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Building America Special Research Project: High-R Roofs Case Study Analysis

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John Straube and Aaron Grin

Abstract:

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Building America Special Research Project
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November 30, 2010

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Preface

Building America Program

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.

Notice

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

A. Introduction

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 are improving to require higher levels of thermal control than ever before for new construction and retrofit programs are helping many people to add insulation to their homes.

This report considers a number of roof insulation strategies that can meet the requirement for improved thermal and moisture control in colder climates. By code, roofs in DOE climate zone 6 require an insulating value of R49. In this report, higher R-value (High R) roofs for zone 6 climates are those that approach or exceed R60 for compact roofs and R75 for vented attics. In a warmer climate High-R may be considered less and in a colder climate high-R may be considered more.

A successful roof (or roof-ceiling assembly) will perform the following tasks

- Provide a water management system to keep precipitation out
- Provide an air barrier system between the indoors and outdoors
- Provide a thermal control system to keep the heat out during the summer and retain heat during the winter
- Provide a vapor control system to maintain a durable environment that does not allow condensation and does not promote mold growth

Roof failures typically occur due to leakage of bulk water (precipitation), or vapor diffusion condensation. By designing the roof enclosure system properly, the majority of all failures can be avoided in new construction.

In retrofit work, the order of work to be considered during construction or home improvements is important. Health and safety issues must be addressed first and are more important than durability issues.[2] And durability issues are in turn more important than saving energy.

This study is an extension of the previous Building America study of High R wall assemblies (Straube and Smegal 2009) and High R foundations (Straube and Smegal 2009); all of these studies have the goal of improving the overall building enclosure and achieving greater energy savings. This study compares 20 roof enclosure designs and—through computer-based simulations and field experience—demonstrates differences in energy consumption, thermal control, and moisture-related issues.

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°F to over 160°F on every sunny day. This generates daytime temperature differences 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].

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[2] The Attic Air Sealing Guide written by Joseph W. Lstiburek, Ph.D., P.Eng. provides the background and approach for the preparatory work necessary prior to insulating an attic or adding insulation to an existing attic. The guide focuses on combustion safety, ventilation for indoor air quality, and attic ventilation for durability. The Attic Air Sealing Details section of the guide provides a scope of work and specification for the air sealing of many points of air leakage in common attic spaces.

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 R-values for these roofs in our study; historically, code values have been lower due to geometric constraints and costs. 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 conditioned space. Locating the ducts in conditioned space saves more energy than the reduction in recommended R-value and increased surface area increases energy use, given typical air leakage of ductwork and air handler systems.

The analysis section of this report is divided into eight sections. These sections introduce the comparison criteria for the analysis, provide BSC's high R-value targets, analyze of the energy implications of high R-value roof systems in two climates and compare a set of roof assemblies based on five criteria. These five criteria are; simulated R-value, durability, buildability, material use and cost.

1. OBJECTIVE

The goal of this research is to find optimally designed, cost effective roof insulation systems that can be included with other enclosure details to help reduce whole house energy use by 70%. This report will compare a variety of roof insulating strategies and present their advantages and disadvantages according to several comparison criteria.

2. SCOPE

This study is limited to roof systems for cold climates; comparisons to warmer climates are made for reference. Previous studies were conducted for wall systems and basement/foundation systems in 2009. In general, only cold climates are considered in this report since enclosures in cold climates benefit the greatest from a highly insulated building enclosure; however, important conclusions can also be drawn for other climate zones.

This study does not deal specifically with retrofit strategies, but application of these assemblies in retrofit applications will be mentioned for any relevant insulation strategies. Many of the solutions that are examined in this report would be suitable for use in a retrofit application.

3. APPROACH

The quantitative analysis for each roof system is based on a two-dimensional energy modeling program and a whole house energy model. Minneapolis, MN (IECC climate Zone 6) was used as the representative cold climate for most of the modeling due to the combination of the cold winters and fairly warm and humid summer months.

4. ROOF ASSEMBLIES EXAMINED IN THIS REPORT

There are a large variety of roof assemblies considering local practices, climate, the architect's design or the general contractor's preference. An attempt was made to choose the most common and most recommended roof systems, and to comment on possible alternatives during the analysis. This list of chosen systems is explained in more detail in the analysis section.

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 have profound implications in terms of 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 (Figure 1) are the lowest cost, highest R-value, and most durable roofs in all climates zones (except perhaps Zone 1 and Zone 2 due to coastal high humidity*) if and* *only if* no ductwork or major air leakage (e.g. recessed light fixtures, discontinuous ceilings geometries) are present above/in the ceiling plane. Given the low cost of ventilated attic insulation (loose-fill fibrous insulation), rather high R-values are justified even in climates with moderate exterior air temperatures, such as Zone 2, and very high levels (R60 to R100) are affordable and economically justified in Zones 5 through 8.

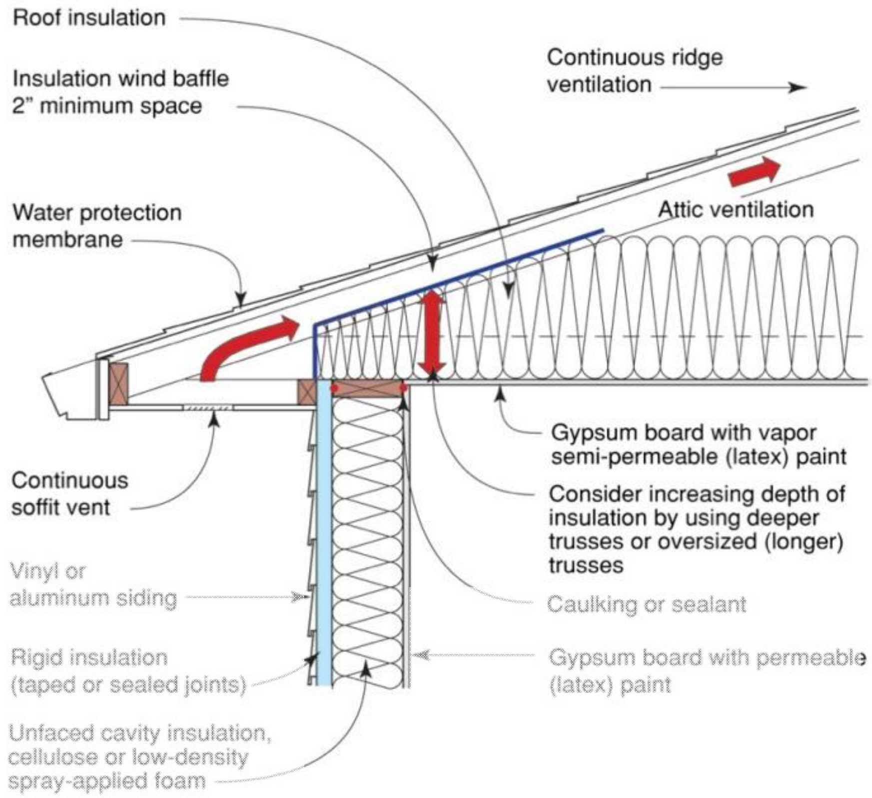

Figure 1: Vented Attic - The lowest-cost, highest thermal performance roof system

The incremental cost of changing from code-mandated levels to R-values of 60 to 100 is 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 by a reasonable depth of insulation. 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/raised heel" trusses or rafter designs to accommodate the increased amount of insulation at the end of the roof.

Providing a truly airtight ceiling plane is very important, and is 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 air leaks takes on great importance. Thus eliminating attic ductwork must be the first step, as well as sealing around all lights, partitions, access hatches, etc.

Good attic ventilation is necessary to remove whatever moisture may leak into the attic space so that it does not accumulate. The roof sheathing will drop below air temperature (by 5 – 20 °F) every clear night, making condensation on the sheathing and framing 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. These assemblies operate under the same fundamental principles 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 insulation materials 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, decreasing moisture removal, and thus increasing the risk of moisture accumulation in the sheathing
- Ventilation requires a direct path from the soffit to the ridge: this only occurs in simple gable roofs over rectangular plans with no dormers
- The air barrier can easily be compromised (and often is, in typical construction) via penetrations through the interior ceiling finish or bypasses
- thermal bridging reduces the true R-value

The limitation on ventilation is the most severe compromise in this design. Very few plans are pure rectangles, not all roofs are gable roofs, and many roofs have dormers, hips, valleys, etc. Typical roof designs intended to be ventilated are not effectively ventilated in practice, and hence cannot recover well from small air leaks depositing moisture in the assembly.

The roof shown in Figure 2 would be appropriate for a High R roof in a warmer climate as its R-value would be limited to roughly R40 with a 12" engineered wood I-beam. However, by using a 16" engineered wood I-beam 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. It has the additional benefit of providing a more positive air barrier between the air-permeable insulation and the ventilation space. The use of more than 12" engineered wood I-beams are rarely justified on the basis of structural need, so the cost of the thicker engineered wood I-beam is part of the cost of increasing the R-value to 60. Airtightness at 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. Some necessary measures might include installation of interior partition walls after the ceiling drywall is installed, banning the use of any ceiling fixtures, and similar measures.

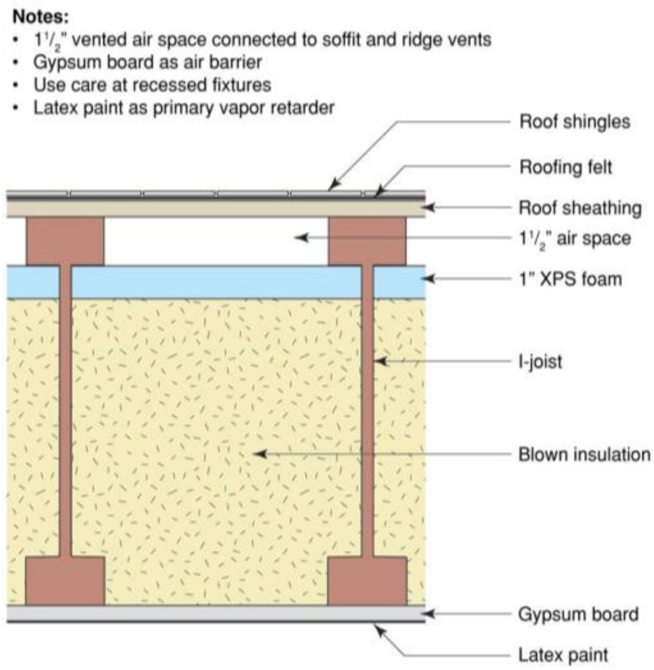

Figure 2: Ventilated cathedral ceiling

Another approach is to apply interior layers of air-impermeable insulation (i.e., rigid foam board stock) as shown in Figure 3. This increases the R-value and decreases thermal bridging. 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 note 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, or if specialized products are used to provide in-roof ventilation at these obstructions.

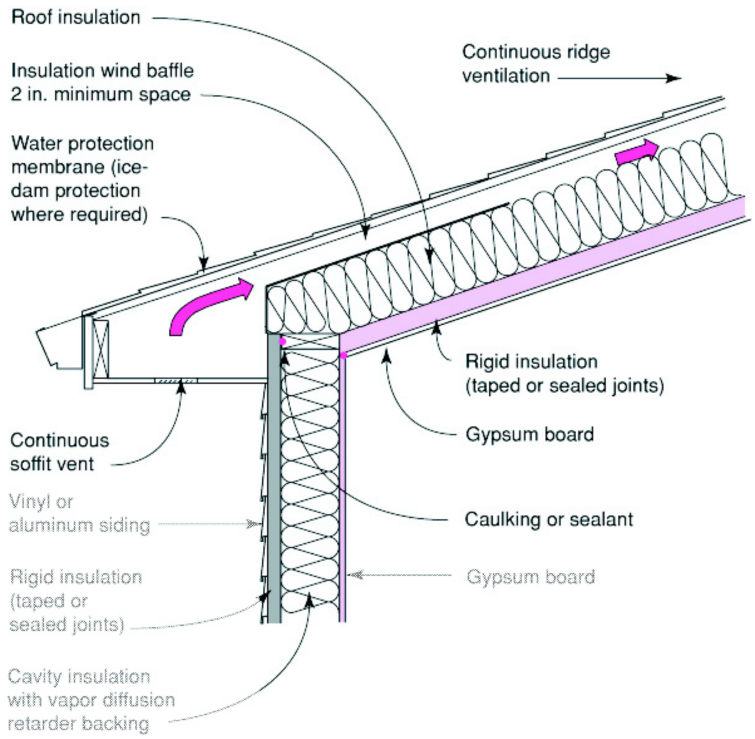

Figure 3: Vented cathedral ceiling

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 4). These problems are:

1. locating ducts/air handling units in the attic space causes major air leaks of conditioned air (and thus forced infiltration/exfiltration), 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.

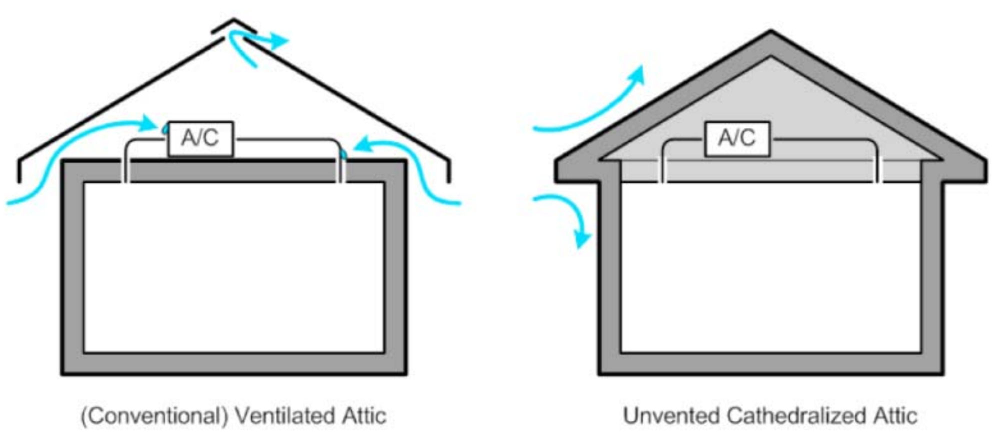

Figure 4: Cathedralized or Unvented Attics

Because High R roofs can be seriously impacted by even small leaks of indoor air, even ducts with 5% leakage are unacceptable: it is difficult to imagine a sensible scenario with a High R roof and ducts in unconditioned space.

If the ducts are to be installed in the attic, then an unvented cathedralized attic is a recommended solution. Alternate solutions for vented attics include covering all ductwork, and the ceiling plane with an uninterrupted layer of spray foam for air sealing (2" of closed cell foam or 3" of open cell 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.

Unvented Cathedral Ceiling Assemblies

A discussed previously, vented cathedral ceiling assemblies are not highly compatible with complex roof geometries because of the restricted ventilation caused by roof obstructions.

All unvented attic and cathedral ceiling designs must provide for either a very high degree of airtightness or avoidance of 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. However, all wood-to-wood joints in the framing must still be solved with sealants or other means. Figure 5 shows the application of spray foam to form an air barrier in a hybrid roof system.

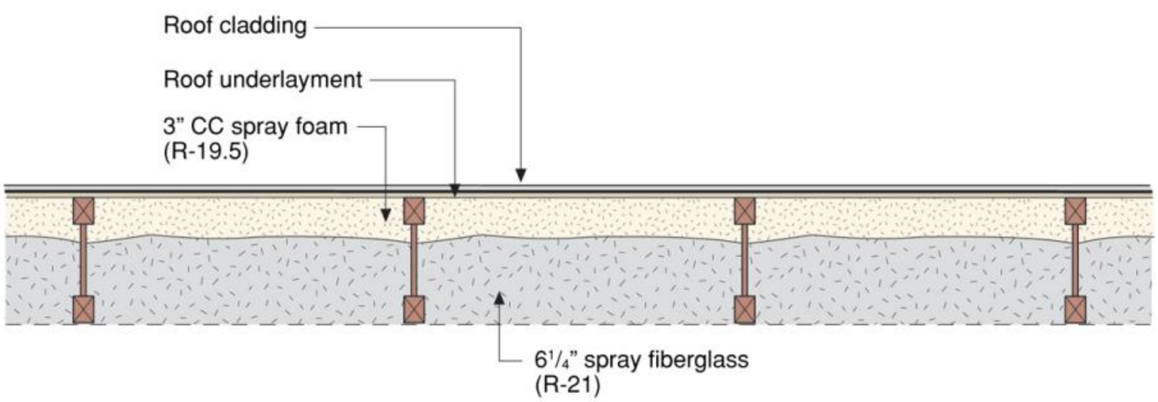

Figure 5: Example High-R hybrid unvented cathedralized ceiling/attic

An alternate design that is 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 (Figure 6). This can be used in both retrofit and new construction. The 2009 IRC (§R806.4) provides the ratios of air impermeable to air permeable insulation required in each climate zone [ICC 2009] which should be considered when implementing roofs such as those in Figure 5 and Figure 6. The ratio requirements are discussed in the analysis section of this report.

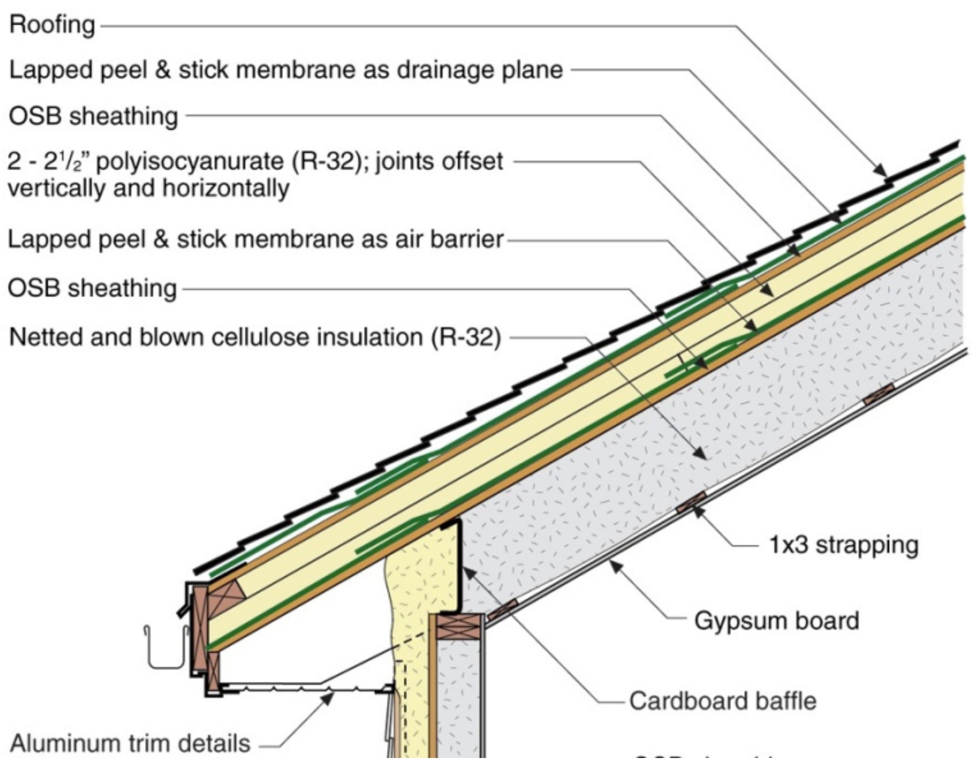

Figure 6: True R60 cold climate unvented cathedral ceiling

5. ROOF ASSEMBLIES REVIEWED

The following roof assemblies were reviewed in this study; the clear system R-values of these assemblies can be found in Table 6 : R-values for simulated roof systems.

Vented Attics

- Roof 1A - 36in Blown Fiberglass Insulation
- Roof 1B - 30in Blown Cellulose Insulation
- Roof 1C - 20in 0.5 PCF Open Cell SPUF
- Roof 1D - 12in 2.0 PCF Closed Cell SPUF
- Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation
- Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation

Vented Cathedral Ceilings

- Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist
- Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist
- Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber

Unvented Cathedral Ceilings or Cathedralized Attics

- Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist
- Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist
- Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber

- Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist
- Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist
- Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss
- Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation
- Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation
- Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation
- Roof 7A - 12in EPS Structurally Insulated Panel
- Roof 7B - 20in EPS Structurally Insulated Panel

B. Analysis

1. ANALYSIS CRITERIA

A comparison matrix will be used to quantitatively compare all of the different roof insulation strategies. A value between 1 (poor) and 5 (excellent) will be assigned, upon review of the analysis, to each of the comparison criteria for each roof. An empty comparison matrix is shown below in Table 1 as an example.

Table 1: Sample Comparison Criteria Matrix

	System Description	Modeled R-Value Rating	Durability Rating	Buildability Rating	Material Use Rating	Cost Rating	Total Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation						
	Roof 1B - 30in Blown Cellulose Insulation						
	Roof 1C - 20in 0.5 PCF Open Cell SPUF						
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF						
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation						
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation						

Each comparison criteria's assigned value will total to give a ranking to the matrix. The roofs with the highest scores are the preferred options. One of the benefits of using a comparison matrix is that it allows a quantitative comparison when some of the criteria (such as cost) may be poorly defined or highly variable. For example, even though the exact costs of different insulations may be uncertain, fiberglass batt insulation is always less expensive than low density (0.5 pcf) open cell spray foam, which is in turn less expensive than high density (2.0 pcf) closed cell spray foam. Therefore, these systems can be ranked accordingly regardless of the actual costs.

Weightings may also be applied to the values to adjust the comparison. As an example, if durability is of utmost importance, it could be assigned a weighting multiplier of 5 (most important) while the other factors could be ranked at weightings of a number less than 5 as being less important. These values totaled would then reflect the specific project needs, and would allow the roofs to be ranked accordingly.

2. BUILDING CODE REQUIREMENTS AND HIGH R-VALUE TARGETS

The following tables and notes were taken from the IECC (ICC 2006). According to the 2006 IECC in climate zones 6 or higher, the building code requires a minimum of R-49 roof insulation, zones 4 and 5 require R38 and zones 1 through 3 require R30. The proposed 2012 IECC increases the roof insulation requirements to R38 in zone 3, and R49 in zone 5.

Table 2 - IECC Insulation and Fenestration Requirements

TABLE 402.1.1
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT[a]

CLIMATE ZONE	FENESTRATION U-FACTOR	SKYLIGHT[b] U-FACTOR	GLAZED FENESTRATION SHGC	CEILING R-VALUE	WOOD FRAME WALL R-VALUE	MASS WALL R-VALUE	FLOOR R-VALUE	BASEMENT[c] WALL R-VALUE	SLAB[d] R-VALUE & DEPTH	CRAWL SPACE[c] WALL R-VALUE
1	1.20	0.75	0.40	30	13	3	13	0	0	0
2	0.75	0.75	0.40	30	13	4	13	0	0	0
3	0.65	0.65	0.40[e]	30	13	5	19	0	0	5 / 13
4 except Marine	0.40	0.60	NR	38	13	5	19	10 / 13	10, 2 ft	10 / 13
5 and Marine 4	0.35	0.60	NR	38	19 or 13+5[g]	13	30[f]	10 / 13	10, 2 ft	10 / 13
6	0.35	0.60	NR	49	19 or 13+5[g]	15	30[f]	10 / 13	10, 4 ft	10 / 13
7 and 8	0.35	0.60	NR	49	21	19	30[f]	10 / 13	10, 4 ft	10 / 13

402.2 Specific insulation requirements. (Prescriptive).

402.2.1 Ceilings with attic spaces. When Section 402.1.1 would require R-38 in the ceiling, R-30 shall be deemed to satisfy the requirement for R-38 wherever the full height of uncompressed R-30 insulation extends over the wall top plate at the eaves. Similarly R-38 shall be deemed to satisfy the requirement for R-49 wherever the full height of uncompressed R-38 insulation extends over the wall top plate at the eaves.

402.2.2 Ceilings without attic spaces. Where Section 402.1.1 would require insulation levels above R-30 and the design of the roof/ceiling assembly does not allow sufficient space for the required insulation, the minimum required insulation for such roof/ceiling assemblies shall be R-30. This reduction of insulation from the requirements of Section 402.1.1 shall be limited to 500 square feet (46 m^2) of ceiling area.

402.2.3 Mass walls. Mass walls for the purposes of this Chapter shall be considered walls of concrete block, concrete, insulated concrete form (ICF), masonry cavity, brick (other than brick veneer), earth (adobe, compressed earth block, rammed earth) and solid timber/logs. The provisions of Section 402.1.1 for mass walls shall be applicable when at least 50 percent of the required insulation *R*-value is on the exterior of, or integral to, the wall. Walls that do not meet this criterion for insulation placement shall meet the wood frame wall insulation requirements of Section 402.1.1.

Figure 7 - IECC Ceiling Insulation Reduction Specifications

Figure 7 contains the IECC provisions for reductions of insulating values. This is important as the code allows reductions of 20-25 percent in R-value for certain situations. However, it is recommended that attempts be made to design so that the need for these R-value reductions is minimized.

Table 3 contains the code requirements with interpretations for compact roofs (ceilings without attic spaces) as well as BSC's recommended High R-value targets for each climate zone.

Table 3 - Code Requirements and High R-Value Targets

Climate Zone	Code Requirements: Vented Attic	Code Requirements: Compact Roof*	High R-Value Target: Vented Attic	High R-Value Target: Compact Roof
1	30	30	40	35
2	30	30	50	40
3	30	30	50	45
4	38	30	60	45
5	38	30	65	50
6	49	30	75	60
7	49	30	90	65
8	49	30	100	75

* Where insulation levels above R30 are not considered possible, the IECC allows R-Value requirements to be reduced to R30. This is limited to 500 square feet.

The 2009 International Residential Code (IRC) section R806.4 allows for unvented attic assemblies. This section also stipulates that a certain proportion of the insulation in an unvented attic assembly must be made up of air impermeable insulation materials such as rigid board foam. Where air permeable insulation is to be installed within the rafters Table 4 stipulates the R-value of board insulation that must be installed exterior to the structural sheathing. Where both air impermeable and air permeable insulations are installed within the rafter, the air impermeable insulation must be next to the structural sheathing. Where only air impermeable insulation is used it must be installed in direct contact with the underside of the roof sheathing.

Table 4 - 2009 IRC Unvented Attics Table 806.4 with IECC R-values

Climate Zone	Minimum Rigid Board on Air-Impermeable Insulation R-Value	IECC R-Value[1]
2B and 3B tile roof only	0 (none required)	30
1, 2A, 2B, 3A, 3B, 3C	R-5	30
4C	R-10	30
4A, 4B	R-15	38
5	R-20	38
6	R-25	49
7	R-30	49
8	R-35	49

1 - Reductions possible

It is important to note the ratio of impermeable to permeable R-values in Table 4. For cold climates the air impermeable insulation is maintained at 50% or more of the total R-value of the roof system. This is for condensation control. When building High-R value roof systems it is recommended that this ratio be maintained or exceeded. If an R-80 cathedral ceiling or cathedralized attic is to be constructed in a cold climate it is recommended that a minimum of R40 (50%) be air impermeable insulation installed according to section R806.4 of the IRC.

3. IMPLICATIONS OF HIGH-R VALUE ROOF SYSTEMS

Energy savings are usually considered when determining the cost of adding insulation, and whether or not it is cost effective. A whole-house energy analysis was completed to show the savings possible from additional roof insulation. A relatively standard new home was modeled in both a Minneapolis (Zone 6) and Phoenix (Zone 2) climate and the level of attic insulation was varied. The base home specifications were as follows:

- 2,800 ft^2
- Slab on grade
- 2 story, detached house
- R-19 Walls
- Vented Attic - Varied from R-10 to R-100
- 90% AFUE Furnace
- 14 SEER Air Conditioner
- BSC Building America target airtightness (0.25 CFM50/ft^{2}of enclosure surface area)

The modeled annual space conditioning site energy is shown in Figure 8 for the Minneapolis climate. Figure 9 contains the modeled annual space conditioning site energy for the Phoenix climate.

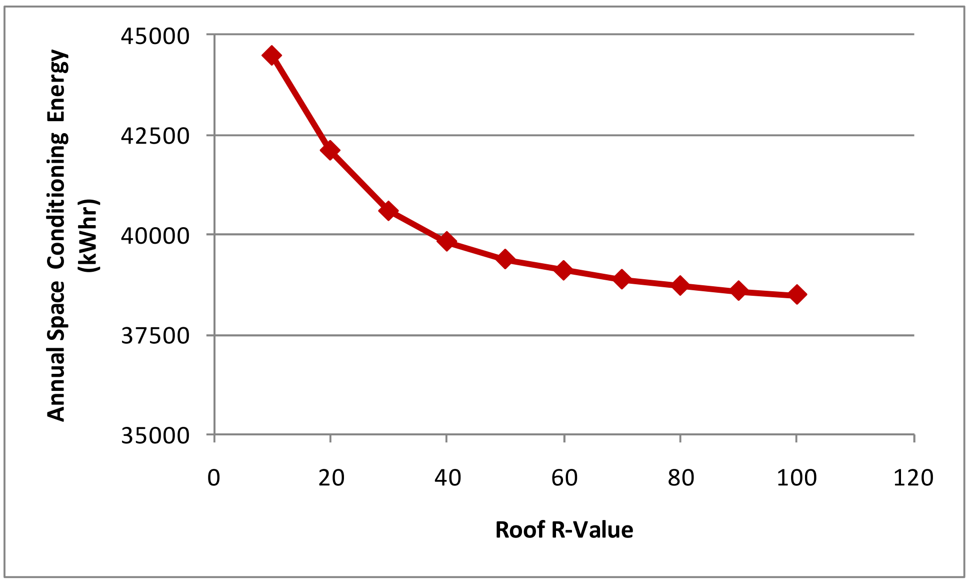

Figure 8 - Minneapolis Annual Space Conditioning Site Energy

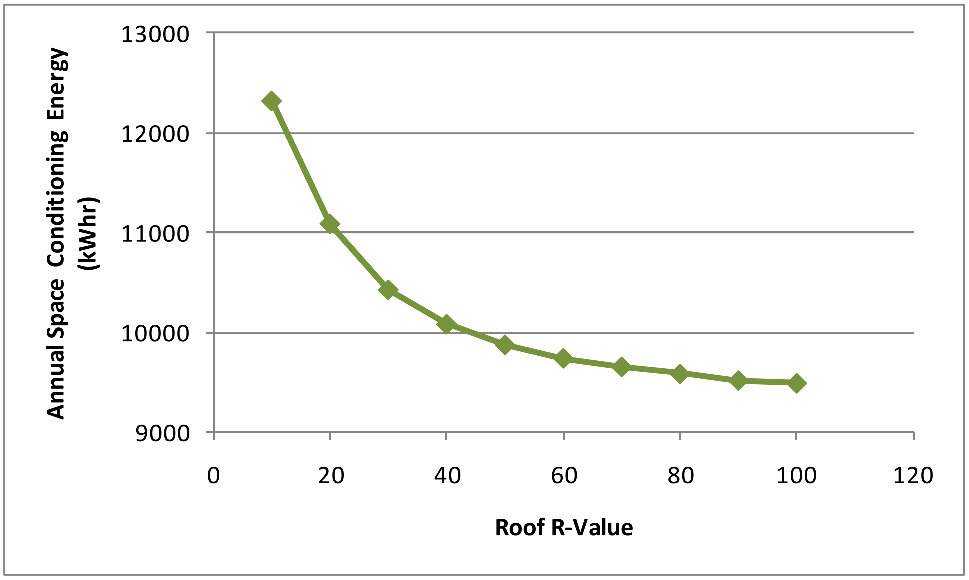

Figure 9 - Phoenix Annual Space Conditioning Site Energy

The asymptotic nature of these graphs is typical for this form of energy use analysis. It is important to note that the energy savings developed are only due to the increase in attic insulation. If these homes embraced a whole house High-R value approach with further improved air tightness, the energy savings could be much more significant. The graphs show modeled data from R-10 to R-100 to include a comparison for vintage homes being retrofitted. In the case of the Phoenix climate, updating a home with little to no attic insulation and increasing the value to a prescribed High-R of R-50 saves approximately 20% annually on space conditioning energy. Upgrading a Minneapolis home attic from R-10 to a prescribed High-R of R-75 yields an annual savings of 13%. Again, further improvements can be attained by improving all house components to the prescribed High-R values.

To ensure the full depth of vented attic insulation is provided at the outside edge of the wall for a trussed roof structure, a larger overhang or high-heel roof framing method may be required. Assuming a normal truss and blown insulation with an R-value of R3.3 per inch, the required overhangs were calculated for a set of R-values while maintaining the full R-values to the outside edge of the top plate. The chart in Figure 10 correlates R-value to overhang requirements for a selection of roof slopes. The graph makes it evident that very few roof designs will allow the full R-value at the outside of the wall top plate using a standard truss and simple blown insulation. Allowances within the code permit a reduction of the attic R-value at the outside edge of the wall, but an attempt should be made to minimize the reduction in R-value for both energy and durability.

Alternate insulation methods can be employed using insulations with higher R-value per inch at the top plate and low height areas of the roof to maintain R-value. Closed cell spray polyurethane foam used to attain R60 would only need to be approximately 10” deep vs. the approximately 20” required using blown insulations. This would make it possible to attain a full R-60 with 2” air baffle at the outside edge of the top plate using a 6:12 pitch roof and 24” overhangs. This detail has the secondary benefit of providing excellent air sealing at the junction of the wall top plate and the ceiling plane.

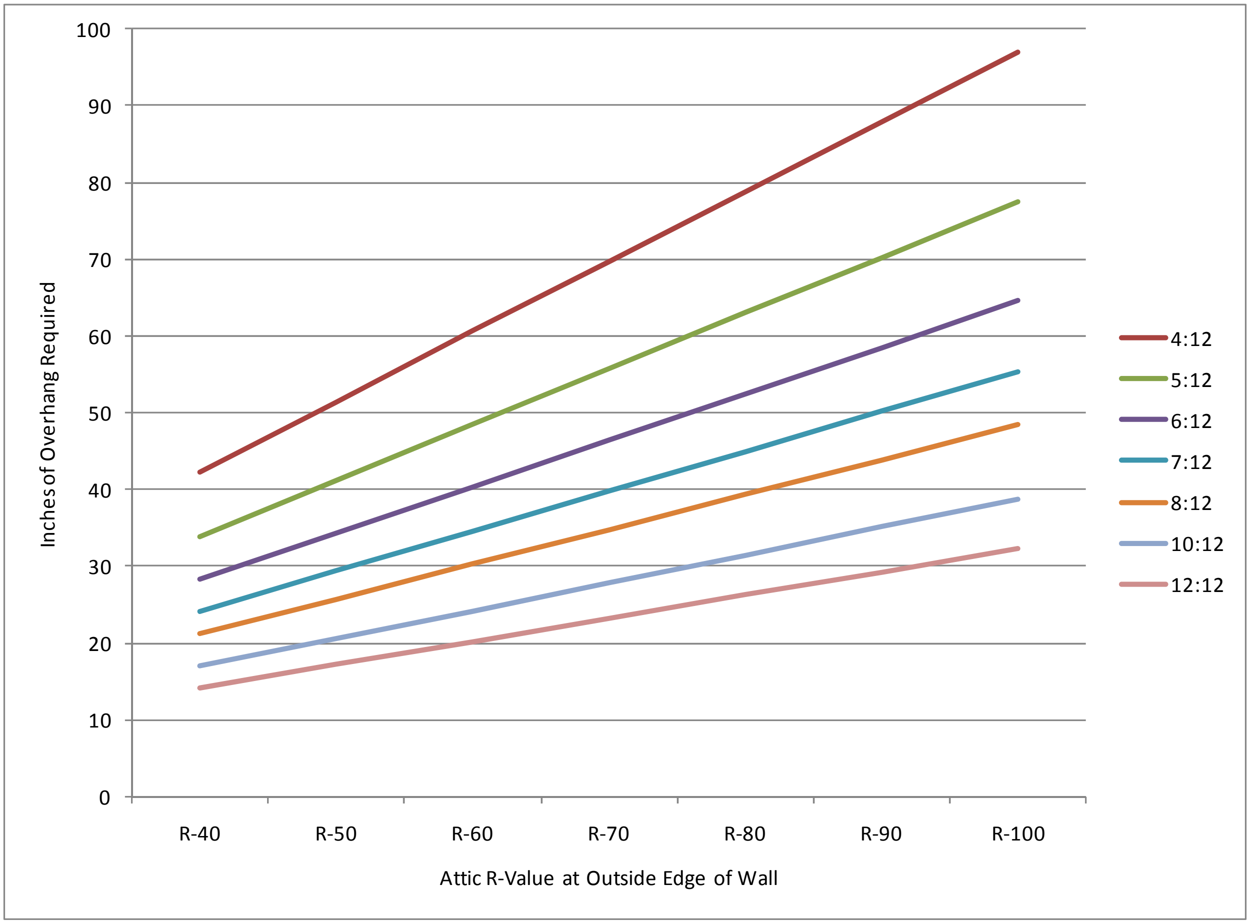

Figure 10 - Overhang Requirements for High-R Values with R3.3/inch blown insulation

4. THERMAL CONTROL AND HEAT FLOW ANALYSIS

Two dimensional heat flow analysis was conducted for each roof using THERM 5.2, a two-dimensional steady-state finite element software package developed by the Lawrence Berkeley National Laboratory at the University of California. THERM was used to calculate the thermal performance of each of the different proposed assemblies including thermal bridging effects.

In many cases, it is generally assumed that installing an R-38 fiberglass batt into a 2x12 cathedral ceiling leads to roof performance of R-38. This does not take into account thermal bridging of the roof framing, which allows heat to bypass the insulation decreasing the whole assembly R-value. THERM can predict the impact of thermal bridging and determine clear assembly roof R-value.

The effect of thermal bridging and different framing details requires a metric more complex than just a single R-value to allow for meaningful comparisons. Five R-values have been and are used in the building industry. We have found it useful to add information and extend their definitions.

1. Installed Insulation R-value

This R-value is commonly referenced in building codes and used by industry. This is simply the R-value labeled on the product installed in the assembly (i.e., nominal value).

2. Center-of-Cavity R-value

This R-value is calculated at a line through an assembly that contains the most insulation, and the least framing (typically the middle of a rafter bay in framed construction).

3. Clear Assembly R-value

R-value of an assembly containing only insulation the and minimum necessary framing materials at a clear section with no windows, corners, columns, architectural details, or interfaces with roofs, foundations or walls.

4. Whole-Assembly R-value

R-value for the whole opaque assembly including all additional structural elements (such as double studs), and typical enclosure interface details, including wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections.

5. True R-value

The R-value of an enclosure assembly that includes all thermal bridging, air leakage, wind washing, convective loops, radiation enhancements, thermal and hygric mass, and installation defects.

Each of these measures is progressively more realistic. The True R-value is very difficult to measure without field measurement and sampling. The clear-assembly R-value will be approximated in this analysis. The ridge in a cathedral ceiling represents a thermal bridge, but due to its minimal percentage of the roof area, this area was not included in the calculation. The intersection between the roof and wall also represents an area where thermal bridging typically occurs. The intersection between the wall and roof is beyond the scope of this report. It is strongly recommended that the insulation value attained in the clear-assembly be continuous to at least the outer edge of the wall top plate. This may require high heel trusses for attics and careful planning to ensure that the rafters are sized appropriately so that a reduction in R-value does not occur at the roof-wall intersection. Air sealing of this area is also of particular importance. A continuous air barrier system must exist wherein the ceiling plane air barrier continues into the wall air barrier system.

The R-value of the roof section was simulated as a cross section perpendicular to the rafters/trusses to best represent the thermal bridging effects of rafters or trusses as shown in Figure 11.

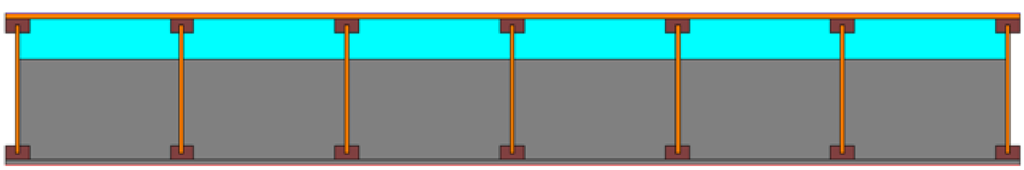

Figure 11 : Cross section of sample cathedral roof for THERM simulation

One drawback of THERM is that it cannot accurately represent air leakage and insulation installation defects, both of which can significantly lower the effective R-value of the assembly by bypassing the insulation in the roof system. There are four main ways in which air leakage affects interact with the enclosure as shown in Figure 12.

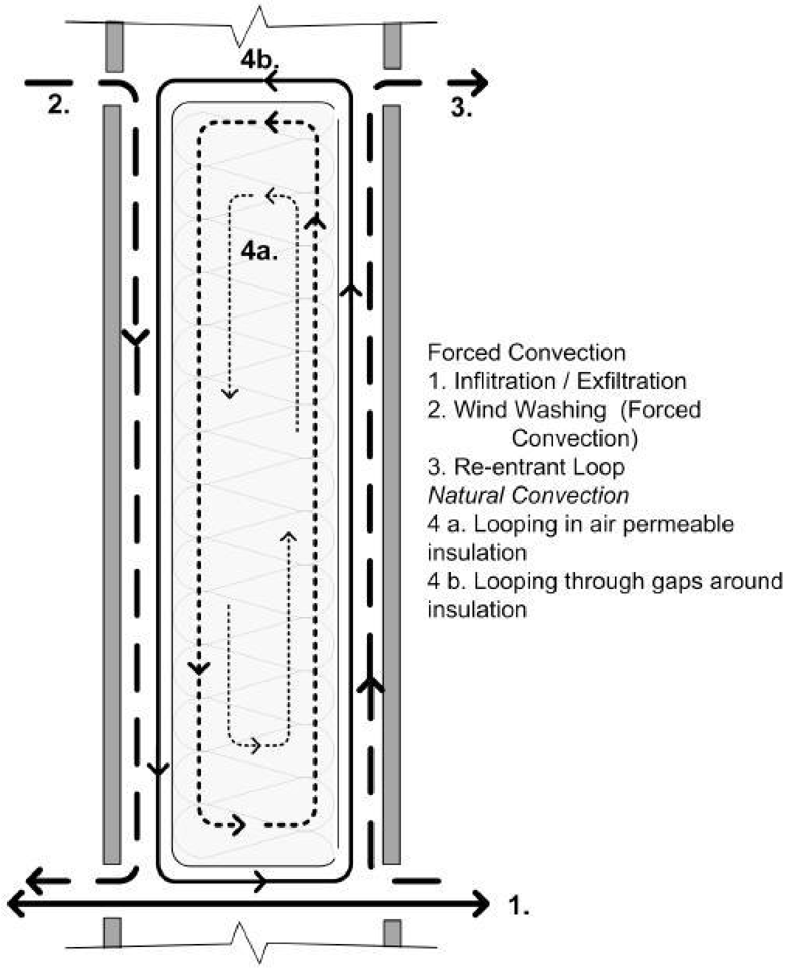

Figure 12 : Common Air Flow Paths in Enclosures

One of the most common areas for air leakage is at roof-wall interface. Depending on which layer of construction is used as the air barrier in the wall, it may be difficult to transition to the material being used as the air barrier in the ceiling. Systems such as the airtight drywall approach (ADA) simplify this transition. Various readily available spray foams, sealants and gaskets can also be used to transition the wall air barrier to the ceiling air barrier. Figure 13 and Figure 14 illustrate two possible methods to transition the air barrier from the walls to the roof plane. Appendix A includes a selection of wall to roof intersections with recommended air sealing techniques.

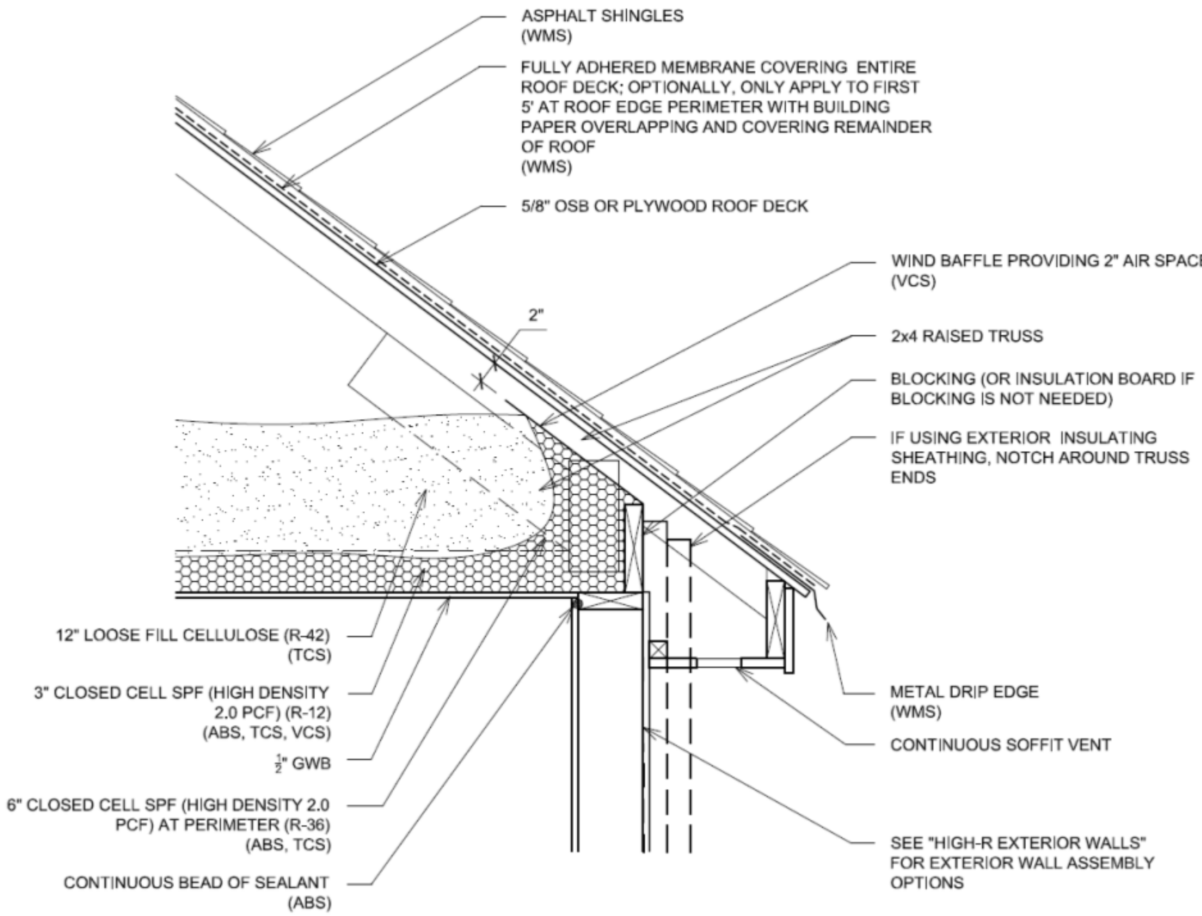

Figure 13 - Attic Air Barrier Transition

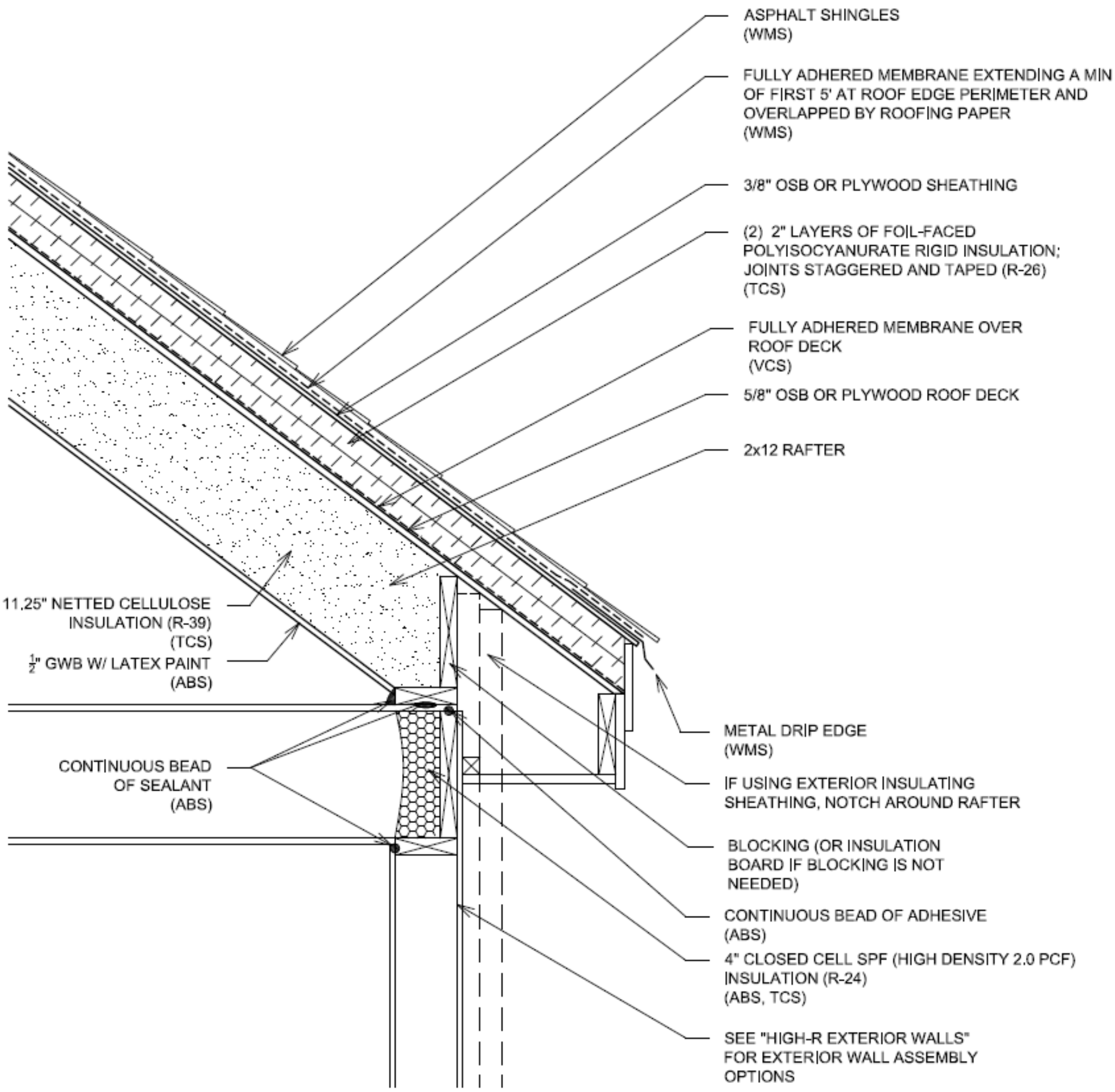

Figure 14 - Cathedralized Attic Air Barrier Transition

Since air leakage cannot be simulated using THERM, the increased convective looping and air movement around poorly installed batt insulation relative to blown insulation, and to a lesser extent blown-in or sprayed fiberglass cannot be captured numerically in this study. Also, the convection suppression through the cellulose insulation relative the fiberglass batt insulation cannot be fully appreciated using this analysis. Neither cellulose nor fiberglass batt are air barriers/air barrier materials, so a continuous air barrier should always be used with either insulation.

All of the THERM analyses were conducted with an interior temperature of 68°F (20°C) and an exterior temperature of -4°F (-20°C) so the results could be compared. These temperatures coincide with the High-R wall and High-R foundations reports created by BSC in 2009. Because the R-value is a weak function of the temperature difference across the enclosure, the results may vary slightly for different temperatures.

A list of the materials used in this analysis and their respective conductivities used in the two dimensional THERM analysis are shown in Table 5. Film conductance values of 9.3 W/m²K for the interior surface and 34.0 W/m²K for the exterior surface were used for all THERM simulations.

Table 5 : Conductivity values used for two dimensional heat flow analysis

Enclosure Component	Thermal Conductivity k [W/m·K]	R-Value Per Inch [hr·°F·ft²/Btu]
Blown Loose Fiberglass	0.053	2.7
Blown Loose Cellulose	0.043	3.3
Dense Pack Cellulose	0.037	3.9
Fiberglass Batt	0.040	3.6
0.5 PCF OC Spray Polyurethane Foam	0.040	3.6
2.0 PCF CC Spray Polyurethane Foam	0.024	6.0
Extruded Polystyrene (XPS)	0.029	5.0
Foil Faced Polyisocyanurate (PIC)	0.022	6.5
Drywall	0.160	0.9
SPF Framing	0.100	1.4
Oriented Strand Board	0.110	1.3
Plywood	0.100	1.4
EPS	0.039	3.7

One of the considerations for thermal modeling was the number of framing components in the roof system. This is usually measured as using the "framing factor", or percentage of a cross-sectional area that is comprised of framing elements. For example, a rafter spacing in a typical roof system is sixteen inches (405 mm) on centre. Modeling the roof with a rafter spacing of 16 inches on centre (Figure 15) results in a 9.4% framing factor.

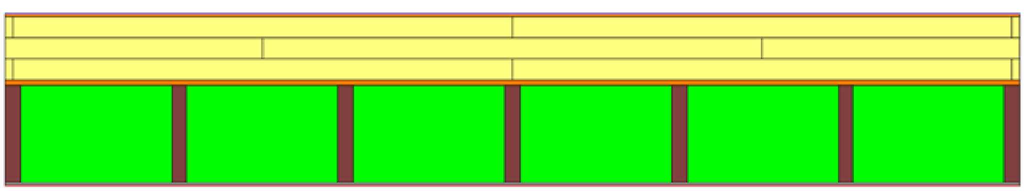

Figure 15 : Typical framing 16"o.c. – 9.4% framing factor

Field studies have shown that the actual average framing factor for walls, using 16" o.c. framing, including studs, bottom plate and top plates throughout an entire house are up to 23-25% (Carpenter and Schumacher 2003). Because this report's focus is roof systems, and the roof is usually fairly uniform in terms of framing elements without additional unnecessary elements, a framing factor of 9.4% will be used for simulation.

Table 6 shows all of the Clear Assembly R-values calculated using THERM simulations. The highest R-values were obtained by the simplest systems. Vented attics (where the addition of insulation is relatively simple) attained R-values approaching R100. More compact vented roofs were between R40 and R80. A variety of materials and systems were built and modeled. Where the insulation was placed between dimensional lumber in the rafter space, thermal bridging occurred and there was a reduction in R-value. Where the insulation was placed in deep engineered trusses the thermal bridging was reduced. The thermal bridging was almost completely eliminated where continuous exterior (or interior) insulation was used. Some of the

R-values increased from their installed R-value: this is because each material in the assembly and the air films were included in the THERM modeled R-value adding to the installed R-value.

Table 6 : R-values for simulated roof systems

	Assembly Description	Installed Insulation R-Value [hr·°F·ft2/Btu]	Clear Assembly Simulated R-Value [hr·°F·ft2/Btu]	Modeled R-Value Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation	97	100	5
	Roof 1B - 30in Blown Cellulose Insulation	100	102	5
	Roof 1C - 20in 0.5 PCF Open Cell SPUF	72	73	3
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF	72	71	3
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation	75	77	4
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation	78	77	4
Vented Cathedral Ceiling	Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist	50	51	2
	Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist	54	54	2
	Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber	38	36	2
Unvented Cathedral Ceiling or Cathedralized Attic	Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist	54	53	2
	Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist	50	50	2
	Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber	68	53	2
	Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	53	52	2
	Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	63	60	3
	Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss	63	62	3
	Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation	66	63	3
	Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation	75	73	3
	Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation	96	92	4
	Roof 7A - 12in EPS Structurally Insulated Panel	44	47	2
	Roof 7B - 20in EPS Structurally Insulated Panel	74	77	4

5. ENCLOSURE DURABILITY

Durability of the building enclosure system was also used to classify the different roof assemblies. Durability is used in this report to group together multiple durability related criteria such as drying of water leakage events, air leakage condensation, built in moisture, and susceptibility of different building materials to moisture related issues. The durability assessment will be determined qualitatively based on the knowledge and experience of building material characteristics such as vapor permeability, hygric buffering capacity, susceptibility to moisture related damage and hygrothermal balance.

Hygrothermal Balance and Boundaries

Assessing moisture related durability risks involves three different moisture processes; wetting, drying and moisture redistribution. These three processes in combination with the safe storage capacity of each component will determine the risk of moisture damage to an assembly. This report only includes a brief overview of the wetting mechanisms, and was covered in more detail by Lstiburek [2006].

There are three main wetting mechanisms generally acting on the roof system. They are:

- Bulk water penetration from the exterior
- Vapor diffusion (from exterior or interior)
- Air-transported moisture (air leakage carrying moisture)

The first source of wetting is bulk water from the exterior. This will cause the greatest amount of damage in the shortest amount of time. The best strategy to avoid water ingress into the roof or living space from the exterior is to properly layer flashings, properly detail roof penetrations and provide a properly applied water management system below the exterior water shedding layer. Vapor diffusion can be handled with a properly implemented vapor control system. Air leakage and the associated possible condensation can be limited with a properly designed and installed air barrier system, and by maintaining possible condensation surface temperatures above the dewpoint of the interior air with proper enclosure design.

Drying is important since nearly all building enclosures will experience wetting at some point. In roof systems, there is drying potential to both the interior and exterior if the enclosure design allows it.

The safe storage capacity (balance of wetting and drying) of an individual material or enclosure system is fundamental to good building design. It is rarely economical to build an enclosure with no risk of wetting: therefore managing the risk is important. In any building enclosure, building materials should be chosen based on moisture tolerance that correlates to the risk of moisture accumulation in the enclosure. In all cases, drying should be maximized, and attention to good design details should be used.

It is important for condensation control to maintain possible condensation surface temperatures above the dewpoint of the interior air. The IRC provides the ratios of air impermeable to air permeable insulation required in each climate zone which are intended to reduce the risk of condensation within the assembly.

Table 7 contains the durability ratings that were assigned to each roof system. These values assume that best building practices have been employed and that a continuous air barrier has been carefully designed and installed, as well as a vapor barrier as necessary. There is a strong relationship between buildability and durability. Durability requires that the building is easily built and reducing the number of mistakes. Fewer mistakes usually relates to a more durable building.

Table 7 - Durability Ratings

	System Description	Durability Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation	4
	Roof 1B - 30in Blown Cellulose Insulation	4
	Roof 1C - 20in 0.5 PCF Open Cell SPUF	4
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF	4
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation	4
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation	4
Vented Cathedral Ceiling	Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist	2
	Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist	3
	Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber	2
Unvented Cathedral Ceiling or Cathedralized Attic	Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist	2
	Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist	3
	Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber	3
	Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	3
	Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	3
	Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss	3
	Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation	4
	Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation	4
	Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation	5
	Roof 7A - 12in EPS Structurally Insulated Panel	4
	Roof 7B - 20in EPS Structurally Insulated Panel	4

6. BUILDABILITY

Buildability is a key comparison criterion for practical purposes. Often, the general contractor and trades will influence design decisions based on the perceived complexity of different construction techniques or deviation from their standard practice. Buildability will vary greatly across the country as trades and construction standards vary across the country. For some contractors, building with exterior insulation is common practice, while in other locations it is considered nearly impossible. The susceptibility of the enclosure system to poorly constructed water management details and poor workmanship is also considered in buildability. The simpler a system is to install correctly, the more preferable it is to use.

We recommend that the relative buildability ratings presented in this report be used as a guide for selected several assemblies for detailed cost and buildability studies for a specific project.

Table 8 contains the buildability ratings that were assigned to each roof system.

Table 8 - Buildability Ratings

	System Description	Buildability Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation	5
	Roof 1B - 30in Blown Cellulose Insulation	5
	Roof 1C - 20in 0.5 PCF Open Cell SPUF	3
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF	2
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation	3
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation	3
Vented Cathedral Ceiling	Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist	3
	Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist	3
	Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber	4
Unvented Cathedral Ceiling or Cathedralized Attic	Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist	2
	Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist	2
	Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber	3
	Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	2
	Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	2
	Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss	2
	Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation	2
	Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation	2
	Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation	2
	Roof 7A - 12in EPS Structurally Insulated Panel	3
	Roof 7B - 20in EPS Structurally Insulated Panel	3

7. MATERIAL USE

Material use is becoming a critical design issue with the increasing concerns of depleting resources, and increasing costs of materials and energy. Some construction strategies use more construction materials, and the advantages of increased thermal control should be balanced against the disadvantages of increasing the building materials and embodied energy.

Embodied energy is the total energy required to get a specific product to the construction site including all energy to obtain the raw materials, processing energy and transportation energy. In some cases, materials that have less embodied energy, or more recycled material, such as cellulose insulation could be used instead of the more energy intensive insulations. Materials that are produced locally require less shipping and decrease the embodied energy required.

In the case of some insulation such as XPS and some spray foams, the global warming potential can be quite high, meaning the effect on global warming can be orders of magnitude greater than other insulation strategies. These significant global warming potentials are caused by the use of blowing agents used in the production of the insulation such as HFC-142b, HFC-134a, and HFC-245fa (Fischer et al., 1991).

Table 9 contains the material use ratings that were assigned to each roof system.

Table 9 - Material Use Ratings

	System Description	Material Use Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation	4
	Roof 1B - 30in Blown Cellulose Insulation	5
	Roof 1C - 20in 0.5 PCF Open Cell SPUF	3
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF	1
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation	4
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation	3
Vented Cathedral Ceiling	Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist	3
	Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist	3
	Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber	2
Unvented Cathedral Ceiling or Cathedralized Attic	Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist	4
	Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist	3
	Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber	1
	Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	4
	Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	3
	Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss	3
	Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation	4
	Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation	4
	Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation	3
	Roof 7A - 12in EPS Structurally Insulated Panel	4
	Roof 7B - 20in EPS Structurally Insulated Panel	4

8. COST

The factor which generally has the greatest influence on implementation of a building enclosure strategy (particularly for production builders) is cost. Because the cost of some materials varies significantly depending on location and case-specific relationships between builders and suppliers, the cost of a building enclosure system will be compared relative to other systems. When deciding which recommended system to use, cost estimates should be determined for the locale and trades specific to the project. The costs associated with this analysis are relative to one-another and based on BSC's experience.

Table 10 contains the cost ratings that were assigned to each roof system.

Table 10 - Cost Ratings

	System Description	Cost Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation	5
	Roof 1B - 30in Blown Cellulose Insulation	5
	Roof 1C - 20in 0.5 PCF Open Cell SPUF	2
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF	3
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation	4
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation	4
Vented Cathedral Ceiling	Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist	5
	Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist	3
	Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber	5
Unvented Cathedral Ceiling or Cathedralized Attic	Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist	5
	Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist	2
	Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber	2
	Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	4
	Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	3
	Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss	3
	Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation	3
	Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation	2
	Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation	1
	Roof 7A - 12in EPS Structurally Insulated Panel	3
	Roof 7B - 20in EPS Structurally Insulated Panel	1

C. Conclusions and Recommendations

There are a large variety of roof assemblies based on local practices, climate, architect's design or general contractor preferences. The most common and most recommended roof systems were simulated and compared, and alternatives (where applicable) were commented on during the analysis. The different approaches taken to provide insulation and airtightness for this diverse set of assemblies have profound implications in terms of cost, durability and performance.

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. recessed light fixtures) 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. Other than requiring an airtight ceiling, the only changes required to achieve twice current code levels of R-value are the provision of "raised heel/high heel" trusses or rafter designs to accommodate the increased amount of insulation. High R roof systems have the capability to save 20% on space conditioning energy annually in warm climates and over 10% in cold climates when upgrading from little to no insulation to high R-value levels discussed previously.

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 air leaks takes on great importance. Thus eliminating attic ductwork must be the first step, as well as sealing around all lights, partitions, access hatches, etc. The Attic Air Sealing Guide (Lstiburek 2010) provides the background and approach for the preparatory work necessary prior to insulating an attic or adding insulation to an existing attic. The guide focuses on combustion safety, ventilation for indoor air quality, and attic ventilation for durability. The Attic Air Sealing Details section of the guide provides a scope of work and specification for the air sealing of many points of air leakage in common attic spaces. Appendix A includes a selection of wall-to-roof intersections, with recommended air sealing techniques.

The roofs were scored on a scale of 1 to 5 for each criterion, one being the lowest, and five being the best performing, and the results are shown in Table 11. The scoring was developed as a team based primarily on collective experience with groups in the building industry and Building America partnerships. Because some of the criteria such as buildability, material use and cost vary regionally, the final results may be different in different parts of the continent. Each project also has specific criteria that are more important. All of the criteria are currently weighted evenly, but they could be changed depending on the concerns of the contractor or homeowner. Using multipliers between 1 and 5 before summing the scores could result in different results based on the importance of different criteria.

Based on the selected criteria the highest scoring, and recommended, roofs were as follows:

Vented Attics

- Roof 1A - 36in Blown Fiberglass Insulation
- Roof 1B - 30in Blown Cellulose Insulation

Vented Cathedral Ceilings

- Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist
- Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber

Unvented Cathedral Ceilings or Cathedralized Attics

- Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation
- Roof 7A - 12in EPS Structurally Insulated Panel
- Roof 7B - 20in EPS Structurally Insulated Panel

Table 11 : Comparison Criteria Matrix with Scoring Results

	System Description	Modeled R-Value Rating	Durability Rating	Buildability Rating	Material Use Rating	Cost Rating	Total Rating
Vented Attic	Roof 1A - 36in Blown Fiberglass Insulation	5	4	5	4	5	23
	Roof 1B - 30in Blown Cellulose Insulation	5	4	5	5	5	24
	Roof 1C - 20in 0.5 PCF Open Cell SPUF	3	4	3	3	2	15
	Roof 1D - 12in 2.0 PCF Closed Cell SPUF	3	4	2	1	3	13
	Roof 2A - 6in 0.5 PCF Open Cell SPUF + 20in Blown Fiberglass Insulation	4	4	3	4	4	19
	Roof 2B - 4in 2.0 PCF Closed Cell SPUF + 20in Blown Fiberglass Insulation	4	4	3	3	4	18
Vented Cathedral Ceiling	Roof 3A - 11.5in Dense Pack Cellulose + 1in XPS inside Engineered I Joist	2	2	3	3	5	15
	Roof 3B - 8.5in Dense Pack Cellulose + 4in XPS inside Engineered I Joist	2	3	3	3	3	14
	Roof 3C - 1in XPS interior insulation + 9.25in Fiberglass Batt Insulation in Dimensional Lumber	2	2	4	2	5	15
Unvented Cathedral Ceiling or Cathedralized Attic	Roof 4A - 14in Dense Pack Cellulose in Engineered I Joist	2	2	2	4	5	15
	Roof 4B - 14in 0.5 PCF Open Cell SPUF in Engineered I Joist	2	3	2	3	2	12
	Roof 4C - 11.25in 2.0 PCF Closed Cell SPUF in Dimensional Lumber	2	3	3	1	2	11
	Roof 5A - 4in 0.5 PCF Open Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	2	3	2	4	4	15
	Roof 5B - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered I Joist	3	3	2	3	3	14
	Roof 5C - 4in 2.0 PCF Closed Cell SPUF + 10in Dense Pack Cellulose in Engineered Truss	3	3	2	3	3	14
	Roof 6A - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in XPS Exterior Insulation	3	4	2	4	3	16
	Roof 6B - 9.25in Dense Pack Cellulose in Dimensional Lumber + 6in Foil Faced PIC Exterior Insulation	3	4	2	4	2	15
	Roof 6C - 11.25in Dense Pack Cellulose in Dimensional Lumber + 8in Foil Faced PIC Exterior Insulation	4	5	2	3	1	15
	Roof 7A - 12in EPS Structurally Insulated Panel	2	4	3	4	3	16
	Roof 7B - 20in EPS Structurally Insulated Panel	4	4	3	4	1	16

D. Future Work

While conducting this analysis, some questions were encountered that require further research, analysis and simulations to better understand the moisture and thermal performance of roof insulation systems. These areas include:

- Determining the effect on drying capabilities of high R-value roofs with exterior low emissivity coatings
- The effect on heating and cooling loads of buildings built with high R-value roofs having low emissivity coatings
- Air tightness of dense pack cellulose in High-R value roof assemblies

E. Works Cited

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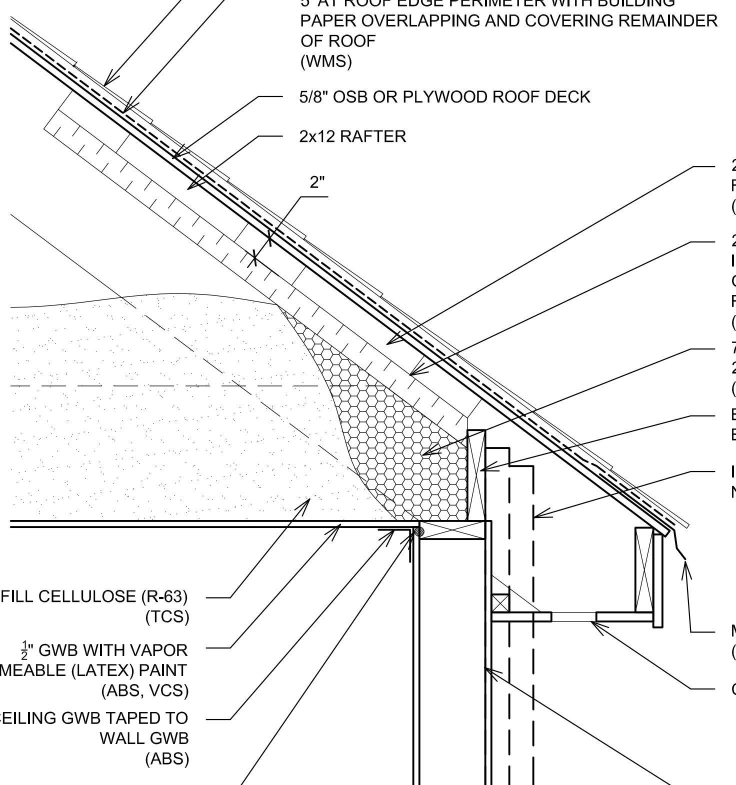
Appendix A

Wall to Roof Intersection Details

Roof Structure: 2X12 RAFTER
Vented or Unvented: VENTED
Attic or Cathedral: ATTIC
Location of Insulation: PERIMETER + WITHIN (AND ABOVE) ATTIC FLOOR JOISTS
Insulation Type, Insulation R-Value:
PERIMETER: 2" FOIL-FACED POLYISOCYANURATE + 7.5" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF) , R-55
ATTIC FLOOR: 18" LOOSE FILL CELLULOSE, R-63
Climate/Zone: COLD / ZONE 5

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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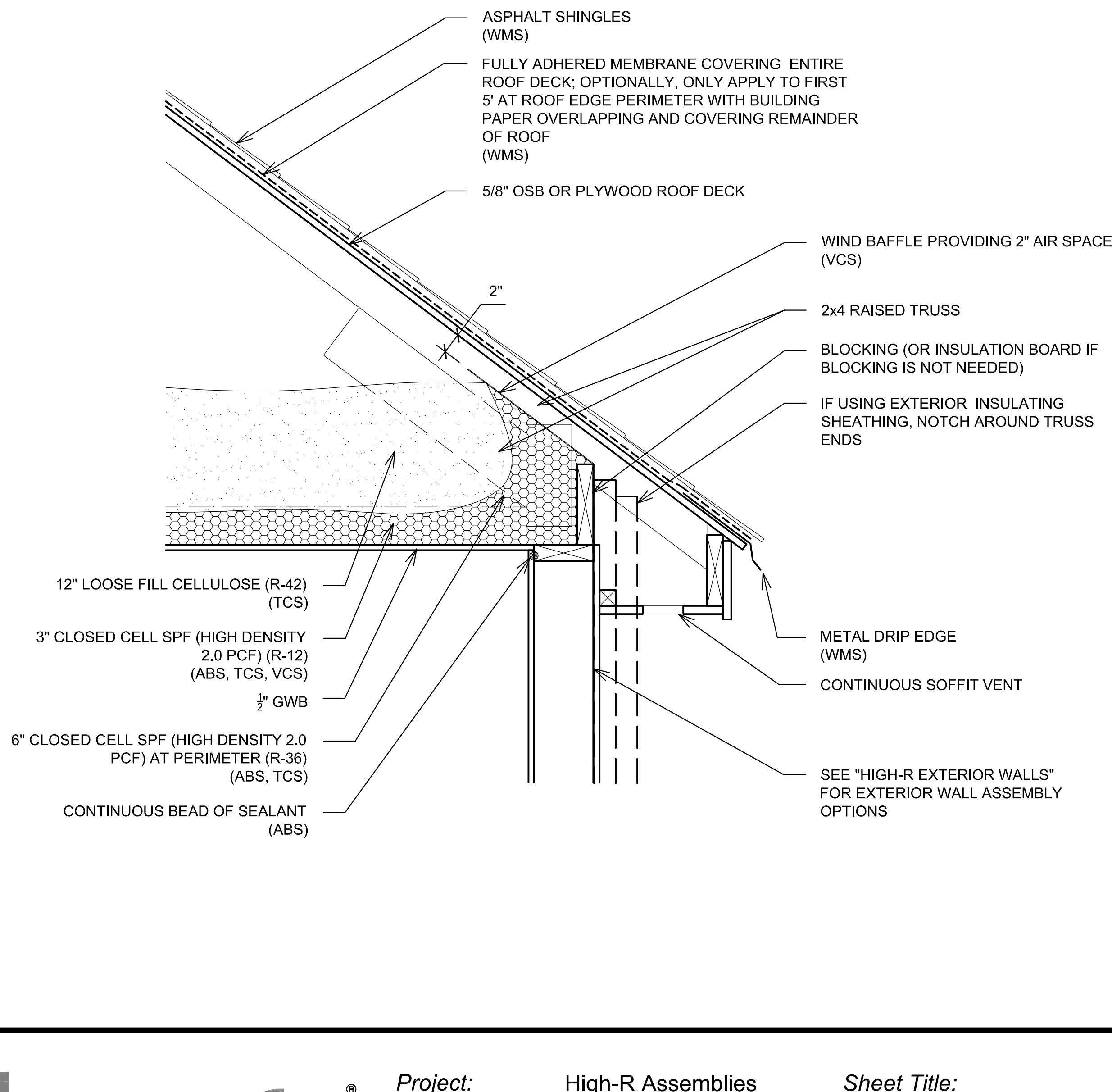
Project:	High-R Assemblies
Date:	2010-02-12 DRAFT
Drawing Title:	Roof Assemblies
Drawing File:	RoofDetails.dwg
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Roof Type #1

Roof Structure: 2X4 RAISED TRUSS
Vented or Unvented: VENTED
Attic or Cathedral: ATTIC
Location of Insulation: PERIMETER + AT ATTIC FLOOR
Insulation Type, Insulation R-Value:
PERIMETER: 3" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-18
ATTIC FLOOR: 3" CLOSED CELL + 12" LOOSE FILL CELLULOSE, R-60
Climate/Zone: COLD / ZONES 5, 6 AND 7

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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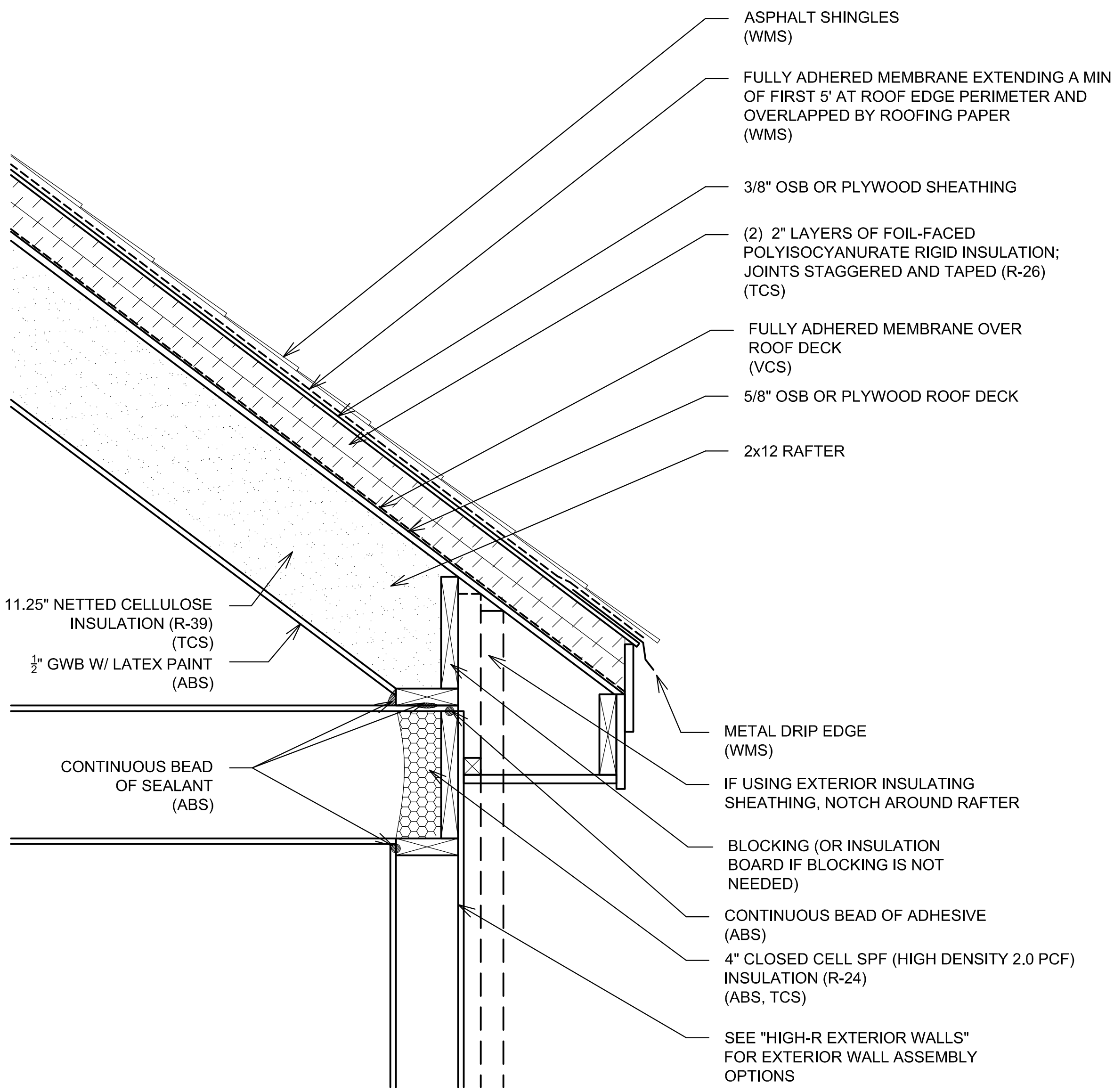
Sheet Title:

Roof Type #2

Roof Structure: 2X12 RAFTER
Vented or Unvented: UNVENTED
Attic or Cathedral: CATHEDRAL
Location of Insulation: ABOVE ROOF DECK AND IN RAFTER CAVITY
Insulation Type, Insulation R-Value:
4" FOIL-FACED POLYISOCYANURATE ABOVE ROOF DECK + 11.25" CELLULOSE IN RAFTER CAVITY, R-65
Climate/Zone: COLD / ZONES 5 AND 6

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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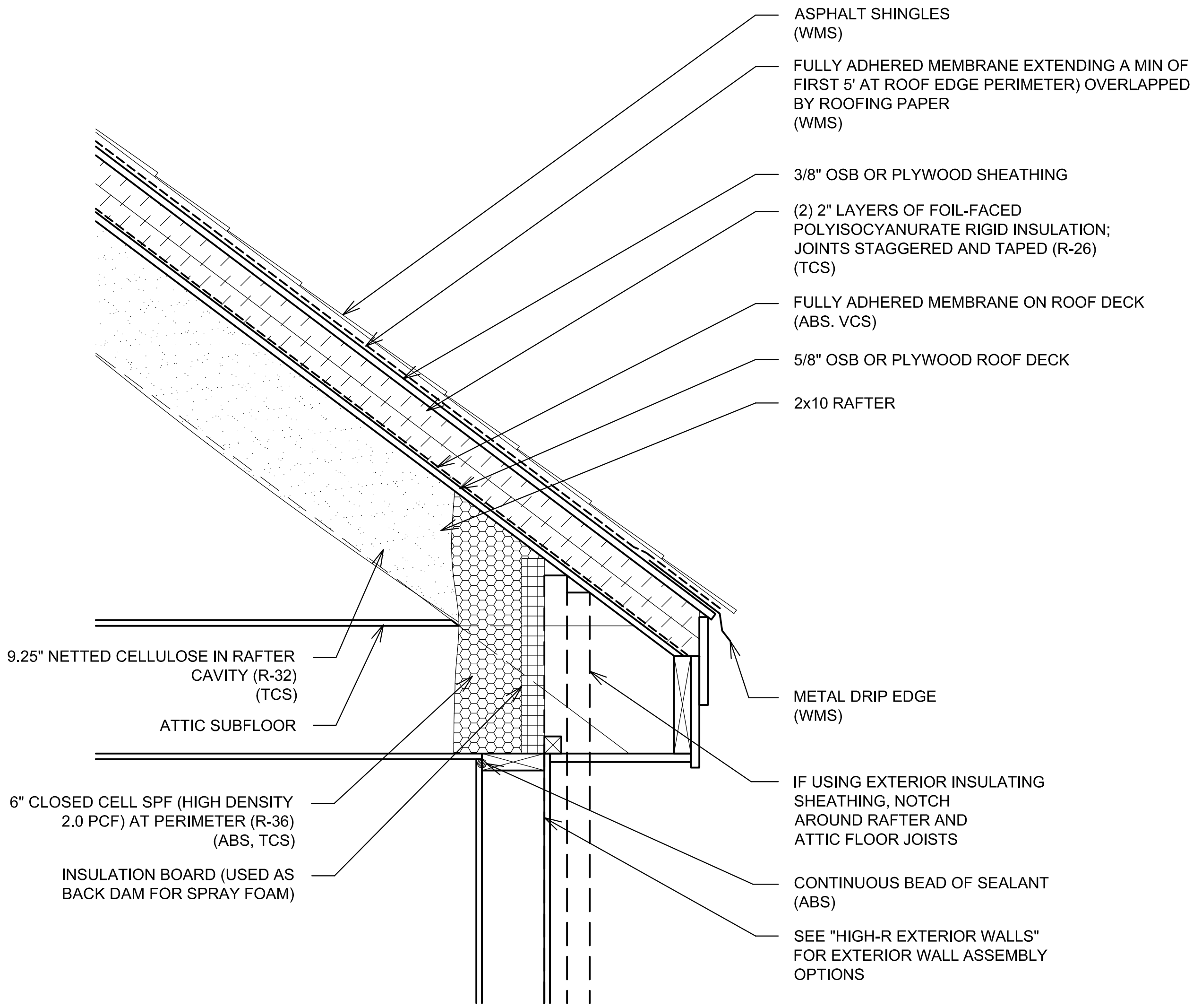
Sheet Title:

Roof Type #3

Roof Structure: 2X10 RAFTER
Vented or Unvented: UNVENTED
Attic or Cathedral: ATTIC
Location of Insulation: ABOVE ROOF DECK AND IN RAFTER CAVITY
Insulation Type, Insulation R-Value:
ROOF: 4" FOIL-FACED POLYISOCYANURATE ABOVE ROOF DECK + 9.25" CELLULOSE IN RAFTER CAVITY, R-58
PERIMETER: 6" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-36
Climate/Zone: COLD / ZONES 5 AND 6

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Drawing Title: Roof Assemblies
Drawing File: RoofDetails.dwg
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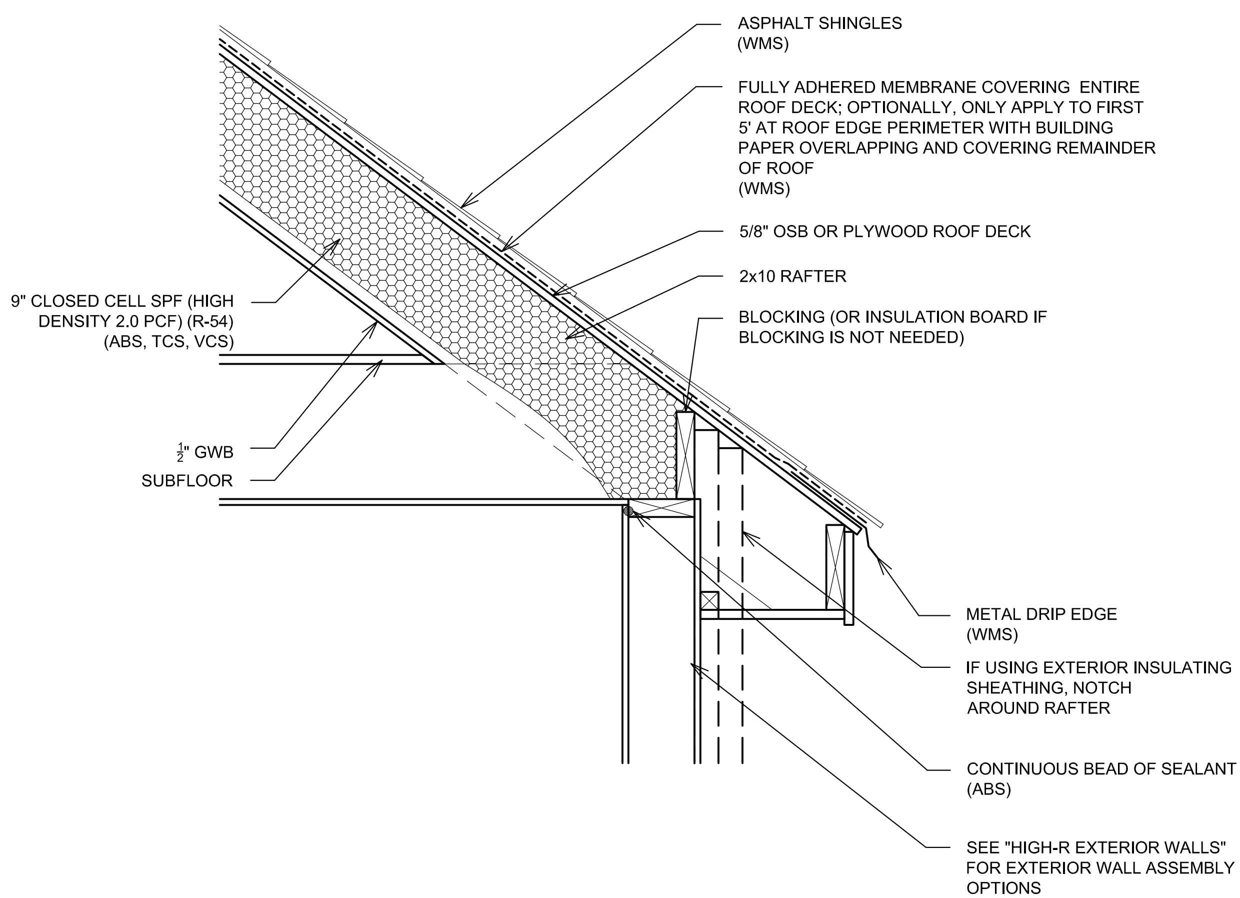
Sheet Title:

Roof Type #4

Roof Structure: 2X10 RAFTER
Vented or Unvented: UNVENTED
Attic or Cathedral: CATHEDRAL
Location of Insulation: RAFTER CAVITY
Insulation Type, Insulation R-Value:
9" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-54
Climate/Zone: COLD / ZONES 5, 6 AND 7

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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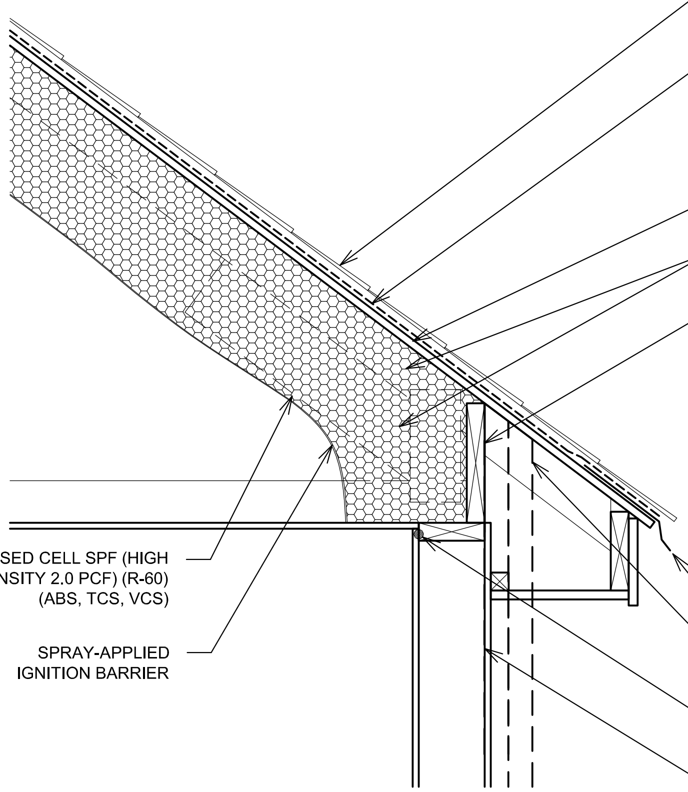
Drawing Scale:	3/4" = 1'-0"

Sheet Title:

Roof Type #5

Roof Structure: 2x4 RAISED TRUSS
Vented or Unvented: UNVENTED
Attic or Cathedral: ATTIC
Location of Insulation: BELOW ROOF DECK
Insulation Type, Insulation R-Value:
10" CLOSED CELL SPF (HIGH DENSITY 2.0 PCF), R-60
Climate/Zone: COLD / ZONES 5,6 AND 7

ABS: *Air Barrier System component*
TCS: *Thermal Control System component*
VCS: *Vapor Control System component*
WMS: *Water Management System component*



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Date: 2010-02-12 DRAFT
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Drawing File: RoofDetails.dwg
Drawing Scale: 3/4" = 1'-0"

Sheet Title:

Roof Type #6

About this Report

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

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