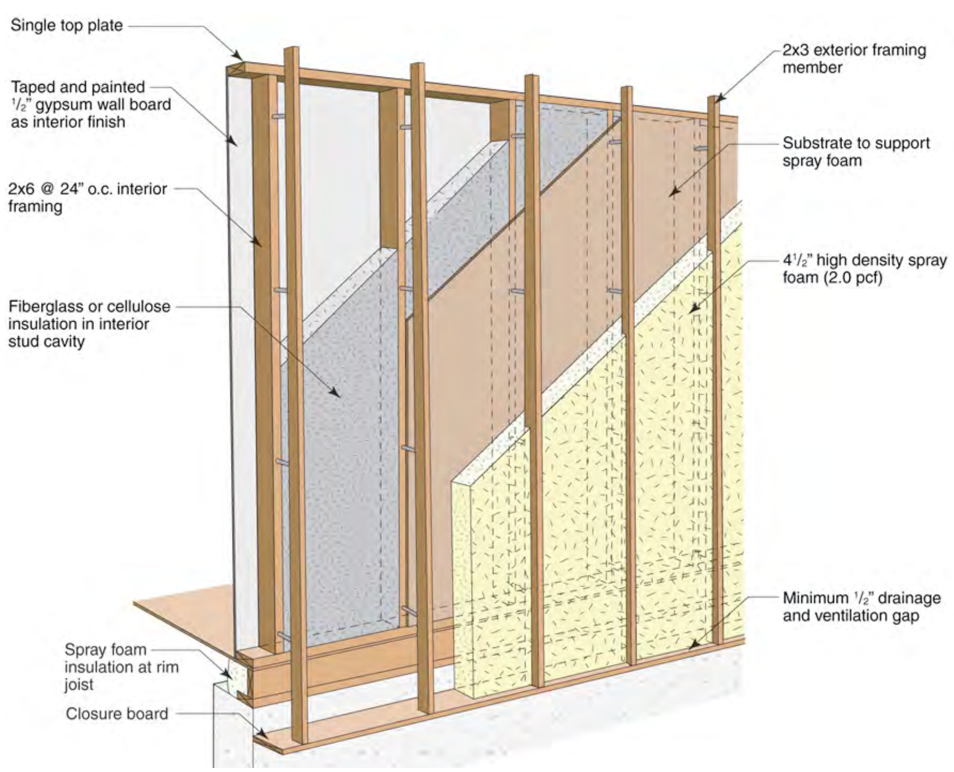

Figure 26: Urethane spray foam

Doors and windows

Windows and doors are common retrofit targets as these components often need replacement at intervals of 35 to 50 years. Window technology has advanced significantly in the last 30 years, and replacement windows are often desired for their comfort and ease of operation independent of any energy savings.

Windows are however expensive components on a square foot basis and hence owners often wish to delay their replacement if the existing windows are still functional. In some cases owners wish to proceed with an external wall upgrade and then wait. However, this raises two possible issues: the first is that one or more windows may leak rainwater into the wall, and given the lower drying capacity of well-insulated and airtight walls, can cause durability problems. The second issue is that when it comes time to replace the windows, it may be difficult to integrate the water, air and thermal control layers.

To reduce the cost of upgrades, storm windows and frames could be added. The cost of such products are often a fraction of the cost of new windows and yet they may be able to reduce heat and airflow as much as new windows. There has been almost no testing of storm windows for either thermal resistance or condensation resistance (a risk of interior or exterior condensation). This type of performance should be investigated further in a prototype applications and using a hotbox / climate chamber.

Thermal Enclosure Retrofits from the Interior

Thermal enclosure retrofits from the interior involve the removal of interior structures (if any) followed by the installation of additional insulation interior to the existing structure.

Although there are only building science drawbacks to interior insulation, there are cases when these are necessary or even desirable. One of the concerns that can be changed are local zoning ordinances that base setbacks on the face of the cladding rather than the face of the structure. Such ordinances did not forsee the need for retrofits, nor do they reflect building science knowledge. These artificial restrictions should be changed to allow for the lowest risk, highest performance retrofits.

Thermal Enclosure Retrofits from the Interior: Masonry Structures

One particular case of interior insulation that deserves particular attention is the retrofit of load-bearing masonry wall structures. These buildings often have historic and aesthetic significance that is not compatible with exterior insulation while preserving their exterior appearance. However, interior insulation (as discussed earlier) results in the original enclosure operating at lower wintertime temperatures and higher moisture content levels. These factors can result in performance and durability problems after the retrofit of insulation, especially in cold climates with significant rain loading.

One of the primary concerns with the interior insulation of masonry structures is the risk of increased freeze-thaw cycling causing damage at the exterior masonry surface. However, current research has produced a limit state design procedure (Mensinga et al. 2010), which uses a combination of material testing and hygrothermal simulations to determine the degree of added risk. One shortcoming, though, is that this testing is relatively costly; as a result, it is seldom-selected excerpt for institutional and/or historically significant projects. The collection of additional data using this method would be useful to produce a greater database of results. This has the potential to determine whether greater generalizations can be made, or if case-by-case analysis is always warranted.

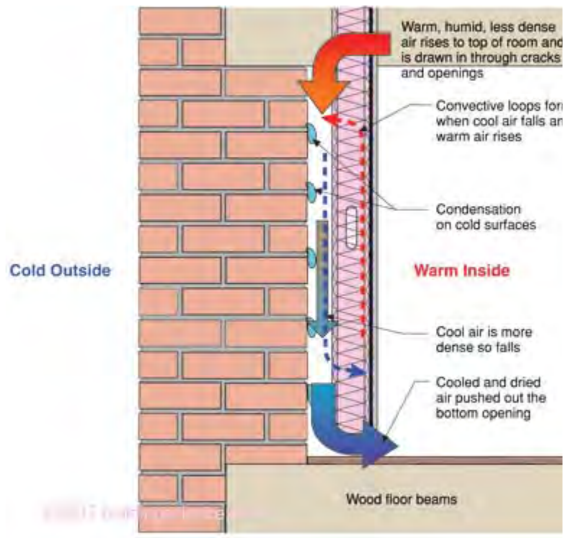

Figure 27: Typical failures of an interior insulated assembly due to air leakage bypassing insulation

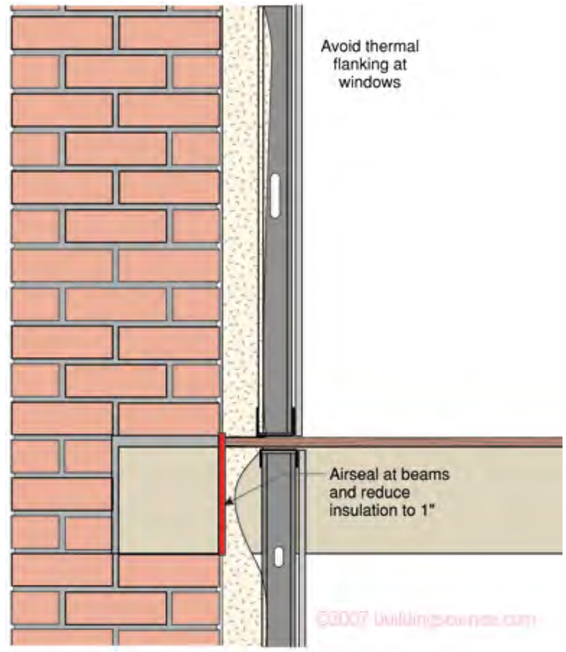

Figure 28: Typical recommended interior insulation assembly (interior spray foam)

Changing an existing building by increasing the airtightness and thermal insulation almost always comes with a risk of moisture damage. Better, more widely disseminated and field-proven methods of assessing moisture risk due to energy retrofits are needed. In particular, guidance is needed to

1. Guide the interior retrofit of solid masonry walls (see BSD-114) to prevent freeze-thaw damage
2. to avoid rot in of embedded wood in masonry or rubble walls,
3. to prevent rain leakage or condensation induced failures in wood framed-enclosures, and
4. to define when it is acceptable to insulate on the inside or between studs, and
5. when walls can be insulated without removing and upgrading the rain control performance of windows.

Roof Retrofits

Some types of roofing, especially slate and tile, may be durable materials and hence will not be replaced at short cycles such as composition shingles. However, these roofing materials may, and often do, leak some small quantity of rainwater. In the existing condition, enough heat and airflow through the assembly occurs to remove this leak water without it causing damage. In an energy retrofit, heat and airflow will be reduced, and hence the ability of such roofs to survive is unknown. One method of enhancing moisture removal is ventilation of the space under the roofing and sheathing. It is not known how much ventilation is needed, or how much drying can be achieved in this type of retrofit.

Attic Insulation Retrofits

Attic insulation retrofits are simple and can be effective if properly executed. The primary issues in attics is providing airtightness: adding insulation without airtightening introduces a serious risk of condensation on the roof sheathing which will now be colder in cold weather. Developing and deploying simple and affordable means of removing existing ceiling insulation and allowing for inspection of the ceiling air barrier. The BSC attic air sealing guide (BSC 2010) provides some of the information needed to air seal existing attics.

Another practical issue to deal with is sealing ductwork that may be in the attics, or removing it and relocating a new system to the inside. Neither approach has been widely investigated and would justify research to define the efficacy of different technologies and protocols.

Roof Overclad Retrofits

Another retrofit solution is to convert attics or ventilated cathedral ceilings to unvented compact roofs. Adding insulation to the exterior of the structure provides the same benefits as exterior insulation to walls. It has the same disbenefit: it requires new roof claddings, and trim details at overhangs, fascias, and roof penetrations. Other than cost, and a lack of accepted industry application guidelines, roof overclads have fewer pressing technical issues.

A common reason to consider an overclad retrofit is to expand living space into a currently ventilated attic by moving the air and thermal control layers to the slope from the flat. Such an upgrade also allows for ductwork to be moved into the living space.

Foundation Retrofits

Interior Retrofits for Basements and Crawlspaces

Homes built before the 1950's rarely had insulation applied to below-grade walls (Cheple and Huelman 2001), basement insulation is still not necessarily prevalent even today. As a result, there is a large energy savings opportunity in insulation retrofits of foundation walls in houses of a variety of ages.

However, this leaves the cases of foundation walls that are known to leak substantial bulk water/rainwater, and/or walls that have an irregular surface (e.g., rubble stone).

In foundations known to leak liquid water, the best solution typically is to address drainage and water control from the exterior: many of the major problems are due to improper drainage (e.g., reverse slope), lack of a drainage system (footing drains, etc.), and/or improper shedding of water (e.g., improperly directed downspouts, roof concentrations). However, minor interior water issues can be addressed by interior insulation assemblies specifically designed to safely drain this water. Major water issues can be addressed with a combination of interior and exterior drainage, which should be judged based on the conditions of a given project. Note, however, that these interior drainage solutions typically require the addition of some type of perimeter drainage system retrofitted to the slab. Overall, these combination interior insulation/drainage are known to work, but they have not been implemented in large numbers. A wider scale implementation would both provide feedback on potential issues and failures, as well as possibly providing the opportunity to determine cost saving measures when executing these retrofits.

In foundation walls that have an irregular surface (e.g., rubble stone), solutions have been developed which utilize field-applied spray two-component urethane foam. The foam can either be applied directly to the foundation (in known dry foundations), or alternately, to the interior of a drainage layer applied to the existing foundation wall (Lstiburek 2010). As per the interior drainage details described above, these assemblies should be drained to an interior perimeter drain. These details have been demonstrated to be robust and durable; however, it is a costly retrofit. Options for lower-cost retrofit methods may be worth further consideration; for instance, mineral wool insulation board might warrant further research, given its ability to conform to slightly irregular surfaces, and its greater resistance to moisture issues relative to fiberglass batt. However, such an assembly would require the addition of an air barrier, for the reasons discussed above.

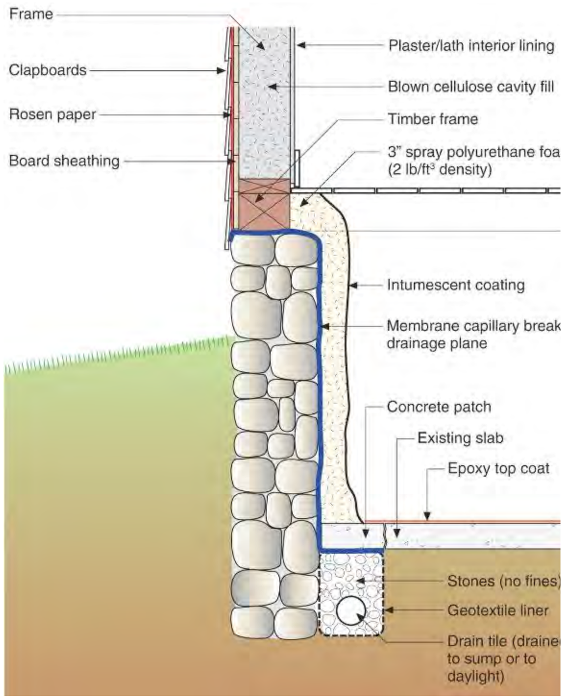

Figure 29: Rubble basement drainage/insulation system, directed to footing drain (Lstiburek 2010)

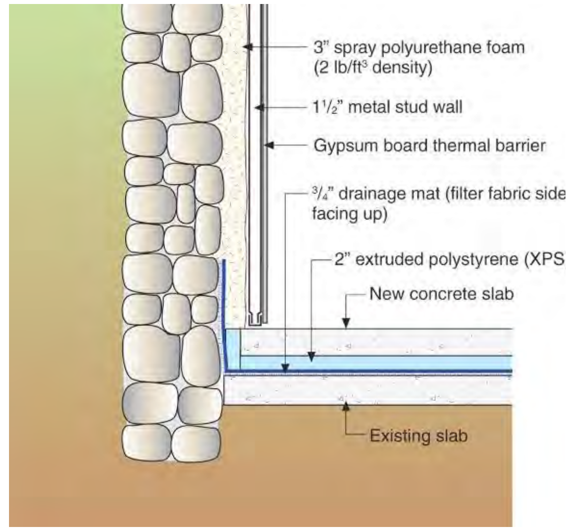

Figure 30: Rubble basement insulation, with drainage through sub-slab drainage mat (Lstiburek 2010)

Two issues commonly raised when adding interior foundation insulation are the perceived increased risk of frost heaving and/or adfreezing (adhesive freezing)[2] of the foundation. Frost heaving was studied extensively in Canada in the 1980s (BETT 1985), demonstrating no additional risks with the addition of interior insulation. The adfreezing issue was determined to be a phenomenon determined by the freezing front direction (and thus the direction of heat flux): therefore, any heated basement (even if well insulated) is not susceptible (Pressnail and Timusk 1987). This also explains why unheated foundations, such as piers or unheated garages, are susceptible to adfreezing. Carefully documented field measurements should be used to confirm and demonstrate these facts to a wider audience.

One final issue that occurs with interior foundation insulation retrofits is at the sill beam of older housing stock built prior to the use of platform framing. These substantial sill beams have often suffered moisture damage over their service life, due to capillary moisture, rainwater splashback, and/or improper drainage details. The addition of interior insulation lowers the temperatures through this beam; in addition, if an impermeable insulation is used (such as spray foam, which is valued for providing insulation and an air barrier), the drying potential to the interior is reduced. When combined with an exterior retrofit of the above grade wall, the drying potential is severely restricted in both directions. The vulnerability of this sill beam in a retrofit condition warrants further study, as well as the development of details that can provide adequate drying, if the typical retrofit increases the risks of damage.

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[2] Adfreezing is the phenomenon where soil freezes and simultaneously adheres to a surface, usually used in relation to foundations. If adfreezing occurs, subsequent heaving in the surrounding soil will transfer loads to the foundation, causing lifting ("frost jacking") as has been frequently observed with piers and short piles.

CHAPTER V: Gaps Analysis and Recommendations

The following section gathers the research needs and knowledge gaps from the previous chapters. This section follows the same sequence of chapters 2, 3 and 4, but where the focus of the preceding chapters is on identifying what we know, this chapter identifies what is not known or is poorly disseminated.

Materials

The lack of materials is not a major obstacle to delivering high R-value enclosures that are durable in all climate zones. However, improving some materials and developing others will help to ease the wider deployment of High R enclosures.

The Global Warming Potential (GWP) of the third-generation foam blowing agents is still very high, and can significantly offset some of the GWP-reducing benefits they offer. A fourth-generation of blowing agents is being developed, and is close to deployment, that has very low GWP. As with any new product, field experience will discover limitations and problems that are different than the last generation: for example, more difficulty spraying, increased shrinkage, lower R-value, temperature sensitivity during installation. It is important that these low GWP products be delivered to the market as quickly as possible and any problems in the field be discovered and solved quickly. Areas for short-term research include: application of low-GWP insulation materials as direct substitutes for conventional insulation materials, focusing on construction details and hygrothermal analysis.

One of the most pressing needs for insulation materials is to provide better non-toxic fire resistance for polymeric foam insulations, or more precisely, the need for fire resistance insulating materials with low air and vapor permeance while also providing mechanical strength. The ability of polymeric foams to control vapor and air flow, resist moisture, to provide significant structural function, and in some cases, to be spray-applied to irregular surfaces is very useful for both new and retrofit applications. However, there are many applications that require lower flame-spread ratings (unfinished basements and attics, crawlspaces) and fire ratings. It is possible that the current code-based fire resistance requirements are inappropriate for new assemblies and uses. Short-term research should be conducted in the following areas:

- alternate fire protection surfacing materials or chemical components for polymeric insulations
- fire testing of polymeric foams for installation in exposed or semi-exposed conditions
- research into possible code amendments or alterations to allow the use of existing materials in certain applications

Cost-effectively integrating phase-change materials into enclosures assemblies requires more research as the current products and approaches are expensive or complex. However, there are very likely applications of PCMs that are near commercialization that should be investigated further. These include:

- PCM integration into windows or other translucent enclosure elements
- cost-effective integration into enclosure components, such as sheathing, framing or foundation structure, cladding materials, etc.

New insulation products such as Vacuum Insulated Panels (VIP) and aerogels have not found wider application because they are too expensive and offer too modest a performance improvement relative to other products & systems. This trend is likely to continue for the next 5-10 years. Research is needed to solve issues with on-site handling and long-term performance (for VIPs) and cost effective applications (aerogels). These high R-value per inch products may find particular application in relatively thin layers (e.g., one or two inches) for retrofits that otherwise would have to settle for less R-value in the space available. Hybrid applications of VIP or aerogel in combination with lower-cost spray fibrous or air sealing spray foam should be investigated further.

Radiant barrier products have a limited role to play in High R-value enclosures as the benefit of low-e building housewraps and sheets is relatively small (i.e., imporvements of R1-2) and well understood. More work is needed to explain to the design and building industry how these products work and their limitations. A major gap is the lack of reliable third-party measurements that tabulate actual performance in practical enclosure assemblies under realistic temperature differences. Such a simple set of tabulated and peer-reviewed data would go a long way to overcoming outrageous and misleading claims.

Below- and at-grade exterior insulation that is insect and moisture resistant are needed: rigid rockwool and foamglass are possible options but have not been widely used in North America. Materials are needed to allow for easy to install, durable, and insect-resistant, finishes that allow insulation to transition from below-grade to above-grade cladding. Although cement parging can be used, it is expensive and not easy to apply.

New Enclosures

Although there are numerous approaches using existing materials, systems, and trades that can be used to deliver High R enclosures (as demonstrated by numerous BA prototype houses constructed by BA research teams), wide-scale adoption is held back by a number of knowledge gaps.

Although not found to be a problem in practice, uncertainty about cladding attachment and window/door installation for walls with thick layers of exterior insulation is a major challenge for the codes and the building design and construction community. There remain misconceptions about the need for "continuous support" behind vinyl siding, and the design of fastenings. The stiffness and strength of rigid foam and semi-rigid mineral fiber insulation when used to resist wind and gravity (shear) forces has not been scientifically established (although there is plenty of practical and anecdotal experience). These gaps are seen as a major obstacle to achieving high-R walls in the short-term, both in new and retrofit construction. The structural capacity (wind and gravity) and thermal resistance of cladding attachment using widely-available (preferably generic) components needs to be assessed, and the codes changed to allow siding attachment over more than 1" of sheathing (the current prescriptive limit). Some of this research work will likely be undertaken by the manufacturers of building materials (insulation materials, cladding materials, fasteners, etc.) but the systems-nature of this gap will require work from researchers concerned with the entire enclosure system.

Some groups claim that the addition of thick layers of vapor impermeable exterior insulating sheathing over wood-based sheathing or framing represents a risk of moisture damage, that exterior insulation will be "the next face-sealed EIFS". The condensation wetting potential and the drying capacity of different high-R assemblies in the field should therefore be measured and demonstrated alongside current walls. The drying capacity of walls with thick layers of exterior foam insulation and double stud walls with exterior sheathing are not well documented and this acts an obstacle to market acceptance.

Increasing insulation levels in walls places wood-based sheathing and some sidings (particularly wood and fiber cement) at risk of moisture damage. Field experience with certain types of high-R enclosures (e.g. SIPS and double stud walls) have shown that wetting due to small errors (for example, convective loops or rain leaks) can occur and drying is very slow: as a result there is a heightened risk of damage if additional measures are not taken. This increased risk of moisture damage is well understood anecdotally by researchers, but it is not well understood by the code and building communities. More research must be done to examine these risks and to identify appropriate, lower-risk applications for these technologies. Well-documented measurements of moisture levels in airtight walls with 8, 10, or 12" of cavity insulation would be useful to strengthen recommendations and quantify the risk. Previous research has shown that back-ventilated claddings can reduce or entirely eliminate the moisture risk to exterior siding and sheathings. However, more research quantifying how much ventilation is required, how effective it is, and the role of insulation levels on the risk in different climates would be useful to empower change in codes and manufacturer recommendations.

Thermal bridging is well understood and can be reasonably accurately predicted for wood framed enclosures with existing two-dimensional steady-state models. Advanced framing and insulating sheathing can make significant reductions in thermal bridging and thus increase thermal resistance without increasing "installed" R-value. Despite this knowledge, the impact of thermal bridging is not properly accounted for in residential codes, which continue to focus on "installed R-value" rather than actual as-built assembly performance. Wide dissemination of proven building techniques and the impact of thermal bridging along with code changes should be pursued. More research is required to understand the consequence of, and efficacy of solutions to, thermal bridging at windows and doors (i.e., installation close to the interior, the exterior, or in the middle) and masonry veneer to foundations with insulation on the exterior.

Alongside the specification of higher levels of thermal insulation, it is equally important to achieve high-levels of airtightness in new construction. Methods and materials that can be easily deployed to achieve these high levels of airtightness need to be developed, demonstrated, documented, and disseminated to a wide range of designers, code officials, and builders. Numerous products, such as spray foam installed in stud bays, are sold on the basis of improved airflow resistance, but controlled measurements of houses insulated in this manner show that care and attention to all wood-wood joints in the enclosure must be applied to achieve their promised airtightness. The increased importance of ever-tighter construction alongside increased true R-values is not well understood. The lack of airtightness requirements in residential codes severely restricts the rate of deployment of airtightness, and airtightness already lags behind insulation in the marketplace.

Fire resistance ratings of many new high-r enclosures are not listed. Such listings are often required for multi-family, especially high-density housing, and zero lot line homes. Many assemblies that require fire ratings are still specified as they were tested 25 and more years ago. As NIST and other government agencies no longer fire test assemblies for ratings, only specific "systems" manufacturers (such as EIFS) conduct fire testing, and this testing only applies to their specific products. More generic and widespread testing would aid the speedy deployment of high-R fire-rated enclosure assemblies.

Exterior insulation retrofits of both single-family and multi-family housing often run into problems with zoning law and fire code setback requirements. While zoning laws can be easily changed, the technical support that exterior retrofits are the most powerful means of deep energy retrofits is often missing when municipalities consider such changes.

More accurate life-cycle costing, which includes historical fuel escalation rates, recognizes the long life and limited maintenance of High-R enclosures, and considers the cost of renewable energy should be used to provide better guidance for code-minimums. This information is needed to better direct investment into these well understood and highly reliable enclosure technologies.

The choice of performance levels of High R enclosures must be better understood relative to the cost of renewable energy generation and total energy consumption in the home. At some point, the cost of added thermal control will be greater than the cost of adding even on-site renewable energy generation (the most expensive current energy). Grid-provided renewable energy generation is already less expensive than site-generated energy, and this will lower the optimal insulation and airtightness targets further.

The heat loss through slabs, either below basements or on grade, is not very well characterized: sub-slab insulation is not even an option in the current version of EnergyGage USA. As a consequence many new highly insulated homes have no slab insulation at all, and some have sub-slab insulation that is equivalent to attic insulation levels! Better-documented field measurements combined with computer simulations are needed to develop better scientifically-based recommendations for High-R insulation levels below both radiantly heated and unheated slabs.

Retrofit of Existing Enclosures

There are many more possibilities and variations with retrofit of existing enclosures than there are for new enclosures. Essentially all of the research questions for new enclosures apply to retrofit. There are additional questions unique to retrofit of existing buildings. A major, and perhaps the most significant challenge, is the financing of deep energy retrofits and the potential lost opportunity of doing small retrofits that payback quickly, but compromise subsequent work. Financing deep energy retrofits over the life of 25 to 30 yr mortgage should likely become normal, as the benefits of new siding, roofing, windows, insulation, and airtightness should all exceed this time frame.

The optimal sequencing of retrofits requires more study. Owners may not have the funds to do a complete retrofit and hence will often conduct only pieces. It is critical to investigate the best sequence of retrofits for the many different conditions that may occur, and minimize lost opportunities, increased costs, or increased risks of failure. For example, HVAC retrofits are often first considered because of equipment age or failure, subsidy programs and the perception that these will address comfort as well as operating cost issues. Later retrofit of the enclosure results in HVAC systems that are often oversized. Given fixed upgrade budgets this is unlikely to change.

Changing an existing building by increasing the airtightness and thermal insulation almost always comes with a risk of moisture damage. Better, more widely disseminated and field-proven methods of assessing moisture risk due to energy retrofits are needed. In particular, guidance is needed to 1. Guide the interior retrofit of solid masonry walls (see BSD-114) to prevent freeze-thaw damage 2. to avoid rot in of embedded wood in masonry or rubble walls, 3. to prevent rain leakage or condensation induced failures in wood framed-enclosures, and 4. to define when it is acceptable to insulate on the inside or between studs, and 5. when walls can be insulated without removing and upgrading the rain control performance of windows.

Some types of roofing, especially slate and tile, may be durable materials and hence will not be replaced at short cycles such as composition shingles. However, these roofing materials may, and often do, leak some small quantity of rainwater. In the existing condition, enough heat and airflow through the assembly occurs to remove this leak water without it causing damage. In an energy retrofit, heat and airflow will be reduced, and hence the ability of such roofs to survive is unknown. One method of enhancing moisture removal is ventilation of the space under the roofing and sheathing. It is not known how much ventilation is needed, or how much drying can be achieved in this type of retrofit.

Basements are a significant opportunity to reduce energy use in existing homes. Tens of millions of homes in Zones 4 and higher have no insulation or very limited insulation over only the top portion of the basement walls. Insulating and finishing basement walls has long been associated with moisture problems, but several techniques have been developed and demonstrated that can solve essentially all common basement wall problems, including leaky basements, while at the same time providing a High-R upgrade and finishes the surface to modern standard. These retrofits also present an opportunity to address moisture & soil gas issues and to 'recover' potentially usable space for the homeowner. Dissemination of this information to the trades and consumers is sorely needed and could empower millions of energy-efficient, comfortable, healthy and durable basements.

Insulating basements will cause the soil outside to become colder. In cold climates insulating basements may cause deeper penetration of the frost line and some feel that this can cause soil expansion and structural damage to the foundation. The risk of this has not been addressed in research and is an important gap to fill. The risk of freeze-thaw damage of existing masonry at grade also requires study to identify how serious this risk is, and develop solutions to it.

Sill beams are a component vulnerable to moisture damage due to air leakage, grade splashback, and capillary rise. Insulating and airsealing the interior or exterior at this component can reduce drying capacity and increase the risk of moisture damage. Techniques for assessing the risk, and practical solutions are needed.

Insulating slabs will become more important and retrofit strategies are not well developed. More research into retrofit slabs will be needed. Given low-head room basements, high-R products such as VIP and aerogels may be a solution for this application.

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Appendix A: High R-value Enclosure Assembly Recommendations for All Climates

The following enclosure assembly drawings are recommended based on the results of the research reviewed in this paper, and many years of practical experience in the field on BSC projects. Many of the specifics presented are based on experience, not science.

Foundations, Walls, Windows and Roofs drawings for new construction and the retrofit of existing buildings are presented. Each drawing indicates the climate zone(s) that the proposed construction is intended for. The materials are labeled for generic construction materials (i.e., product neutral) and the enclosure function is indicated for each (i.e., rain penetration control, air flow control, vapor control and thermal control).

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