Practical Residential Wall Systems: R-30 and Beyond

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1 ABSTRACT

With uncertainty of energy prices and an increased interest in sustainability, more builders and designers are striving for dramatic levels of home energy efficiency. Performance of the home's envelope is clearly critical in this endeavor. In colder climates, several builders are moving towards whole-wall thermal resistances above 30 ft^{2}hr°F/Btu (4.9 m^2°C/W). While there are numerous high-performance wall systems, the authors focus here on three of the most practical methods to achieve whole-wall performance of R-30 or above. Working with builders in cold climates, the authors have found that these three approaches are often the most well-established, use readily available materials, and are buildable by contractors without substantial additional equipment or sub-contractors:

- Double framed walls with blown or sprayed insulation;
- 2x4 or 2x6 insulated, framed walls with exterior rigid foam insulation;
- Structural insulated panels (SIPs).

This paper documents key components, advantages, and challenges for each wall system, including:

- Material choices and options;
- Structural issues, durability, and moisture management;
- Requirements of builders and trades (framing, insulation, plumbing, electrical, siding, etc.);
- Cost considerations.

The "best" choice for a wall system will vary with region, with fluctuating material prices, with building design and type, and with builder experience and preference. From experience working with builders using these techniques, the authors have prepared this paper to provide key considerations and guidelines for designing and building homes using these wall systems and achieving at least R-30 performance.

2 INTRODUCTION

In this paper, the authors present descriptions, materials, construction methods, and cost elements related to three high-performance, cold-climate wall systems with whole-wall R-values of at least 30 ft^{2}hr°F/Btu (4.9 m^2°C/W). As there are many wall systems in use – and more are being developed constantly, this effort is by no means exhaustive. This presents three walls systems which builders have successfully implemented (and continue to employ) and which the authors

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feel are among the most widely accepted, practical, and "buildable" high-performance wall systems.

Each primary section of this paper describes one of three wall systems that the authors have found to be among the most practical to achieve whole-wall thermal resistance of 30 $ft^2hr°F/Btu$ (4.9 $m^2°C/W$). "Whole-wall" R-value is defined by publications from Oak Ridge National Laboratory as "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)" (ORNL 2004).

The paper refers often to "conventional frame construction." In cold climates, this typically refers to 2x6 framed walls (with framing nominally at 16" on center) with cavities filled with batt fiberglass, blown cellulose or fiberglass, or spray foam. The whole-wall R-values for these conventional walls vary with the type of insulation and – equally as important – with its quality of installation. In this paper, authors compare the three wall systems to a 2x6 wall with 20% framing factor insulated with dense-blown cellulose achieving a whole-wall R-value of 17 $ft^2hr°F/Btu$ (2.8 $m^2°C/W$).

It is with some trepidation that cost data is presented in this paper, as costs of labor and building materials vary tremendously with time and geography. Authors have attempted to present amounts of materials and estimated labor (time) required for various methods. Labor required, however, can also vary tremendously. In order to make comparisons among the various wall systems, simple, example costs for the 800-ft^2 "baseline" wall (100 linear feet, eight feet high) are outlined in TABLE 1 below. These costs include framing, sheathing, air sealing of the sheathing, and insulation. Other factors (such as house wrap, siding, interior drywall and finishing, etc.) are not included in this baseline as these costs are relatively consistent from system to system (though different requirements and incremental costs are noted in the appropriate sections below).

TABLE 1. Labor and costs for the proposed baseline wall: 100 feet of 8' wall, 2x6 framing with 20% framing factor, insulated with dense blown cellulose. Costs include framing, exterior sheathing, and insulation only.

Framing, Sheathing, and Air Sealing Labor	40	person-hours
Labor Cost, $35/hour	$1,400	
Framing Material	$512	(2x6 framing)
Sheathing Material	$250	(OSB)
Blown Cellulose Insulation	$1,500	(material and labor)
Material and Labor estimate for Framing, Exterior Sheathing, and Insulation	$3,662	

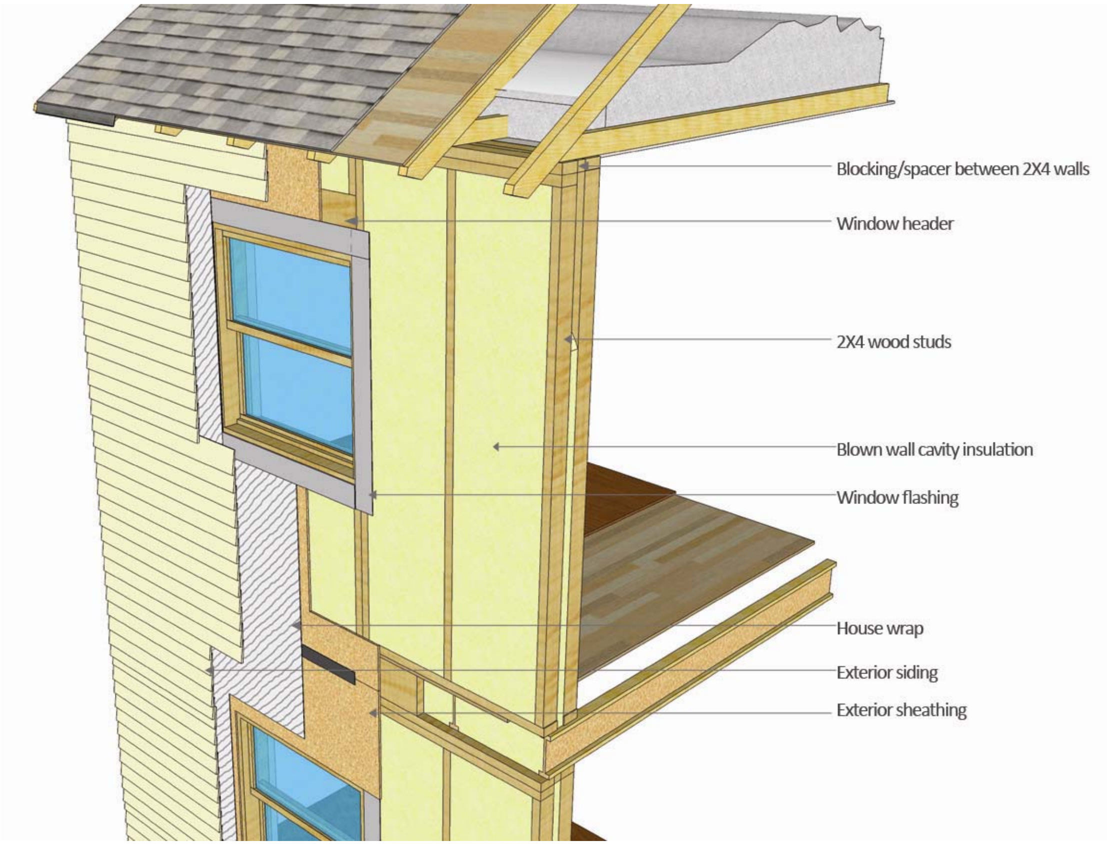
Even within small geographic areas, builders with varying experiences and preferences have selected very different wall systems as the most practical for their home designs, construction practices, sub-contractors, etc. The labor and costs presented here certainly cannot accurately reflect all changing, real-world conditions, but it's hoped that this paper will provide solid background information and can serve as a useful framework to designers and builders when considering high-performance wall systems.

3 DOUBLE WALLS

3.1 Materials and Options

To increase thermal performance of typical frame construction, one rather intuitive solution is to simply increase the thickness of the framing and thereby the insulation cavity. While this is certainly an option, dimensional lumber for wall framing can be very expensive and difficult to work with (2x10 or 2x12 framing is usually necessary to achieve whole-wall R-values of 30 $ft^2h°F/Btu$, 4.9 $m^2°C/W$, using cellulose or fiberglass insulation). Engineered wall framing – such as TJIs – are also an option, but these can be equally expensive and cumbersome.

Several builders have successfully used "double wall" systems to more practically achieve higher R-values in thicker, framed walls. In this context, a double wall consists of a load-bearing external frame wall usually constructed with 2x4 framing at 16" on center. This wall is built and sheathed as a typical exterior frame wall, and windows and siding are installed using conventional methods. After the building is enclosed, an additional frame wall is constructed several inches inside the external load-bearing wall.



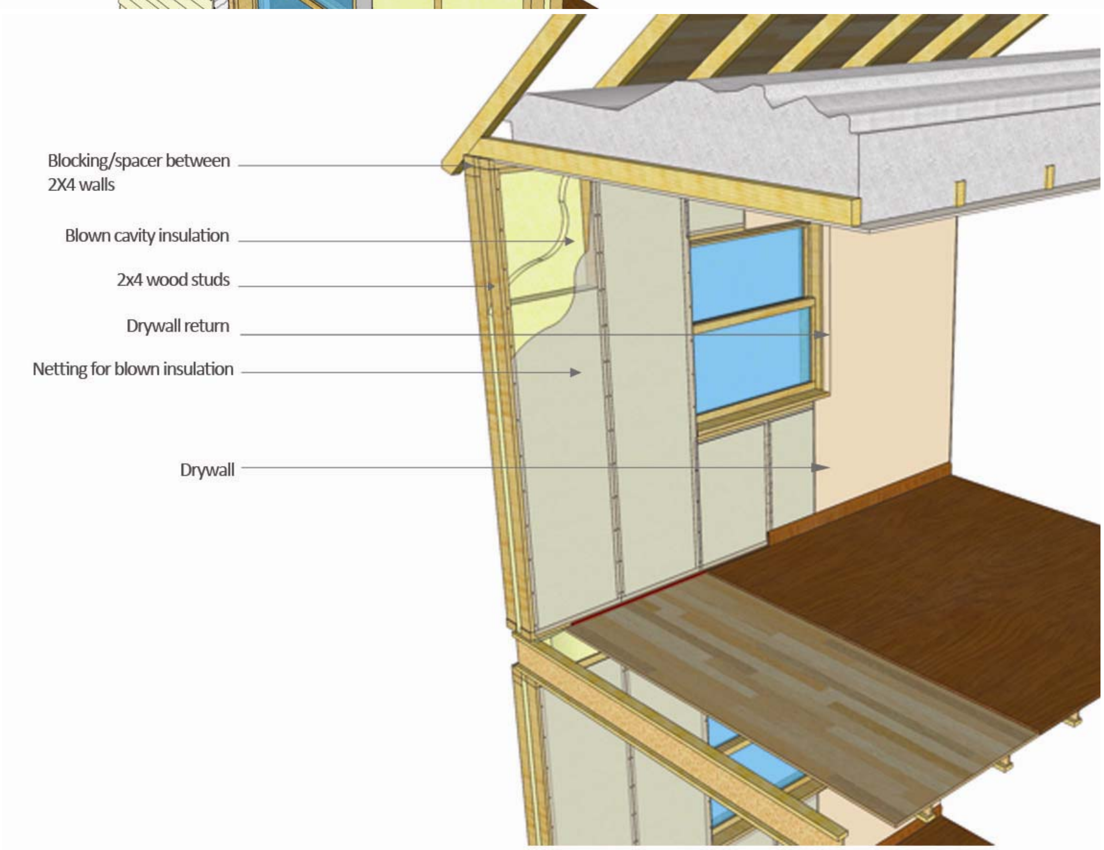


Figure 1. Simple cut-away details of double-wall construction.

This second wall can be constructed when interior framing begins; it can be constructed of 2x4 or 2x3 framing at 16” or 24” on center. Framed openings for windows and doors usually are aligned square with the openings in the exterior walls for simplicity and best thermal performance, though 45° side and top returns are also possible for aesthetic purposes (see Figure 2).

Figure 2. Windows in double walls. From the left: a framed window opening with square returns; a finished window with square returns; a finished window with 45° returns.

Electrical rough-in in double walls can be slightly simplified as wires can be laid between the two framed walls; drilling is not necessary. Electrical boxes are installed normally on the interior wall. After electrical rough-in, insulation netting or reinforced polyethylene (when a vapor retarder is required) is usually installed on the inside of the interior framing. The entire wall cavity is typically filled with blown-in fiberglass or high-density cellulose insulation.

Figure 3. Double wall before and after insulation with dense, blown cellulose.

As the gap between the two walls is filled completely with insulation, there is no thermal bridge through the wall system. TABLE 2 shows that this thermal break results in whole-wall R-values very close to nominal R-values.

TABLE 2. R-values for double walls of varying thicknesses. Values represent 2x4 framing with a 20% framing factor for both inner and outer walls. Cavity insulation R-value is 3.7 per inch.

Space Between 2x4 Walls	Total Insul. Depth	R-values [ft^{2}hr°F/Btu] Nominal	Whole-Wall
1 in	8 in	30	26
2 in	9 in	33	30
3 in	10 in	37	34
5 in	12 in	44	42

As with any high-performance wall system, air sealing is critical. Before insulating, meticulous caulking and/or foaming of exterior sheathing, top and bottom plates, penetrations, etc., is strongly advised. In lieu of this, using a thin layer (1-3") of spray foam insulation can provide the air sealing. For cost reasons, the remainder of the cavity is usually still filled with blown cellulose or fiberglass.

3.2 Structural, Durability, and Moisture Issues

To builders of conventional stick-framed homes, often one of the most appealing features of double wall systems is that there are very few new exterior details. Exterior sheathing, structural bracing, house wrap or building paper, window and door flashing, and siding attachment are usually identical to good details in conventional, framed wall systems.

While these details are very similar, there is sometimes less room for error in double-wall systems. For example, studies have documented colder temperatures of exterior sheathing which can lead to increased chances for condensation from air exfiltration (Straube 2009). Meticulous air sealing is especially important in double walls to minimize these risks.

Location of vapor retarders (or lack thereof) is also critical in double wall systems. Some double wall systems include approximately 2 inches of spray foam against the exterior sheathing before the remainder of the cavity is filled with blown cellulose or fiberglass insulation. High-density foam (2 lbm/ft^3) in this application is a class I or II vapor barrier, and modeling has shown that the inner surface of this foam can be well below the dew point of interior air (Straube 2009). For this reason, low-density, open-cell spray foam (approximately 0.5 lbm/ft^3) is recommended in this application.

Interior vapor retarders will limit wall drying capability towards the indoors. Such wall drying capability can make the wall system more forgiving in the event of moisture in the wall system (from construction, severe weather, etc.). For this reason, an interior vapor barrier is generally not recommended unless specifically required by building codes.

3.3 Implications for Builders and Trades

Framing. The additional time and material required for framing is the most significant and costly change from traditional frame construction. Because window and door openings in the inner frame wall must be carefully aligned with windows and doors, framing the interior wall can sometimes take more time than the exterior framing. Builders of double-wall homes estimate that time needed for the interior framing is 4-5 person-days for approximately 100 linear feet of exterior wall (Gadomski, 2009; Perkins 2009).

It's important to note that these homes are usually very square, and they are designed for double walls. A conventional framed home with more corners, non-right angles, and relief requires substantially more framing time and material. When using double walls, this extra framing cost is at least doubled, so designers should be very conscious of the benefit of simple home footprints.

There is wide leeway in the framing material and spacing, especially on the interior frame wall. While 2x3 framing is often proposed for cost savings, the authors have received considerable feedback that it is challenging to find 2x3 lumber that is consistently square and straight. Because of this, most builders the authors have interviewed use 2x4 framing for both exterior and interior walls.

As with more conventionally framed walls, advanced framing strategies can save material and labor. As the inner wall is not load-bearing, framing spacing can sometimes be reduced to 24" on center. With careful structural planning, framing in the exterior wall may also be reduced to 24" on center in some instances. On the inner wall, double top plates and jack studs are often not necessary (though jack studs may still be used for more consistent alignment of window openings). Two-stud corners are very simple to implement in on both the outer and inner framed wall, as no drywall is attached to the outer wall, and no exterior sheathing is attached to the inner wall.

Such advanced framing strategies are encouraged as they can certainly save framing material and labor, but because of the thermal break between the two walls, reducing framing does not dramatically increase the thermal resistance of the wall system (see TABLE 3). While studies have shown that typical framing factors in homes (with studs at 16" on center) are near 25% (Carpenter 2003), with efficient framing techniques, this framing factor can rather easily be reduced to 20%. Even lower framing factors are possible when moving to 24" stud spacing. This analysis primarily uses 20% framing factors for double wall systems. Because of the substantial thermal break between the walls, there is also very little thermal impact when inner and outer studs are aligned compared to staggered-stud configurations.

TABLE 3. Thermal effects of framing factors on double walls. Whole-wall R-values for double wall systems with 3" of insulation separating two 2x4 framed walls. Cavity insulation is R-3.7 per inch.

Framing Factor	Whole-Wall R-value [$ft^2hr°F/Btu$]
16%	35
20%	34
25%	33

Exterior Finishing and Siding. As discussed above, exterior siding and finishing of these wall systems is very similar to that of conventional framed wall systems.

Insulation. In the authors' experience, dense-blown cellulose is the most common insulation used in these assemblies. Blown fiberglass is certainly an option, and spray foam can also be used. Primarily for cost reasons, spray foam is probably best used as an air sealing tool – i.e. approximately two inches sprayed against the outside sheathing before the remainder of the cavity is filled with blown insulation.

Typical densities for dense-blown cellulose insulation in standard 2x6 framed walls are 3-3.5 lbm/ft^3. Studies have shown, however, that slightly higher densities (near 4 lbm/ft^3) may be required in the larger cavities of double walls to prevent settling (Rasmussen, 2003). TABLE 4 shows the volume and mass of cellulose insulation required for several wall assemblies.

Blown or sprayed fiberglass is considerably less dense than cellulose. To achieve a similar R-value (3.7 $ft^2hr°F/Btu$ per inch), manufacturers recommend fiberglass densities are approximately 1.0 lbm/ft^3. Because of the lower density of fiberglass – and the use of adhesive in some sprayed fiberglass systems, higher density is not required in larger wall cavities. Volume and mass of fiberglass insulation required in various wall systems is shown in TABLE 5.

TABLE 4. Approximate volume and mass of dense-blown cellulose insulation required for various wall assemblies measuring 100 linear feet by eight feet.

Wall Framing	Single 2x6	Double 2x4, 10" cavity	Double 2x4, 12" cavity
Wall Area [ft^2]	800	800	800
Insulation Density [lbm/ft^3]	3.5	4.0	4.0
Framing Factor	20%	20%	20%
Insulation Volume [ft^3]	293	573	707
Insulation Weight [lbm]	1027	2293	2827

TABLE 5. Approximate volume and mass of blown fiberglass insulation required for various wall assemblies measuring 100 linear feet by eight feet high.

Wall Framing	Single 2x6	Double 2x4, 10" cavity	Double 2x4, 12" cavity
Wall Area [ft^2]	800	800	800
Insulation Density [lbm/ft^3]	1.0	1.0	1.0
Framing Factor	20%	20%	20%
Insulation Volume [ft^3]	293	573	707
Insulation Weight [lbm]	293	573	707

Aside from the added insulation material, the time to install the blown insulation is slightly higher. However, the considerable preparation time (primarily installing netting for blown insulation) is very similar to time required when blowing a conventional framed wall. Additional time needed to insulate 800 ft^2 of a 12” double wall with dense blown cellulose (when compared to insulating a single 2x6 wall with blown cellulose) is approximately two person-hours. Total incremental insulation cost is approximately 30%; additional insulation material accounts for most of this cost (Tauer, 2009 and Perkins, 2009).

The method of blowing insulation is somewhat different than in single frame construction. Because the wall is not divided into discrete stud bays, the exterior walls for each story basically include one large insulation cavity. When using dry, dense-blown insulation, insulators typically fill this cavity by moving around the home in a circular pattern; each section of the wall is partially filled. After the walls are nearly completely filled, the insulator makes one more circuit around the home blowing through each interior stud bay until the insulation reaches the desired density (Tauer, 2009).

Venting and Wall Penetrations. When an entire story of a home has a single 9-12” wall cavity filled with insulation, adding penetrations after walls are insulated is not straightforward. In conventional frame construction, rough-in for exhaust fans, plumbing, combustion appliances, etc. are installed before insulation. In double-wall homes, careful planning for these penetrations is even more important. Some appliances require venting extensions, and all trades should be aware of the special requirements of the wall system.

Because of the single insulation cavity mentioned above (i.e. there are not discrete stud bays filled with insulation), some builders have chosen to install insulation netting around critical wall penetrations. In this way, if a vent pipe must be accessed or repaired for some reason, insulation in the entire wall is not compromised; only insulation around the penetration must be replaced (see Figure 4).

Figure 4. Insulation netting surrounds vents and plumbing penetrations in an exterior double wall. If these vents and pipes need to be accessed in the future, blown insulation in the rest of the wall need not be compromised.

Electrical. There are no significant changes that electricians need to make in double-wall homes. Electrical rough-in can be slightly simplified as drilling through studs is not necessary in exterior walls; wiring (in or outside of conduit) can be run between the two walls.

Plumbing. Aside from careful coordination of wall penetrations mentioned above, there are few - if any - changes required of plumbers in double-wall homes. As in all homes, plumbing in exterior walls should be eliminated or minimized to avoid insulation displacement and chances of pipes freezing.

Drywall. When window openings in the interior framed wall are square with windows, window returns (often drywall) are larger. Other than this size factor, however, window finishing is no different than in a 2x6 framed wall. When the interior wall is framed to allow for beveled window returns, drywall (as well as framing) requires more time.

3.4 Cost Considerations

As discussed above, the additional framing requires approximately 4-5 person-days (32-40 person-hours) for each 100 linear feet of double wall. This is rather independent of wall height, but many corners, dormers, windows, and/or doors can substantially increase this value. Labor costs vary tremendously, but using an example framer's rate of $35 per hour, additional labor cost is $1,120 - $1,400 for each 100 linear feet of wall.

The amount of exterior framing lumber needed is doubled, but this is usually somewhat offset by the exterior wall being constructed of 2x4 framing rather than 2x6 (required to meet code in most cold climates). As shown TABLE 6, using a simple 20% framing factor calculation, each 100 linear feet of an eight-foot-high double wall will require 2,560 feet of 2x4 (160 2x4x16' boards) assuming both the interior and exterior framed walls are constructed with 2x4 lumber. Approximately half of this value of 2x6 lumber (1,280 linear feet, 80 2x6x16' boards) can typically be credited to the cost of the wall system. As 2x6 framing is often significantly more expensive than 2x4 framing, increased lumber costs for double walls are much less than labor costs. A survey of several lumber suppliers in the authors' New England region showed that 2x6 framing is currently 60% more costly than 2x4 framing of the same quality and length. Example costs are shown in TABLE 6.

TABLE 6. Example framing lumber required to construct 100 linear feet of 2x6 wall and double-2x4 wall. Costs are shown as an example only; pricing varies widely over time and region. This simple analysis does not include any waste factor.

	Length of 8' Wall	Framing Factor	Framing Needed	Framing Cost per Foot	Framing Cost
Single 2x6 Wall	100 feet	20%	1280 feet	$0.40	$512
Double 2x4 Wall	100 feet	20%	2560 feet	$0.25	$640
			Net increase for Double Wall		$128

Additional savings in material are possible when 2x3 framing is used for interior walls. However, some builders have found that obtaining consistently straight 2x3 framing is not feasible.

Many of the framing-related costs – especially labor – can be managed by good building design and careful planning. These planning costs, however, may require more initial effort from the design team. Once familiar with the systems, there is not a substantial amount of additional time needed to design homes with double walls.

After framing, insulation is the largest cost of a double-wall system. Unlike framing, the main cost element is the extra insulation itself; the extra time needed to install the insulation is secondary. From working with builders of 12" double walls with blown cellulose insulation (i.e. double 2x4 walls with a 5" gap), insulation costs increase 30-40% over the cost of insulating a comparable 2x6 framed wall (Tauer 2009, Perkins 2009). For the 12" example wall system discussed here (100 linear feet by eight feet high) the recent insulation costs seen in the northeast are approximately $2,000 – compared to approximately $1,500 to insulate a 2x6 wall of the same size with blown cellulose (Tauer 2009, Perkins 2009).

While all of these costs can vary tremendously from region to region, builder to builder, and even building plan to building plan, using the examples here the total incremental construction costs for the 800-ft^2, 12" double wall system insulated with cellulose are approximately $1,900 (see TABLE 7).

TABLE 7. Approximate incremental construction costs for an example 12" double wall (100 linear feet by eight feet tall) insulated with dense blown cellulose. Costs are compared to construction of a conventional 2x6 framed wall of identical dimensions with blown cellulose.

	Approx. Cost
Framing Labor	$1,260
Framing Lumber	$128
Insulation	$500
Total	$1,888

One noteworthy feature of the costs discussed above is that the additional framing labor is by far the largest component of the incremental costs, and this item is independent of wall thickness. It is primarily the insulation cost that increases with wall thickness, and this is not a linear relationship. For example, moving from an 800-ft^2 conventional 2x6 wall insulated with blown cellulose to a nine-inch, R-30, double wall (two 2x4 walls with a 2" gap) may cost an additional $1,700; construction costs for the 12-inch, R-42 double wall example is only $200 more than the nine-inch double wall.

These costs are primary construction costs; builders may experience costs related to additional design services, larger building footprints (to accommodate thicker walls), etc., but these will vary widely and are difficult to quantify.

4 FRAMED WALLS WITH FOAM SHEATHING

4.1 Materials and Options

Another option for achieving walls which exceed R-30 is to install several inches of rigid foam board sheathing on the exterior of a conventional frame wall. Given typical construction practices, moisture concerns and availability of materials, 2x4 or 2x6 walls with blown-in insulation and 4” of extruded polystyrene (XPS) are valid high R-value options in cold climates.

The frame wall cavity insulation can consist of blown or batt fiberglass, blown cellulose, or spray foam. Because installation is typically more uniform, a spray or blown in product is recommended to achieve the highest overall wall R-value. Of the available sprayed or blown-in options, cellulose insulation has the lowest embodied energy (Cole 1996) and offers increased fire resistance (Straube 2009).

Types of rigid insulation typically recommended for this application include polyisocyanurate (polyiso, R6.5/inch), expanded polystyrene (EPS, R4/inch) and extruded polystyrene (XPS, R5/inch). Availability and climate should be considered when selecting the right rigid insulation.

These walls can be framed using 2x4 or 2x6 lumber. The following table shows whole-wall R-values for each scenario when combined with blown-in cavity insulation and 4” of XPS sheathing using 3 different framing factors. Because of the continuous insulation over the exterior of the framing, the thermal bridging from the framing becomes negligible and, therefore, the framing factor becomes much less important where the overall wall R-value is concerned. Advanced framing becomes about cost savings and material conservation as opposed to overall R-value.

TABLE 8. Nominal and whole-wall R-values for framed walls + sheathing and cavity insulation of R-3.7 per inch.

		R-values [$ft^2 hr°F/Btu$]				
		XPS	Cavity	Whole-Wall		
Wall Studs	Dim [in]			15% FF	20% FF	25% FF
2x4	3.5	20	13	34	33	33
2x6	5.5	20	20	40	39	38

Elimination of structural sheathing (OSB or plywood) and/or house wrap is a possibility when using rigid insulation, but builders must check with their local code departments for verification. Although elimination of these items would result in initial cost savings, doing so results in incorporating more advanced framing and drainage plane details and training for subcontractors, thus resulting in higher labor costs.

As with any high-performance wall system, air sealing is critical. Before insulating, meticulous caulking and/or foaming of exterior sheathing, top and bottom plates, penetrations, etc., is strongly advised.

4.2 Structural, Durability, and Moisture Issues

As noted above, the elimination of structural sheathing may be an option, but this would require the use of other methods to ensure structural stability such as let-in bracing or shear wall construction. In areas where wind loading and seismic issues are common, eliminating the structural sheathing may not be an option at all. Table R602.10.1 in the 2009 IRC lists the wall bracing options accepted for different wind loads and seismic design categories.

The elimination of structural sheathing has also resulted in home security concerns due to the ease of breaking through the wall with nothing more than a utility knife. Again, location of the project should be taken into account when considering this option.

There are multiple moisture management issues that need to be considered when constructing a wall with several inches of exterior rigid insulation. In general, the goal of moisture management is to limit moisture entering into the assembly while allowing maximum drying if water should penetrate. In cold climates, code requires a Class I or Class II vapor retarder on the warm-in-winter side of the wall assembly (IRC 2009). Should water enter the cavity, it is assumed that any necessary drying would take place to the outside. Because of its low vapor permeance, several inches of XPS could prevent this from happening and could cause moisture to be trapped in the wall cavity. To ensure that drying can occur, the interior vapor retarder should be eliminated allowing drying to the interior of the home. Recent code changes adopted in the 2009 IRC dictate that this wall assembly – 2x4 or 2x6 with 4” of rigid insulation – is not required to have a Class I or Class II vapor retarder. Class III vapor retarders (latex paint) can now be used instead of Class I or II vapor retarders if the conditions of Table R601.3.1 Class III vapor retarders are met (IRC 2009).

Installing cellulose insulation in the wall cavity further increases the moisture resistance and drying ability of the wall assembly. It has been found that cellulose cavity insulation helps to redistribute moisture, allowing for quicker drying of the structural sheathing. (Straube 2009). Since many manufacturers of cellulose insulation recommend against a vapor barrier on the warm-in-winter surface of the home, this wall assembly works well with cellulose.

Another moisture concern is the possibility of condensation on the interior side of the exterior sheathing. A well insulated wall tends to have lower temperatures at the outer surfaces because of the reduction in heat transfer from inside to outside of the home. These lower temperatures could reach the dew point of the air allowing condensation to form. Several inches of rigid insulation provides an excellent level of condensation resistance because the inside face of the exterior sheathing stays warmer than with conventional wall construction; therefore the assembly is less prone to condensation (Straube 2009).

Finally, consideration should be given to inward vapor drive which is typically caused when the sun heats up a wet surface forcing the moisture through the wall to the inside. Climate and choice of exterior wall finish have the biggest affect on inward vapor drive. A wall assembly with 4” of exterior rigid insulation has a low occurrence of inward vapor drive (Straub 2009). This would be decreased even further with an air gap between the siding and the rigid insulation. Furring strips installed outside of the rigid foam can provide this air gap while streamlining siding attachment as well.

4.3 Implications for Builders and Trades

Framing. Because of the reduced thermal bridging in this wall assembly, 2x4 wall framing can be used instead of 2x6 without compromising the overall wall R-value. Added blocking may be need for various penetrations and the builder may choose to employ advanced framing techniques, but no major changes to conventional practices are necessary.

Cavity Insulation. Cellulose and fiberglass batts have similar R-values per inch, but in practice standard installation usually results in higher R-values for blown-in insulation because of gaps and compression of poorly installed batts (Straube, 2009). Although not required, blown-in cavity insulation is recommended.

Windows & doors. One of the biggest changes from conventional frame wall construction is the framing and finishing of the window and door openings. Doors are set to the inside of the home, and extensions jambs are required to finish the opening to the exterior, tying them into the exterior trim and siding.

Windows, on the other hand, can be installed either at the plane of the exterior structural sheathing (interior mount or inset) or at the outer-most plane of the rigid insulation (exterior mount or outset). Each configuration poses its own challenges and must be flashed and tied into the drainage plane in a different way.

Windows can be attached to the house with or without mounting flanges. Inset windows require extension jambs to the exterior which are attached to the house using angle flashing. The window flashing is installed over the structural sheathing and tide into the drainage plane.

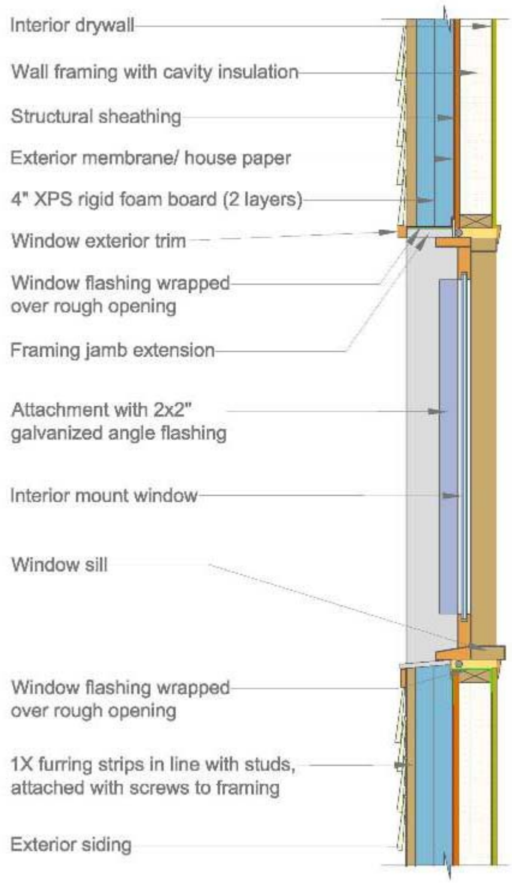


Figure 5. Detail of inset window mount.

Outset windows are attached to a window buck that has been sized to span the entire depth of the opening. Special care must be taken to tie this window into the drainage plane which is typically at the outer surface of the structural sheathing. Interior window finishing will require extension jambs or drywall returns to make up for the deeper than normal opening.

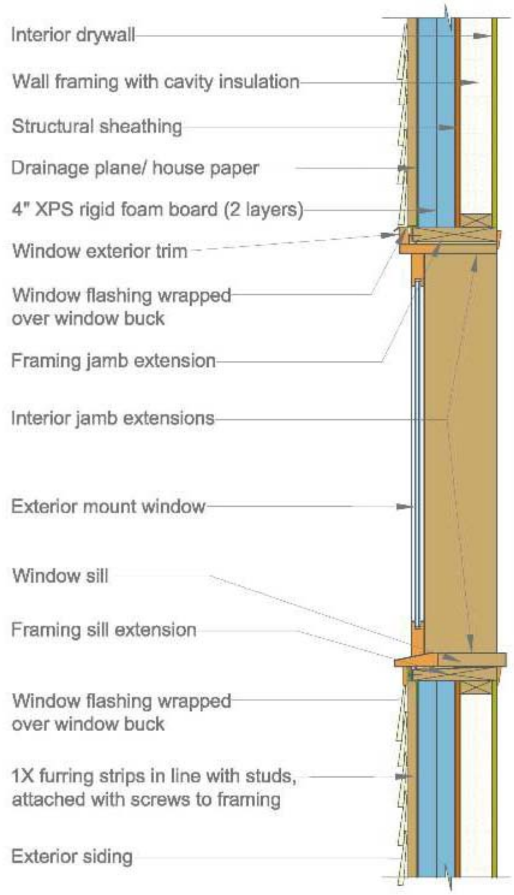


Figure 6. Detail of outset window mount.

Roof details. Another exterior finish detail affected by the addition of the rigid insulation concerns the roof wall connection. Two effective options exist. The first entails stopping the rigid insulation at the soffit and extending the attic insulation over the wall to the outside edge of the rigid as seen in Figure 8.

Figure 7. Outset window installation.

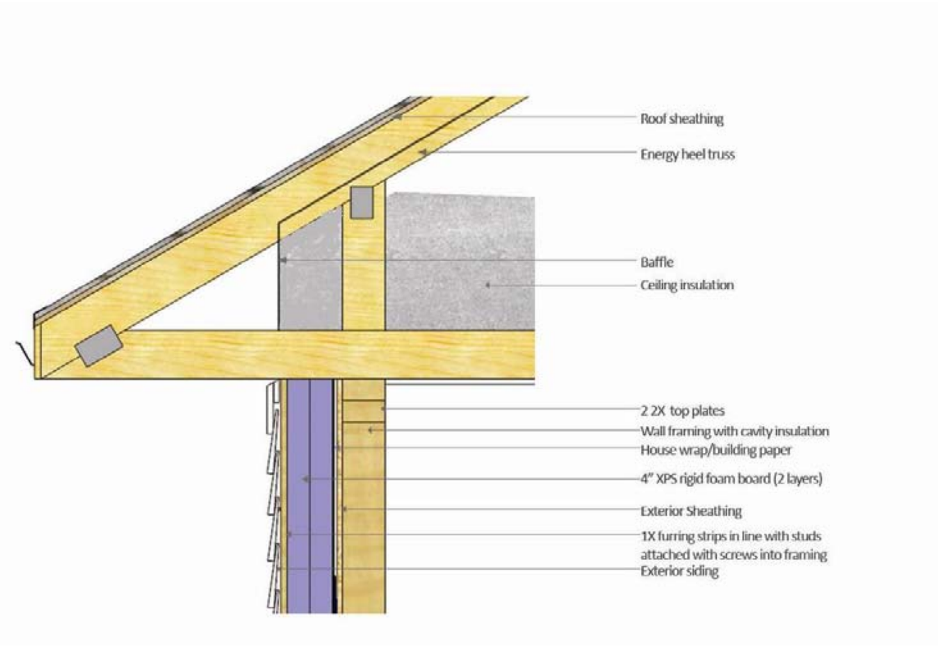


Figure 8. Detail of rigid foam stopping at soffit.

Another viable option (shown in Figure 9) involves extending the rigid insulation up past the top plate. This method may involve notching the rigid insulation around the rafter tails depending on the type of roof framing employed.

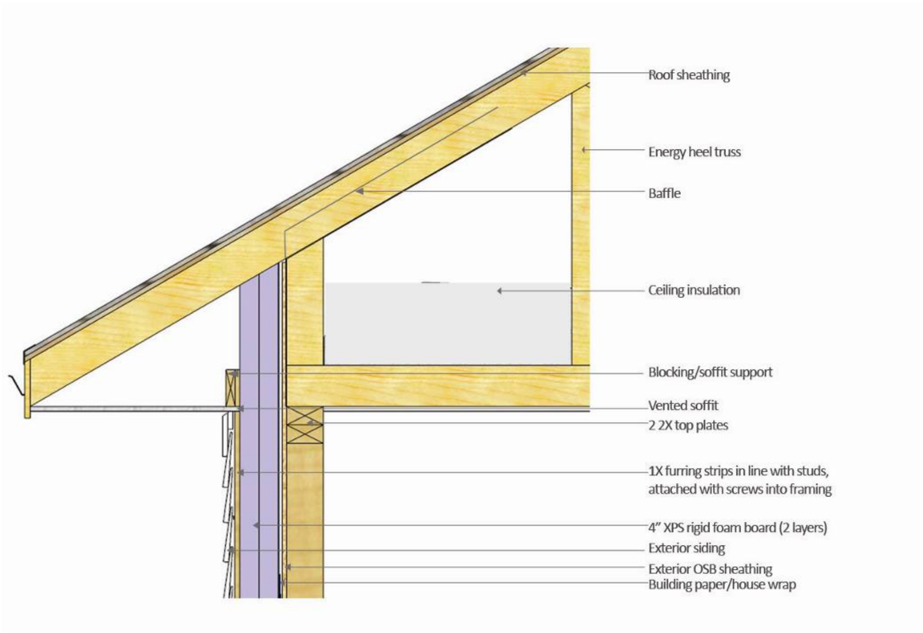


Figure 9. Detail of rigid foam extending past top plate.

Siding choices. All types of siding can be employed with this wall configuration, but adjustments to the normal installation procedure will likely be necessary. For instance, when used with brick, a wider seat on the foundation will be necessary. Cement, vinyl and wood clapboard all have requirements for spacing and fastener depth and type.

When installing cedar clapboard and shingles, an air gap is recommended behind the siding for proper drying to prevent warping and deterioration. The maximum spacing for furring is 16" on center (Western Red Cedar Lumber Association, 2007). The Western Red Cedar Lumber Association guidelines have very specific recommendations for installing their product over rigid foam sheathing including pre-finishing, the specific products that work best, and the use of building paper.

Refer to the manufacturer's recommendations for fastener type and spacing, flashing details and finishing requirements for whichever type of siding will be installed.

The cost and availability of fasteners long enough to attach furring strips and siding to the wall studs can be challenging. With 4" of rigid exterior insulation, screws as long as 6 ½ inches would be necessary assuming ½ inch structural sheathing, ¾ inch furring strips and the need to imbed the screw into the wall stud at least 1 ¼ inches. Costs for these fasteners can be as high as $0.60/fastener.

Flashing. Window header and roof step flashing can be slightly recessed into the face of the rigid insulation.

Venting & Wall Penetrations. Installing extra blocking and support at penetrations may be an extra step necessary to securely attach outside flanges, finish plates, exterior lighting, etc. The added wall depth needs to be considered as well.

Electrical. Interior electrical work is not a problem with this wall system. The framing is the same as a conventional wall system. Exterior lighting and electrical outlets should be properly blocked for stable attachment.

Plumbing. Again, there are no significant changes to interior plumbing, but extra blocking may be necessary for stable attachment of exterior plumbing fixtures such as hose bibs, vents, etc.

Drywall. Drywall returns may be needed if windows are exterior set. If advanced framing techniques are applied, then proper drywall blocking must be installed. Otherwise, there are no significant differences from conventional frame construction.

Miscellaneous. On-site storage and protection of rigid insulation is very important. Both expanded and extruded polystyrene and unfaced polyiso should be protected from UV radiation. EPS breaks easily, especially around the edges and needs to be handled with care. Foil faced polyiso needs to be protected from moisture exposure as it can warp and cup. All boards should be stored in a protected, covered location, and exposure to the elements should be minimized before the siding is installed.

Code Issues. In some areas, codes require nailing pattern inspections for the structural sheathing. When installing rigid insulation, this requires an extra inspection because the code official must perform the inspection before the rigid is installed.

As discussed earlier, eliminating the structural sheathing is an option but does require approval by local code departments. Cross bracing and other structural changes will have to be implemented if eliminating OSB/plywood.

4.4 Cost Considerations

For the reference 800-ft^2 wall, it is estimated that this wall configuration costs over $3,000 more than a conventional 2x6 frame wall with cellulose insulation; the majority of that cost comes from materials. Elimination of the OSB and advanced framing could result in a reduction in this cost, but must be evaluated based on structural requirements by location.

TABLE 9. Estimated incremental costs of foam sheathing assembly (above the cost of the reference, 800-ft^2, 2x6 wall).

	Material		Labor		
Component	# of units	$/unit	hours	$/hour	Total
Furring strips (10' boards)	110	$3.00	4	35	$470
Extruded Insulation (2x8 sheets)	100	$15.00	15	35	$2,025
Fasteners (individual)	1000	$0.60	--	--	$600
2 x 4's (board feet)	800	-$0.25	--	--	-$200
Blocking/jambs (board feet)	200	$1.00	8	35	$480
				Total Cost:	$3,375

When dealing with costs, the question of embodied energy is commonly encountered when recommending this type of assembly. The initial embodied energy in buildings refers to the energy consumed to produce and acquire the materials being used. According to a study conducted by Cole and Kernan (1996), the embodied energy in polystyrene insulation is over 30 times that of cellulose insulation on a volumetric basis. This can be reduced slightly if the R-value per inch of cellulose vs. that of polystyrene is taken into account, but it is still unquestionably more costly to produce polystyrene rigid insulation than cellulose. Very careful consideration should be given to availability of materials and the proper application of exterior rigid insulation before deciding on the right wall insulation strategy.

5 STRUCTURAL INSULATED PANELS (SIPS)

5.1 Materials and Options

Structural Insulated Panels (SIPs) represent another choice for builders seeking alternatives for R-30 (or higher) walls for single and multifamily construction. Although a substantially different system than the more typical frame construction methods also considered in this paper, SIPs can achieve equally impressive results cost-effectively if the nature of the product, its variables, and its limitations are well understood by the designer and the builder.

SIPs are a manufactured “sandwich” panel most commonly utilizing two exterior facers of oriented-strand-board (OSB) encasing a core of expanded polystyrene foam insulation (EPS). The material used for the exterior facers and the foam insulation core can vary depending on the manufacturer and the desired properties of the final wall system. Alternate insulation cores include extruded polystyrene (XPS), polyisocyanurate and polyurethane. In addition to OSB facers, some manufactures either specialize in or offer as options alternatives such as plywood, straw board, and cement board. Panels with interior gypsum board or tongue-and-groove pine boards are also available but are easily damaged during transport and set and must be treated carefully. The overall thickness of the foam core (and thus the R-value achieved) is also variable and is typically available in dimensions closely mimicking traditional framed walls. Common foam-core thicknesses are 3-1/2”, 5-1/2”, 7-3/8”, and 9-3/8”. Prescriptive code approval for SIP construction is included in Section R-613 of the 2009 International Residential Code (IRC 2009), but is limited to more conventional panels with wood structural panel facers.

The overall, nominal R-value of a SIPs wall is a function of its thickness and the type of core insulation used. Typically EPS foam is R-4 per inch, XPS is R-5 per inch, and polyisocyanurate and polyurethane are approximately R-6.5 per inch (the higher R-value cores are correspondingly more expensive). TABLE 10 shows common thicknesses and R-values for EPS SIPs, the most common type. The number of headers, posts, and other framing materials affects the whole-wall R-value. Using best practices, the R-value will usually be de-rated by approximately 7% (ORNL 1999). As TABLE 10 shows, a 10.25” EPS SIP is needed to obtain whole-wall R-values of at least 30 $ft^2hr°F/Btu$.

TABLE 10. Approximate R-values for EPS SIPs.

EPS SIP	R-values [$ft^2hr°F/Btu$]	
Thickness	Nominal	Whole-Wall
4.5"	15	14
6.5"	23	21
8.25"	31	28
10.25"	39	36

5.2 Building Design and Planning Considerations

Panel-Friendly Design. SIP’s are, as the name indicates, panels, and as such they are far more effective if the building project they are intended for has been specifically planned to be panel-friendly. What this entails generally is a building design that is simple in form without excessive jogs, bump-outs, non-90 degree angles, and where the envelope openings are planned to coordinate with panel dimensions. SIPs can be used with virtually any house design, but with a non-panel friendly plan the amount of waste, internal posts, headers and structural panel slice lumber will quickly add up diminishing the cost and performance advantage of a more optimized design.

Standard Panel Sizes. The use of standard heights is equally critical in controlling costs and minimizing waste. Since the largest panel generally available is 8’ x 24’ (based on the limits of available OSB manufacturing), horizontally placed SIPs have a maximum wall height of 96”. Correspondingly, vertically placed SIPs have a maximum width of 96”, but can be used full height to achieve 8’, 9’, or even 10’ high walls. Because of its more brittle nature, cement board SIPs are more limited in dimension than OSB SIPs, with typical sizes of 3’ x 8’, 3 x 9’, and 3’ x 10’ and are therefore always placed vertically.

Size limitations and building planning aside, higher performance and lower cost will always be achieved when using the largest practical panels for a given application. For moderate-cost housing with 8’ ceilings, a 24’ long panel provides the best value, with the least waste, splices, and connections. For taller walls, a 9’ or 10’-tall x 8’-wide panel covers the most area with the fewest pieces. Large panels do have one drawback: a crane is needed to set them due to weight considerations. Small panels can be hand set by a crew without a crane.

Custom Precut Panels. For most applications SIPs are precut at the manufacturer’s plant based on the home plans. These systems are typically automated and linked to in-house CAD departments which will create optimized panel layouts for homes. Headers, posts, openings and other features can be installed in the factory prior to shipment. The panels are then sequentially numbered (#1 being the first panel to be set, etc.), and trucked to the jobsite for assembly. Many home designs can be erected in a single day. Overly complicated designs will require more time to assemble on-site, more custom site work, and will result in more material waste.

Stock panels. For low-budget projects, stock un-cut panels are also available. These can be appropriate for very simple, rectilinear plans where on-site cutting would not be unduly time-consuming. Site cutting SIPs is not difficult but does require specialized techniques and equipment due to the panel thicknesses and their non-monolithic nature. This is particularly true for thicker panels which are required for R-30 walls.

Fire protection. Under nearly all typical residential applications a “thermal barrier” is required to cover the interior OSB surface of the SIP. Protection requirements may vary based on insulation core type, and factory installed interior surface. Cement board skinned SIPs may not require the additional covering, but specific ASTM testing, and Evaluation Service Legacy reports must confirm the acceptability of the non-protected application. The most common thermal-barrier is a ½” layer of standard joint-taped gypsum board.

Maximum Temperature Exposures. Although not normally a concern for vertical wall assemblies, SIPs have upper limits for temperature exposure based on both the limitations of the foam cores and on the adhesives used to bond the core to the skins. Above these temperatures, the core may deform diminishing the structural value of the assembly. Common not-to-exceed temperatures for OSB/EPS SIPs are usually near 160°F. Different material assemblies will have different limitations, and should be confirmed early in the planning stage. Upper temperature limit constraints can be a critical issue in SIP-roof applications in hot climates where summer time roof deck temperatures can easily surpass 160°F.

5.3 Panel Assembly

Panel Splines. Structural attachments are required at the vertical seams between panels. These panel attachments, or splines, most often take one of three configurations: OSB splines (Figure 10); 2-by splines (Figure 11); or insulated block splines (Figure 12). OSB splines, referred to by the 2009 IRC as surface splines, are simple strips of OSB placed vertically at each side of the panel joint directly against the interior side of the OSB facing. The foam cores are routed out to accept the vertical OSB strips. Screws or nails spaced at 6" on-center secure the panels together. 2-by splines are dimensional lumber inserted vertically at the panel joint with the core of each panel recessed by ¾" to accept the spline. Block splines are essentially vertical SIP posts with OSB at two opposite surfaces. The out-to-out dimension of the block spline is the same as the core of the SIP panel to be joined, with the foam SIP core recessed accordingly. The mechanical fastener spacing for the 2-by and block splines is the same as for OSB splines.

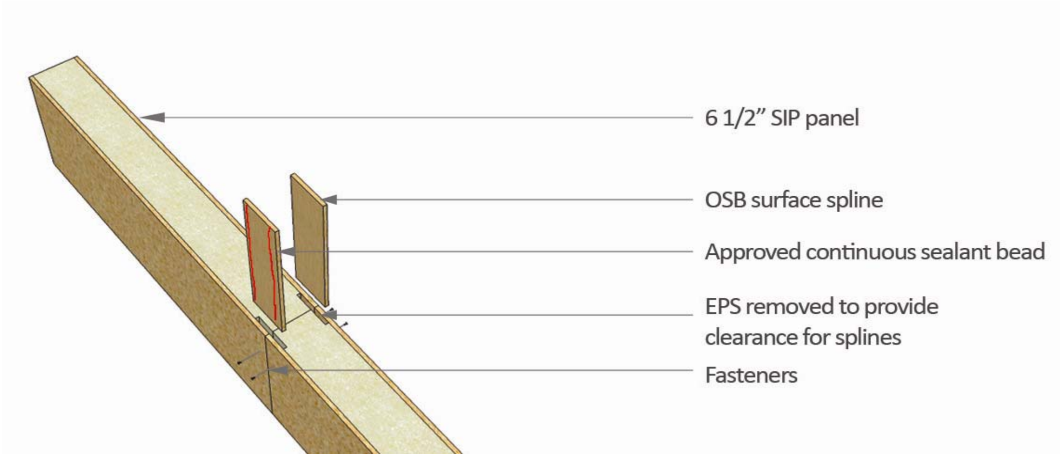


Figure 10. OSB panel splines.

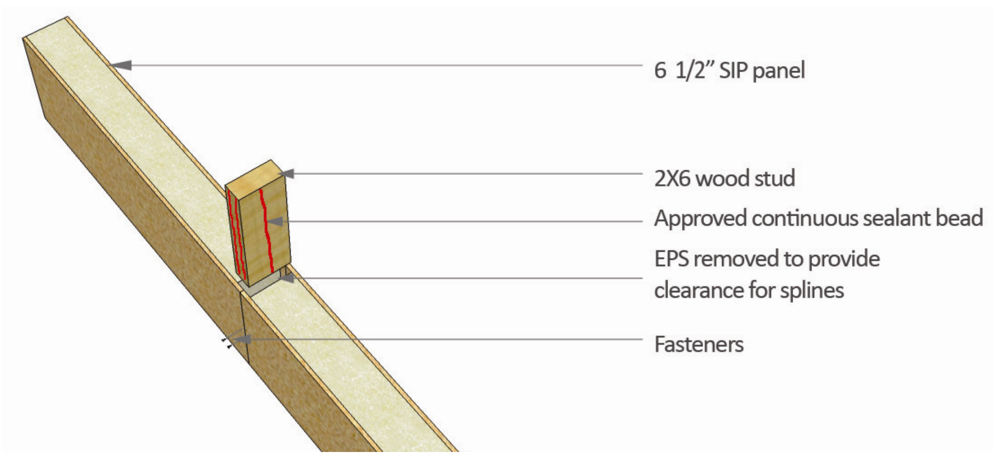


Figure 11. 2x6 stud panel spline.

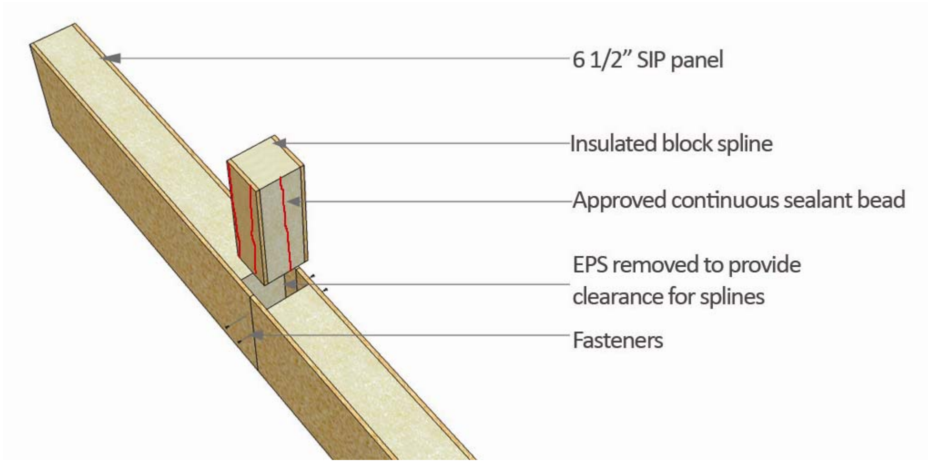


Figure 12. Insulated block spline.

Top and Bottom Plates. Inserted horizontally along the top and bottom edge of the SIP is a minimum of one 2-by plate. The bottom plate is site-installed prior to the panel being set and fastened to the slab or floor deck, with the bottom of the SIP ploughed to accept the foam-width 2-by plate. The foam-width top plate is installed at the top of the SIP wall assembly and acts to tie the top of the adjacent panels together much like a bond beam. A second full-width cap plate is then installed. Typically a 2-by member, the cap plate is secured to the top surface of the top plate and matches the full SIP thickness overlapping the facers on both sides of the panel (Figure 13). The cap plate overlaps the top plate joints at corners and overlaps non-corner top plate joints by 24”.

Structural Headers. Like with any bearing wall system, when a large opening for a door or window is planned a structural header capable of spanning that opening is required. In a SIP wall the structural requirement for given header span is exactly the same as in a comparable frame wall and expressed as pounds per lineal foot, a singular point load, or a combination of the two, and is sized to accommodate moment, deflection, and shear. Often headers in SIP walls can be 11-7/8” deep SIP panels themselves with either single or double plate enclosures top and bottom depending on loading requirements. Most manufacturers provide load and span charts for easy header selection. Section R613 of the 2009 IRC also includes a span chart for smaller spans and common loading conditions. More substantial loads or longer spans require custom built-up headers similar to frame construction.

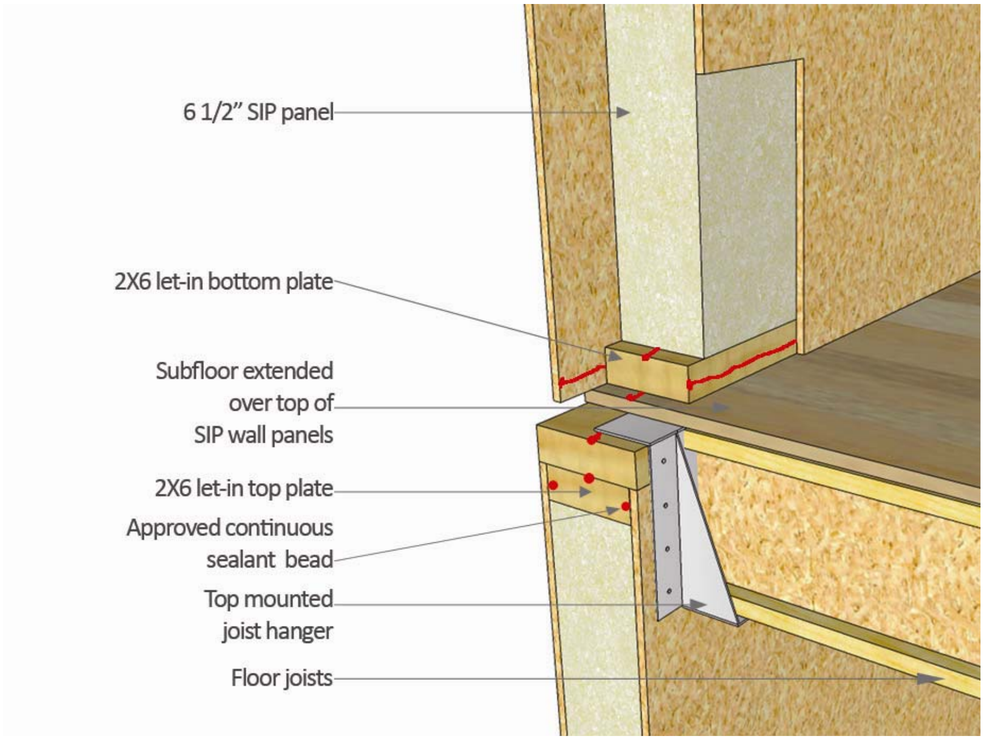


Figure 13. Plate detail for SIPs.

Posts. As a structural concept, SIPs are ideal for supporting uniformly distributed loads but may need additional structure when supporting point loads such as the ends of headers. Inserting a post is similar to installing a dimensional lumber panel spline in that solid lumber is most common and that the post needs to occur at the edge of a panel. Small loads can sometimes be adequately handled by a single post, with larger loads requiring a double or even triple 2-by post. Where two panels are joined together at inside or outside corners, an "L" shaped post will occur with additional supports typically not needed.

Assembly and Air Sealing. Precut panels are numbered and set sequentially. Following installation of the bottom plate, each panel is placed and secured with either nails, long screws, or both. Critical during this operation is the application of adhesive caulk and sealant at all lineal panel-to-sill connections, and spline to panel connections. Manufacturer recommendations vary somewhat, but should be closely followed for each specific product. Typically, a continuous adhesive caulk bead is applied to the inside and outside top edges of the plate, and a continuous adhesive caulk bead or foam sealant bead is applied on the top surface of the plate. For wide plates (larger than 5-1/2") two spaced continuous beads should be applied. The primary purpose of this step is air-sealing. Even though SIP's are generally considered to be inherently air-tight, short-cutting this step will lead to a leaky building and even a potentially catastrophic failure. One such failure has been documented in a Juneau, Alaskan community where air-leakage at roof panel joints caused condensation and subsequent decay to the OSB roof deck; ultimately this required significant repair (Lstiburek 2002). Many SIP manufacturers now recommend a specialized surface-sealing tape also be used at roof panel joints. Installing contiguous panels requires the same caulking and air-sealing in the vertical plane to assure an air-tight seal between panels, but techniques will vary by type of spline utilized.

When installing SIPs it is equally important to assure a snug fit between panels and other frame elements. Failure to do so will result in gaps between foam cores and infill elements compromising air-tightness and thermal performance. If potential gaps are identified during panel set, spray foam can be used during assembly to fill expected voids.

Figure 14. Wall SIPs being set on a small home.

5.4 Structural Considerations

SIPs use a significantly different structural concept than traditional wood frame buildings. Whereas wood frame construction is really a refinement of the ancient practice of post-and-beam construction using many small posts in lieu of a few large ones, SIPs are, in theory, a structural diaphragm capable of supporting a lineal continuous load without the benefit of posts. The vertical axial loads are instead transmitted uniformly across the top surface of the SIP and transmitted downward through the structural skins. The foam insulation cores act to hold the skins apart and in a constant vertical plane without significant bending. If the skins can be kept braced in the vertical position the limiting factor becomes the compressive strength of the structural skins. Most manufacturers provide load charts for the prescriptive design of SIP wall systems in typical residential applications. Addition prescriptive sizing information is provided in Section R613 of the 2009 IRC.

In reality SIP homes are a combination of panel-diaphragm loading and concentrated point loading. Each time the continuity of the panel surface is interrupted, such as with a large window opening, or if a point load is imposed from above, the point load will exceed the compressive strength of the area on which it is bearing, and a structural post will be required. Because structural posts inserted into SIP walls are fully braced with respect to their lesser dimension, the capacity of a given post will be higher in a SIP wall than in standard frame construction.

SIP buildings can achieve exceptional levels of lateral strength, and are therefore an excellent fit for rigorous applications such as hurricane or seismic risk zones. Even though the basic concept of SIP walls is compatible with high lateral loading, the building design must be configured to take advantage of those strengths. As with any wall system, there is no substitute for advanced planning in achieving the desired result.

5.5 Durability and Moisture Considerations

SIP buildings, taken to their most efficient configurations, will rely on the diaphragm action of the interior and exterior facings for most axial loading. This reliance on the structural facings means that, unlike typical frame walls, a built-in vertical load redundancy does not exist. If the facings are compromised, so is the structural capacity of the entire wall system. For this reason, appropriate material selections and proper detailing for moisture control are paramount. Bulk water and moisture vapor control are critical considerations especially in climates with significant rainfall. Drainage planes, weather resistive barriers, flashings, siding and trim, exterior caulk, and exterior mounted accessories and wall penetrations all require consideration in both planning and execution.

Protection from insects and wood-destroying-organisms is also essential, as it is with typical frame construction. The normal best-practices for both methods are essentially the same including borate treated assemblies in high-risk areas, and elevate wood components away from grade and other moisture collecting surfaces.

5.6 Implications for Builders and Trades

Conceptually and physically, a SIP building is considerably different from a conventional frame building, and assembling and finishing a SIP building does require some additional knowledge and skills. The variance in skills required is small, however, and basic frame construction skills translate easily to SIP construction. With a minimal learning curve a trained framing crew will be conversant in SIP construction in a few days. Nearly all the materials and tools are the same, and any required new methods, tools and techniques are variations on familiar tools and skill sets.

Wiring. Installing electrical boxes and running wiring in the exterior walls of SIP homes is significantly different than in standard frame homes. The SIP industry, however, has developed wiring methods which are production friendly and, with minimal training, easily understood and adopted by the electrical trades. Typically, 1-1/2” horizontal and vertical wire chases are cored into the foam insulation at the time of panel manufacture. These horizontal chases are placed at 16” for outlets, and 44” for switches. Vertical chases are placed as required during the panel layout drawings to conform to the requirements of the plan. Major horizontal runs may also be run through the floor framing above or below the SIP wall with local vertical and branch horizontal runs extending to the wall devices. Plates and dimensional lumber splines must be site-drilled to align with the foam core chases. Electrical boxes are secured to the OSB skins with surface type fasteners with box locations just offset from chases so as to not block chase runs. The hole cut for the box should be just large enough to receive the box. After wiring, the gap between the box and the OSB skin should be sealed.

Plumbing. Since all plumbing is discouraged in exterior walls, especially in very-high performance homes, no changes to standard practice are required for a home with SIP walls.

Finishing and Siding. Being continuously sheathed with wood structural panels, a continuous attachment surface is provided for a variety of standard residential sidings and trims. Appropriate siding materials include wood, fiber-cement, and vinyl. Reservoir sidings (those that can hold moisture) require additional scrutiny in order to keep the exterior facing dry. All wood should be back-primed, and the choice of weather-resistive-barrier should be carefully considered to avoid moisture drive and subsequent wetting of the OSB. Brick veneer assemblies over house wrap are also especially susceptible to vapor drive wetting of the structural sheathing. Weather protective material selections, detailing, and execution of these assemblies are essential.

As with the other R-30 wall systems considered in this paper, the wall thickness is increased relative to standard construction. With SIPs, the position of the exterior structural sheathing is the same as standard construction; the increased dimension occurs toward the home’s interior. This results in window and door attachments, and trim and siding details remaining basically unchanged from standard practice. Deeper window and door jamb extension will be needed on the interior to accommodate the increase in wall thickness.

5.7 Code Issues

The inclusion of prescriptive language for SIP buildings in the IRC code is a big step forward for understanding the system for both builders and code officials. Although the 2009 IRC code is new and not universally adopted, it does provide a useful template for understanding what the code officials will look for when inspecting SIP buildings. Structural panel attachments, fastener spacing, cap plates, cutting and notching, headers and other considerations are addressed and will require visual inspection for approval. As such these components must be available for visual verification or somehow documented to the satisfaction of the inspector. Prior to more widespread adoption of the latest IRC code, additional engineering analysis may be required for more complicated plans or in particular risk zones or jurisdictions.

5.8 Cost Considerations

SIP construction can be directly competitive with frame construction, especially when compared to other high-performance R-30 wall systems. The extent of changes required in SIP construction to achieve R-30 is less than the changes required to achieve R-30 in hybrid frame wall systems. The largest changed require is the thickness of the panel and associated accessories. Thicker panels will require higher shipping costs because they take up more room. Weight is not a significant factor as the largest contributor to weight (the OSB) remains the same. The larger panels will require some additional increment of time to set, but not a substantial increment. Beyond the learning curve for the electrician, wiring a SIP home is comparable to wiring a frame home, so once trained no additional cost should be anticipated.

The walls of a simple SIP home can be set by a trained crew in a single day. Increasing the wall thickness to 8-1/4" or 10-1/4" will not significantly alter framing time, and therefore it will not extensively add too labor costs. Additional material cost will be incurred due to the additional foam core material utilized and the larger plates and posts.

An approximate installed cost for the 8-1/4" SIP wall, including lumber, sealants and labor is $6.40 per square foot; a 10-1/4" EPS SIP wall of the same area would cost approximately $7.40 per square foot (LeRoy 2009). TABLE 11 shows incremental costs for the reference wall of $1,500-$2,500 range. As in all cost examples presented, costs can vary tremendously with region, material prices, and expertise and builders and trades.

TABLE 11. Approximate installed costs for SIP walls. The reference wall is 100 linear feet, 8 feet tall.

Wall System	Whole-Wall R-value [$ft^2hr°F/Btu$]	Installed Cost	Incremental Cost
2x6 Frame Wall	17	$3,662	-
8.25" SIP	28	$5,120	$1,458
10.25" SIP	36	$5,920	$2,258

6 DISCUSSION AND CONCLUSIONS

6.1 Double Walls

One major appeal of double wall systems is that framing, sheathing, window and door installation, flashing, and siding practices are very similar – if not identical – to construction practices in conventional framed homes. The primary construction cost is the extra labor for constructing the second frame wall. As this cost is not related to wall thickness, there is often not a tremendous cost difference when building a 12-inch double wall over a nine-inch double wall. While costs can vary tremendously, authors believe that an incremental cost range of

$1,500 - $2,500 may be reasonable when comparing 800 ft^2 of double wall to 800 ft^2 of the baseline 2x6 wall.

Planning for double walls is key, and complicated or convoluted building designs (many angles, curves, irregular dimensions, dormers, etc.) can dramatically increase the time and cost of double wall systems.

6.2 Exterior Foam Sheathing

Constructing a wall using several inches of rigid insulation is one method of achieving an R-value of 30 or higher. When constructed using 2x4 lumber, blown-in cellulose insulation, 4" of XPS and a vented cladding system, the result is a highly efficient, durable wall system.

When compared to a conventional, 2x6 wall with cellulose insulation, the pro's of this wall system include:

- No training for advanced framing techniques
- Lower cost of 2x4 lumber
- Reduced condensation potential
- Good drying potential (when no interior vapor barrier is installed)

The con's include:

- Added cost for XPS – material, installation
- Added cost for furring – material, installation
- Added cost for finishing window and door openings – material, installation
- High embodied cost of XPS

While costs for the system can vary tremendously, in the example described here incremental costs for the 800-ft^2 example wall are between $3000 and $3500 (when compared to the conventional 2x6 wall).

6.3 SIPs

Structural Insulated Panels (SIPs) are a viable option for achieving R-30 wall assemblies for high performance housing in North America. With skilled contractors working with well-designed homes, advantages over conventional wood frame construction including speed of assembly and inherent air-tightness. One of the main drawbacks of SIP construction (among the wall systems discussed here) is that it is very different from conventional frame construction. However, many builders and contractors who have become familiar with SIP construction feel that the dramatic increase in speed of construction – especially the time needed to enclose a building – offers net cost savings. As code requirements increase and the demand for higher performance homes grows, SIP construction will likely gain additional market share.

Going from a standard 4-1/2" SIP wall to an 8-1/4" SIP wall is an incremental change requiring few changes from current SIP standard practice, while yielding significant thermal benefits. The largest difference is the amount of foam insulation, which leads directly to the benefit we seek. Initial planning of the home is critical in taking advantage of SIP construction benefits. Simple rectilinear forms are preferred, while irregular, complicated building designs will quickly erode potential cost benefits. When compared to the reference 800-ft^2, 2x6 wall, incremental costs for a simple 8-1/4" SIP wall may be approximately $1,500; a 10-1/4" SIP wall may cost approximately $2,250 more than the reference frame wall.

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8 REFERENCES

Benesh, I. 2009. Remote, A Manual. Cold Climate Housing Research Center (CCHRC).

BERC - Whole-Wall R-Value Explained. Oak Ridge National Laboratory (ORNL). May 26, 2004. November 2, 2009. <http://www.ornl.gov/sci/roofs%2Bwalls/whole_wall/rvalue.html>

Carpenter S.C. Schumacher C. 2003. "Characterization of Framing Factors for Wood-Framed Low-Rise Residential Buildings" ASHRAE Transactions. Vol. 109, Pt. 1 (February), pp. 101-108.

Cole, R. J. & Kernan, P. C. (1996). Life-Cycle Energy Use in Office Buildings**.** *Building and Environment*, Vol. 31, No. 4, 1996. pp. 307 – 317

Gadomski, Stanley. Lead carpenter, Rural Development, Inc. Personal conversation. October 2009.

International Code Council, Inc. 2009. International Residential Code for One and Two-Family Dwellings.

LeRoy, J. Panel Pros, Inc. Personal conversation. October 2009.

Lstiburek, J. 2005. Guide to Insulating Sheathing. Building Science Press.

Perkins, Anne. Director of Homeownership Programs, Rural Development, Inc. Personal conversation. October 2009.

Rasmussen, T. V. 2003. "Verification of density predicted for prevention of settling of loose-fill cellulose insulation in walls." Journal of Thermal Envelope and Building Science. Vol. 27, No. 1 (July), pp. 49-69.

Straube, J. and J. Smegal. 2009. Building America Special Research Project: High-R Walls Case Study Analysis. Somerville, MA: Building Science Corporation.

Tauer, Jonathan. President, Celluspray Insulation. Personal conversation. October 2009.

Western Red Cedar Lumber Association. 2007. How to Install Western Red Cedar Siding. www.wrcla.org.

9 BIBLIOGRAPHY

Benesh, I. 2009. Remote, A Manual. Cold Climate Housing Research Center (CCHRC).

Canadian Architects. 2008. Measures of Sustainability. http://www.canadianarchitect.com/asf/perspectives_sustainibility/measures_of_sustainablity/measures_of_sustainablity_embodied.htm

Cedar Shake & Shingle Bureau. 2004. Exterior and Interior Wall Manual. www.cedarbureau.org.

Cole, R. J. and Kernan, P. C. (1996). Life-Cycle Energy Use in Office Buildings**.** *Building and Environment*, Vol. 31, No. 4, 1996. pp. 307 – 317

International Code Council, Inc. 2009. International Residential Code for One and Two-Family Dwellings.

Kosney, J., Christain,j., Desjarles, A. June 4, 1999. "Whole Wall Rating/Label for Structural Insulated Panels: Steady State Thermal Analysis".

Lstiburek, J. 2005. Guide to Insulating Sheathing. Building Science Press.

NAHB Research Center. 2008. Code Issues that Limit Innovative Systems, Deliverable Number 4.D.1. Upper Marlborough, MD. U.S. DOE Building America Program.

SIPA 120908-10 Listing Report 2009-08025. NTA , INC., 305 North Oakland Avenue, Nappanee, IN Issue/Revision Date 8/25/2009

Straube, J., J. Smegal. 2009. Building America Special Research Project: High-R Walls Case Study Analysis. Building Science Press.

U.S. Department of Energy, Office of Building Technology. 2000. Technology Fact Sheet: Wall Insulation.

Western Red Cedar Lumber Association. 2007. How to Install Western Red Cedar Siding. www.wrcla.org.