1. PROJECT 1: HIGH R-VALUE ENCLOSURES

1.1 Executive Summary

High R-value Enclosures Overview

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

The research detailed in this report is divided into four parts:

A. Theoretical Background
B. Prediction: Modeling and Analysis
C. Measurement
D. Implementation

BSC is pursuing research activities in each of these parts simultaneously in a variety of subprojects. The following report discusses theoretical work done to explore the influence of air infitration/exfiltration on thermal performance, and a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommends appropriate R-values for these components in cold climates.

Under Part B: Prediction: Modeling and Analysis, a thermal performance and durability assessment has been completed on a list of wall assemblies and similar work has been started on foundation, roofs and retrofit assemblies.

In FY09, no physical measurements of high R-value enclosure proposals were completed but BSC did conduct a review of the commissioning and calibration of a precision guarded hot box built to the specifications outlined by John Straube's 2008 paper "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls". It is expected that this equipment will be able to provide specific measurements of large-scale wall assemblies under a range of temperature and air pressure gradients. BSC will observe and report on the results of this work.

In the "Implementation" category, BSC has completed a set of high R-value wall assembly drawings, including details for window and door installation and the treatment of common enclosure penetrations. Similar recommendations for foundations, roofs, and retrofit details have been proposed and are under internal review as further analysis is conducted.

The approach for the remainder of this multi-year plan will be to complete the review of the review of the remaining enclosure details and to continue to explore factors that degrade thermal performance in common construction assemblies and new materials and methods that seem likely to offer additional options for high R-value construction.

Key Results

BSC has produced final recommendations for six high R-value wall assemblies, including details for windows, doors and enclosure penetrations. These recommendations are accompanied by building science notes on thermal performance, durability, cost and constructability, presented as two-page illustrated case studies. In addition, BSC is reviewing and analyzing details for high R-value foundation, roof and retrofit assemblies. These work products are supported by fundamental research into the thermal performance of materials and systems, as well as the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions that influence thermal performance.

Gate Status

A complete response to each of the Stage Gate Criteria is given in Section 1.3 of this report. Table 1 below provides a brief summary.

Table 1: Stage Gate Status Summary

"Must Meet" Gate Criteria	Status	Summary
Source Energy Savings and Whole Building Benefits	Pass	High R-value enclosures provide significant source energy savings and whole building benefits. BSC's research work aims to establish a set of recommended assemblies for that have approximately 50% greater thermal resistance under installed conditions. The work to date has demonstrated this for Cold Climate walls and has produced promising results for foundation, roof and retrofit assemblies.
Performance-based Code Approval	Pass	All of the high R-value enclosure recommendations detailed under Part D: Implementation meet performance-based safety, health and building code requirements. We consider these enclosure assemblies ready for deployment in prototype research houses. Some BSC prototype houses have employed recommended enclosure assemblies in FY09. Further examination of some code-related issues is expected in FY10.

"Should Meet" Gate Criteria	Status	Summary
Prescriptive-based Code Approval	Partial Pass	Some of the enclosure assemblies have not yet been fully reviewed and do not meet all prescriptive requirements. However, the recommended high R-value wall assemblies detailed under Part D: Implementation have completed internal review and meet prescriptive safety, health and building code requirements for use in new homes, with some restrictions on cladding types and applicable wind zones.
Cost Advantage	Pass	Both the recommended High R-value wall assemblies and the roof, foundation, and retrofit assemblies still under review, provide strong potential for cost benefits relative to current systems when considered as part of the whole building. All of the assemblies developed for this research project have undergone a detailed thermal performance analysis. The assessment is intended to increase our understanding of physical characteristics (such as thermal bridging, susceptibility to convective air looping, resistance to infiltration/exfiltration, etc.) that degrade the performance of the assemblies. We have selected assemblies for our recommended list that will perform as close as possible to the nominal R-value of the insulating materials used – thereby providing the "best value" compared to similar wall assemblies designed and constructed in a manner that results in poorer performance.
Reliability Advantage	Pass	Where possible, BSC has developed high R-value enclosure recommendations that are based on conventional technologies and existing products that offer the level of reliability that would be expected from assemblies with lower thermal performance. Durability assessments have be finished for wall assemblies and are being conducted for roof, foundation and retrofit assemblies, with the goal of providing recommended assemblies that both substantially increase the thermal performance of the enclosure and have less risk of moisture-related problems.
Manufacturer/Supplier/Builder Commitment	Pass	BSC has found that there is generally strong support for this research from both manufacturers and builders. There are some supply issues that have been identified as new enclosure assemblies are developed. Long shank screws suitable for the attachment of thick insulating sheathing, for example, were not found to be available "over-the-counter" at typical residential building supply stores, but were easily sourced in most locations from commercial roofing suppliers. We anticipate that supply issues such as these will be resolved an high R-value enclosures are more widely deployed.

Gaps Analysis	Pass	More detail will be added to our analysis of the major technical and market barriers as research work progresses. However, this research project has already identified a number of important barriers that must be addressed: - Attachment of various cladding materials over insulating sheathing. - Fire-testing of high R-value assemblies with foam sheathing. - Use of combustible foam insulation in exposed applications. - Wind design requirements impact high R-value construction. - Understanding the influence of airflow on heat transfer.

Conclusions

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

In addition, other whole building benefits will be realized with the development of high R-value enclosure technology. In particular, homeowners will benefit from increased thermal comfort (through better control of surface temperatures), homes that are quieter on both the inside and the outside (better sound insulation and airtightness), homes that can be heated or cooled with smaller, more efficient mechanical equipment (reduced enclosure loads and reduction of perimeter cold spots), and buildings that are more durable and healthier than houses typically built today (improved water management, resistance to interstitial condensation, and “vapor open” assemblies).

1.2 Research Plan Overview and Sub-Project Reports

1.2.1. Research Plan

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

Previous work has identified a combination of advanced wood framing, insulating sheathing, spray applied cavity insulation and "smart" membranes as the best approach to meet this mid term target.

The practical limitation in wall assemblies is the wood frame thickness of 5.5 inches (the width of a 2x6). Insulating sheathing thickness is currently limited by constructability issues to 2 inches. Thus, at present, the most commercially viable high thermal resistance wall assembly is a 2x6 wood framed wall with up to 2 inches of insulating sheathing.

The practical limitation in roof assemblies is typically the thickness of the top chord of wood trusses (also 5.5 inches – a top chord of 2x6 which is "pushing" cost and performance limits and requires "re-engineering" as the truss assembly is no longer optimized for strength, but optimized for both strength and "insulatability" – the ease and ability to insulate truss members.

In hot humid climates in flood zones, elevated crawlspaces are the most practical construction approach. Crawlspace construction, particularly vented crawlspace construction provides significant challenges with respect to moisture control, insect and vermin control and fire control. Use of insulating sheathing and spray foams are desirable in these assemblies, but the moisture physics and performance of these approaches has yet to be determined.

In order to improve the thermal performance of these assemblies the cavity insulation values have to be improved/increased. The most commercially viable technology to improve the performance of cavity insulation is the use of spray-applied insulations: spray-applied foam insulation, spray-applied cellulose insulation and spray-applied fiberglass insulation.

Spray insulations have numerous advantages that make it attractive to many custom builders.

They can fill any shape cavity without cutting; some systems (i.e. spray foams) provide air sealing as part of the insulation process; and they can provide high R-value per inch. Higher costs for spray insulations typically limit their use in production and affordable housing. Eliminating exterior structural sheathing can offset some of the extra cost of spray insulations.

As thermal resistance increases, heat flow across the assembly decreases. This is a desirable result from the perspective of energy efficiency. However, it is a liability from the perspective of durability. As the thermal resistance of building enclosures increases the ability of the assemblies to dry decreases. This has lead to an unfortunate linkage between mold, decay and high levels of thermal resistance.

It has been clear that if drying potentials decrease due to increases in thermal resistance, some other means of increasing drying potentials must be provided. Additionally, decreasing wetting potentials must also be provided.

The more vapor open (permeable) the interior and exterior linings of building enclosures, the greater the drying potential of the building enclosures. Installing interior vapor barriers that prevent inward drying is a serious problem that was identified by the work done on moisture control and high-R assemblies.

Additionally, insulating sheathings were identified as one of the most cost effective means of significantly increasing the thermal resistance of building enclosures. However, most insulating sheathings have low vapor permeance and inhibit outward drying. Hence, the ability to dry inwards is a critical requirement for the use of insulating sheathing. Developing vapor open insulating sheathings and vapor open/vapor closed “smart interior linings” are necessary.

Combining all of these differing materials in an integrated manner that is commercially viable – i.e. constructible and affordable with standard trades is the focus of this research project.

The research plan is divided into four phases:

E. Theoretical Background

F. Prediction: Modeling and Analysis

G. Measurement

H. Implementation

Sub-projects have been planned in each of the four phases, some of which run throughout this multi-year plan. The following sections of this report provide a summary of past work complete in each phase, a full report on work completed or in progress during the 2009 calendar year, and planned future research.

Research Partners

Industry Partners participating in this project are:

- Dow Chemical (Material Supplier/Manufacturer)
- Honeywell (Material Supplier/Manufacturer)
- DuPont (Material Supplier/Manufacturer)
- Huber (Material Supplier/Manufacturer)
- US GreenFiber (Material Supplier/Manufacturer)
- Icynene® (Material Supplier/Manufacturer)
- Cosella Dorken (Material Supplier/Manufacturer)
- Georgia Pacific (Material Supplier/Manufacturer)
- Johns Manville (Material Supplier/Manufacturer)
- Owens Corning (Material Supplier/Manufacturer)
- Tamlyn (Material Supplier/Manufacturer)
- Zeta Homes – San Francisco, CA (Builder Partner)
- David Weekley Homes, TX, SC and NC (Builder Partner)

- Synergy Construction, MA (Builder Partner)
- GreenCraft Homes, TX (Builder Partner)
- Nelson Homes, CT (Builder Partner)
- Ark Contractors, CT (Builder Partner)
- Moser Builders, PA (Builder Partner)
- Colter Construction, DE (Builder Partner)
- TKTMJ Construction - "Project Home Again", LA (Builder Partner)

1.2.2. A. Theoretical Background

Phase 'A' projects establish the theoretical background for sub-projects in subsequent phases. In past years, several research papers have been completed. Here is a summary of the past work done under this phase of the research plan:

1. Straube, John F. "Review of the R-value as a Metric for High Thermal Performance Building Enclosures" Completed December 2007.

   Abstract: The report summarizes the extensive existing research of heat flow through walls and highlighted physical mechanisms that are not usually included in codes and designer specifications. From this review, a need was identified for measuring and rating heat flow across a wall under realistic temperature ranges, both cold exterior and hot exterior conditions. The impact of thermal bridging, and convective loops, although well understood, has not been sufficiently well quantified to allow for prediction. Air exfiltration through walls can have a major impact on heat flow, and was identified as a major unquantified heat flow mechanism in current testing.

2. Straube, John F. "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls" Completed December 2008.

   Abstract: The goal of this work is the development of a new metric for the thermal performance of building enclosures that better accounts for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions. The metric will employ equipment and techniques based on existing ASTM procedures as much as practical. The new metric is intended to represent actual thermal performance of building enclosure systems in service and will enable marketing staff to make legitimate claims about systems; designers to make informed decisions and accurate load calculations; and builders and contractors to reduce callbacks due to moisture and comfort issues associated with poor thermal performance.

1.2.2.1. Influence of Air Flow on Heat Loss in High R-value Enclosures

This report investigates the role of airflow in heat transfer through high R-value building enclosures, particularly the effects of airflow that are not captured by blower test data converted to heat loss. John Straube discusses air tightness standards for assemblies and enclosures and examines airflow's contribution as a percentage of total thermal performance. Studies involving field and laboratory measurements are then reviewed and it is noted that although many air flow-related influences have been studied, few have been documented in sufficient detail to reliably quantify the affect on thermal performance.

Other flow paths are considered and it is observed that as the R-value of an assembly increases (to R-20 or R-40) even small flows can begin to comprise a significant proportion of total heat loss. Natural convection inside the wall assembly and around cavity insulation is examined as a significant contributor to heat loss in high R-value assemblies. Wind washing of air permeable insulation is also considered and explained.

The following conclusions and recommendations are made:

Implications for High R-value Assemblies

The influence of airflow within and through building enclosures on heat transfer is significant, much more significant than for standard enclosures. For many high R-value walls, basements, and roofs the proportion of heat flow due to airflow effects increases as R-value increases. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored.

Higher airtightness standards for both whole buildings and assemblies need to be imposed for high R-value enclosures. Airtightness targets that approach 1.0 l/s/m2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

The interaction of airflow and heat transfer is poorly understood. There appears to be a real impact, and for accurate assessments heat flow due to conduction and heat flow due to through-enclosure convection cannot simply be added. However, the precise interaction has not been experimentally quantified and is likely in the order of more than 10% impact for high R enclosures.

Airflow within enclosures influence heat flow in all walls. However, small defects and a limited amount of wind washing can be tolerated in enclosures with R-values of 10 to 20 without serious reductions in performance. For high R-value enclosures, even small, perhaps even unavoidable defects, can begin to have a more significant influence on heat flow for high R-value enclosures. Hence, techniques to reduce the impact of these mechanisms need to be implemented. For example, the use of wind washing barriers, multiple layers of insulation and insulation with higher resistance to airflow may be required.

Final report (see appendix):

- Straube, John F. "Influence of Air Flow on Heat Loss in High R-value Enclosures" December 2009.

1.2.2.2. Heat Losses Below Grade in Low Energy Buildings

This report documents a literature survey of predictions and measurements of below-grade heat loss through slabs and basement walls, as well as recommends appropriate R-values for these components in cold climates (DOE Climate Zones 5 and higher). Methods of prediction of heat loss through slabs are examined and found to be notoriously inaccurate. Field data from several studies is then reviewed and used to develop a better understanding of below slab soil temperatures. With assumptions based on the reviewed literature, straightforward calculations indicate that, among other recommendations, a sub-slab insulation of level at least R5 should be strongly recommended for all cold climate zones.

Final report (see appendix):

- Straube, John F. "Heat Losses Below Grade in Low Energy Buildings" December 2009.

1.2.2.3. Planned Future Work

The following work is planned for FY10:

- "Review of literature on air flow interacting with conductive flow both energy and moisture"

  As the heat flow by conduction drops to very small values, the relative impact of small amounts of air leakage and wind washing on some enclosure systems grows. In the high R wall systems developed to date, the heat flow carried by air leakage is approximately equal in magnitude to the heat flow by conduction. There has been an assumption that airflow and conduction can be simply added to assess the impact. However, this has not been conclusively demonstrated experimentally, and in fact, there is research to indicate a more complicated relationship, especially when moisture effects are considered.

  As a precursor to developing and conducting combined air flow and heat flow testing of high R-value walls, a literature review of the research will be prepared. A test procedure, based on ASTM standards where possible, will be proposed.

- "Limits to High R-value Walls"

  In general, the analysis of most housing designs has shown that the lowest cost means of reducing the energy use was better insulation, windows and airtightness, in short, a high performance building enclosure. Moving to high R-value walls was almost always the lowest cost measure to reduce energy consumption. As the cost of generating energy via photovoltaic's continues to drop, there will come a point at which increasing the performance of the enclosure will be more expensive than generating an equivalent amount of energy by PV. This point is being reached by some of the best of the high R-value walls, roofs, and basements and in some of the milder and sunnier climate zones of the United States. A research project will examine the limit to High R walls in the context of different PV price scenarios, and different types of enclosures and climate zones.

- "High Thermal Resistance Enclosures for Residential Buildings in All Climate Zones"

  On behalf of the BA program, BSC will lead the development of a white paper on "High R" enclosures for high performance residential buildings. This paper will review and synthesize published research conducted in this area by the Building America Program research teams and the National Laboratories supporting the program. Key gaps that currently limit the broad delivery of high thermal resistance enclosures, including below-grade elements, walls, roofs and windows, will be discussed in the context of a systems approach to high performance building design. To prepare the final draft of this paper, BSC will review the findings of projects conducted by BA teams and solicit review comments on the white paper based on the anticipated results of unpublished research. The draft paper will be circulated to designated reviewers on each team for comments. As a tentative plan to be confirmed in 2010, BSC will host a meeting in August of that year to collect further input from industry experts outside the program.

1.2.3. B. Prediction: Modeling and Analysis

Modeling and analysis was continued from 2008 with additions and improvements to the High R-value Wall Report and the development of two page summaries for all High R-value walls analyzed. A new study was conducted on foundations and basements in cold climates to further the advancement of High R-value building enclosures. Future work includes a study on roofs and attics in cold climate construction. A full description of the work conducted is given below.

1.2.3.1. Updates to 2008 High R-value Wall Case Studies Report

The 2008 High R-value Wall report was reviewed both internally and externally in 2009 to address feedback from different groups including contractors, builders and other building scientists. There were four walls added from the Supplemental Case Studies (explained below) but no other major changes to the report. The modified High R-value Walls report is included as an appendix to this report.

Two page "case study" summaries of the original eight proposed walls from the High R-value Walls report were developed as quick reference guides that can be used and understood by homeowners, builders and consultants with references to further explanation and information on the internet or in other reports. The case studies were posted on BSC's website.[1] The two page summaries have been included in the appendix for all of the High R-value wall systems.

1.2.3.2. High R-value Wall Supplemental Case Studies

Following the completion of the High R-value report, it was decided based on feedback, that four additional walls should be added to the analysis. These were:

- Case 9: Hybrid system with closed cell foam spray foam and fibrous insulation
- Case 10: Double Stud wall with 2" of closed cells spray foam and fibrous insulation
- Case 11: Offset Frame Wall with exterior closed cell spray foam and fibrous insulation in the wall cavity
- Case 12: Exterior Insulation Finish Systems (EIFS)

The same approach was used for the four new walls analyzing the performance based on thermal control, durability, buildability, cost and material use.

It was found that the hybrid (flash and fill) system performed better than standard construction with less potential for air leakage condensation but the thermal bridging through the framing decreased the thermal benefits of adding closed cell spray foam.

The double stud wall with 2" of closed cell spray foam had less risk of air leakage condensation than a traditional double stud wall, but there was still significant risk in cold climates if the interior air barrier system is not perfectly detailed. The air leakage condensation risk could be minimized by:

- Perfect interior air barrier
- Increasing the amount of closed cell spray foam to raise the temperature of the condensation plane
- Use a more vapor permeable sheathing material to allow the wall to dry to the exterior.

These ideas resulted in the development of a double stud wall that is constructed with an interior structural wall of 2x6 advanced framing, sheathed in structural fiberboard, and an exterior 2x3 framed wall also sheathed in fiberboard. This wall has several improvements over traditional double stud walls:

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[1] http://www.buildingscience.com/documents/information-sheets/high-r-value-wall-assemblies/

- An extra level of air tightness with taped or sealed structural fiberboard in the center of the insulation
- The wall has a lower permeance exterior sheathing able to dry to the exterior
- Electrical and plumbing can be run inside of the structural fiberboard so fewer penetrations are required
- The extra insulation is placed on the exterior of the structural wall instead of the interior resulting in increased interior space.

CAD design drawings were done for this wall system, but thermal and hygrothermal simulations are required for all cold climates to determine any limitations of this wall construction technique.

The offset frame wall in the supplemental report is an excellent wall system that can be used for new construction or retrofits that uses closed cell spray foam on the exterior of the sheathing as a drainage plane, as well as air and vapor barrier. This is a very durable, energy efficient wall system, and could be used in remote locations very easily since spray foam is shipped as liquids.

Exterior Insulation Finish Systems (EIFS) have had a tarnished reputation based on poor construction installation in the past but is a very durable wall system provided it is drained properly. It performs very similarly to advanced framing with insulated sheathing, but provides the look of a stucco finish, which is often desirable from an architectural perspective.

All four of these supplemental case studies were added directly to the High R-value Wall report, shown in the appendix. Two page summaries for quick reference were also designed for these walls and are included in the appendix.

1.2.3.3. High R-value Foundation Case Studies

Following the completion of the High R-value Wall Report, basements and foundations in cold climates were analyzed for energy and moisture related performance.

Fourteen Basement insulation strategies were analyzed representing historical construction practices, current practices, and recommended best practices listed here;

1. Uninisulated Foundation wall and slab
2. R10 continuous roll batt with poly
3. 2x4 wood framed wall with R13 fiberglass batts
4. 1" XPS against foundation, 2x4 wood framed wall with R13 fiberglass batts
5. 2" XPS against foundation, 2" foil faced polyisocyanurate (PIC)
6. 3.5" 2.0 pcf closed cell spray foam
7. 6" 0.5 pcf open cell spray foam
8. 2" XPS against foundation, 2x4 wood framed wall with R13 fiberglass batts
9. 2" PIC against foundation, 2x4 wood framed wall with R13 fiberglass batts
10. 6" 0.5 pcf open cell spray foam, 2x4 wood framed wall offset from foundation 2"
11. 4" XPS on the exterior of the foundation wall
12. 4" XPS in the center of the foundation wall
13. ICF – 2" XPS on the interior and exterior of concrete foundation wall
14. 2" XPS against foundation, 2x6 wood framed wall with R19 fiberglass batt

Similar to the High R-value Wall report these 14 wall systems were analyzed and compared based on thermal control, durability, buildability, cost and material use.

Thermal analysis on all proposed wall systems was conducted with Basecalc developed from the Mitalas method from the NRC. Basecalc has a simple menu driven user interface but calculates energy lost based on complicated finite element analysis.

A sensitivity analysis was conducted with Basecalc to determine the differences in heating energy by changing the amounts of foundation wall insulation, underslab insulation, and thermal break insulation around the perimeter between the slab and the foundation wall, which showed that compared to an uninsulated wall, even a small amount of insulation created large energy savings. A practical analysis was conducted using a Building America prototype house in Westford MA, designed by Building Science Corporation.

Hygrothermal analysis was conducted with WUFI, similar to High R-value Wall report. The moisture regime for a foundation wall is much more complicated than an above grade wall since both the temperature changes over the entire height, and the relative humidity is different for the above grade and below grade portions of the wall.

Wetting in the basement can come from bulk water movement, vapor diffusion, air leakage condensation and capillary wicking. Only vapor diffusion and air leakage condensation are simulated in this report, although capillary wicking is considered qualitatively.

All of the walls are given a rating between 1 to 5, one being poor, and 5 being excellent in five categories including

1. Thermal control
2. Durability (wetting/drying)
3. Buildability
4. Cost
5. Material Use

The scores for each of the criteria are added for the total score for each proposed wall system. The advantage of this comparison system is that it can be done qualitatively, without knowing exact values for the criteria. For example, the cost of fiberglass batt will always be less expensive that open cell foam which will be less expensive than closed cell regardless of geographic area or the specific prices of each insulation. Also, it is easy to judge that a 2x6 wall will use more material than a 2x4 wall with the same stud spacing, but assigning a quantitative value for material use is difficult.

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: uninsulated	-	-	-	-	-	
Case 2: R10 continuous with poly (roll batt)	1	1	5	5	5	**17**
Case 3: R13 batt, 2x4 wall with poly	1	1	4	4	5	**15**
Case 4: 1" XPS, 2x4 framed wall with fgb	2	3	3	3	4	**15**
Case 5: 2" XPS, 2" PIC	4	4	3	3	3	**17**
Case 6: 3.5" 2.0pcf cc spuf	4	5	5	3	3	**20**
Case 7: 6" 0.5pcf oc spuf	4	4	5	4	4	**21**
Case 8: 2" XPS, 2x4 framing with fgb	3	3	3	3	4	**16**
Case 9: 2" PIC, 2x4 framing with cellulose	3	3	3	3	4	**16**
Case10: 2.5" 0.5 oc spuf, 2x4 framing with same foam	4	4	4	3	3	**18**
Case 11: 4" XPS on the exterior	4	4	2	2	3	**15**
Case 12: 4" XPS in the centre of foundation wall	4	4	3	1	3	**15**
Case 13: ICF - 2" XPS interior and exterior	4	5	4	1	3	**17**
Case 14: 2" XPS, 2x6 framing with fgb	5	4	3	2	3	**17**

Figure 1 : Analysis matrix for High R-value Basement Proposed Wall Systems

In the current analysis matrix, all of the comparison criteria are weighted evenly. Another advantage of this analysis method is that the criteria can be weighted to reflect the concerns of the homeowner or designer. The five criteria can be ranked in order of importance from 1 to 5 as a multiplier for the scores in that criteria and then summed for a total score out of 75.

A final draft of this analysis report is included in the appendix. The next step for this analysis report is to undergo a rigorous review and feedback period, first internal, and then for external review before it is published in its final form.

1.2.3.4. Planned Future Work

The following work is planned for FY10:

- High R-value Roof Case Studies

  Another proposed task is the analysis of different roof and attic insulation systems similar to the wall analysis report described above. This analysis will be conducted in Minneapolis climate, similar to the wall analysis, and conclusions may also be made for other climate zones. Some comments will be made about unvented and vented attics in general as well as some of the reasons that they are chosen, as well as air leakage problems. Cathedral ceilings will also be considered in the analysis. Possible construction techniques for analysis may include:

  - Standard vented attic construction (fiberglass/cellulose)
  - Attic plus Spray foam against ceiling
  - Unvented sloped roof with spray foam
  - Unvented Densepack cellulose
  - Spray foam and spray applied fiber (fiberglass densepack cellulose)
  - Exterior foam board insulation (polyiso, XPS, EPS)
  - Hybrid - foam board on exterior and fibrous fill between rafter
  - Cathedral ceiling with spray foam

- Low slope roofs

- High R-value Enclosures for Retrofit Applications

  In FY10, BSC will expand our high R-value enclosure work to develop recommendations for existing buildings. The work products will be of a similar form to research reports and case studies for new construction. The work will rely on analysis work already completed as part of the High R-value Enclosure project. It is expected that some aspects of this research work will overlap with existing building prototypes and communities, including low-rise multi-family buildings.

- High R-value Wall Research Integration

  NREL has begun to use 3-D heat flow models of high R-value wall systems. BSC will collaborate with NREL by comparing the modeling assumptions and wall designs we have used to those of NREL. For similar agreed up walls, BSC and NREL will compare the results of pseudo-3D 2D Therm models and full 3D models. Results from full-scale testing of large high-R wall systems will be used to calibrate both BSC and NREL models. Any results from ORNL will also be included to begin the process of developing a large database of well-documented test and simulation results for high R-value walls.

1.2.4. C. Measurement

In FY07 BSC completed a report entitled "Review of the R-value as a Metric for High Thermal Performance Building Enclosures" that summarized the extensive existing research of heat flow through walls and highlighted physical mechanisms that are not usually included in codes and designer specifications. The impact of thermal bridging, and convective loops, although well understood, has not been sufficiently well quantified to allow for prediction. Air infiltration and exfiltration through the wall assembly were identified as a major unquantified heat flow mechanisms in current approach to building enclosure thermal testing. From this review, a need was identified for measuring and rating heat flow across a wall under realistic temperature ranges (both cold & hot exterior conditions) and under the influence of air movement (both in and through the building enclosure).

This was followed by a FY08 report entitled "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls" that outlined a new metric for the thermal performance of building enclosures. New equipment and techniques, based on existing ASTM standards, were proposed to better account for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions.

BSC assembled a consortium of 6 building product manufacturers to participate in the privately funded development of the new thermal performance metric and the associated test method. These partners include:

- NAIMA (North America Insulation Manufacturer's Association) with technical representatives from Certainteed and Johns Manville
- Huntsman Polyurethanes
- Honeywell
- Icynene
- Dow Chemical
- US Greenfiber

BSC designed and built a novel hot box apparatus to permit the highly accurate measurement of heat flow under realistic operating conditions. This following section summarizes the apparatus commissioning and calibration that was undertaken by the research partners in 2009.

1.2.4.1. Laboratory Studies – Hot Box Calibration and Commissioning Report

The R-value has long been the industry standard for assessing the thermal performance of insulation materials. Building designers directly apply R-value to the thermal performance of building enclosures. This practice has recently come into question as energy-cost and security issues have generated demand for building enclosures that exhibit higher levels of thermal performance. The market has responded with new insulation products and novel building enclosure systems such as: various types of spray foam and spray-applied fibrous insulations, exterior insulated sheathing, Structural Insulated Panel Systems (SIPS), Insulated Concrete Forms (ICF), and Radiant Barrier Systems (RBS), etc.

Because contemporary insulation materials and systems control heat flow in different, new and non-traditional ways, they are more or less sensitive to thermal bridging, workmanship (i.e. quality of installation), internal convection and through convection (i.e. infiltration, exfiltration, windwashing & re-entrant looping). The impact of such 'anomalies' and 'defects' is not captured in the R-value metric. Furthermore, the discrepancy between the real heat flow and that predicted by combining R-values increases the absolute temperature, the temperature difference and the net resistance to heat flow increase. These realizations have generated an increasing amount of interest in the development of a new metric for the thermal performance of building enclosures.

The goal of this report is to document the development of a new metric for the thermal performance of building enclosures that better accounts for the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions. The metric employs equipment and techniques based on existing ASTM procedures as much as practical, making use of a special test apparatus (pictured below).

Figure 2: Precision Calibrated Hot Box

In general the test apparatus has been designed & constructed in accordance with ASTM C1363, "Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus." A number of modifications were made to meet the specific objectives of the research.

The key improvements over other (i.e. conventional) hot box testing is the ability to test higher R-value enclosure assemblies (which have lower heat fluxes), a procedure and apparatus that exposes enclosure wall samples to realistic temperature differences while maintaining the interior temperature at normal room temperatures, and the ability to measure the impact of imposed air flow.

The TM hot box uses some novel systems and features to maximize its operating modes while reducing as many errors and as much noise as possible. Early calibration and testing work demonstrate that the apparatus meets the objectives laid out in BSC's FY08 report entitled "Development of a Test Procedure and Apparatus for Measuring High Thermal Performance Walls".

Final report (see appendix):

- Schumacher, Christopher. "Building America High-R Enclosures Research Project: Construction, Commissioning & Calibration of a Novel Hot Box Apparatus for High-R Enclosure Performance Measurement" December 2009.

1.2.4.2. Planned Future Work

The following work is planned for FY10:

- "Measure impact of flaws in insulation installation" (to support the HERS installation rating of insulation)

  HERS ratings currently have a multi-stage approach to inspecting and de-rating fiberglass batt insulation. There is little research indicating what the energy-consumption consequences of different flaws are. There is even less information available to support quantification of the impact of insulation flaws for other systems, such as foam sheathing, spray applied cellulose, densepack cellulose, spray foam, etc. We would propose to conduct testing in a precision hot box to provide this information.

- "Drying of High R-value Walls"

  The reduction of heat flow that is the goal of high R-value walls carries with it the natural consequence that less heat is available to dry materials with walls should they become wet during construction or via leaks during the service life.

  One of the potential challenges is the drying of retained water that is retained on drainage planes behind insulating foam sheathing. The location of a drainage plane / air barrier behind the foam sheathing has the advantage that it is protected from extremes of temperature, and hence is more likely to perform over the long term. Another benefit this that the housewrap is supported on both sides in this application, increasing its durability (by reducing wind loads) and increasing its airtightness. One disadvantage is that some drainwater may be retained between the foam sheathing and the wood framing. The rate at which this water will dry in a high R-value wall is uncertain. Testing of drainage, retention and drying would help answer this question and define the risks.

1.2.5. D. Implementation

To assist builders and designers with implementation of high R-value assemblies, detailed design drawings were drawn in CAD format for recommended high R-value enclosure strategies for walls, foundations, and roofs. BSC has also undertaken a multi-year project to implement advanced framing at a production scale. This project involves most BSC research prototype houses and communities in a number of climate zones.

1.2.5.1. High R-value Enclosure Details

To accompany the analysis reports for high R-value walls, foundations and the proposed analysis report on roofs and attics, detailed design drawings were drawn to assist builders and designers with properly implementing high R-value enclosure strategies. These detailed drawings clearly specify all of the required components and details for successful implementation.

The table below shows the High R-value Enclosure Detail Packages and their status. All of the design details for implementation are included in the appendix.

High R-value Topic	Status
High R-value Walls	Recommended, Complete
High R-value Foundations/Crawlspaces/ Slab-on-grade	Proposed – Under review pending analysis
High R-value Roofs/Attics	Proposed – Under review pending analysis
High R-value retrofit penetration details	Recommended, Complete

Future work for 2010 includes revising all proposed drawing details and determining the recommended design drawings based on thermal, and hygrothermal simulations and experience in the field. Also in the future, we will continue to add to our library of recommended retrofit details based on projects we work on the specific requirements for those retrofit projects. We expect significantly more retrofit-based research projects in 2010.

The following detail drawings have been developed. Final and draft versions have been included as an appendix to this report.

Table of Recommended High-R Wall Types – Cold Climate

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier
Wall-02-1: 2X6 with 1.5” exterior insulating sheathing	Vented lap siding	5.5” cellulose in cavity + 1.5” foil-faced polyisocyanurate rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-2: 2X6 with 2” exterior insulating sheathing	Vinyl or aluminum siding	5.5” cellulose in cavity + 2” XPS rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-3: 2X6 with 4” exterior insulating sheathing	Vented lap siding	5.5” cellulose in cavity + 4” foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach
Wall-02-4: 2X6 with 4” exterior insulating sheathing	Wood shingles over ½” plywood nail base	5.5” cellulose in cavity + 4” foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier
Wall-04-1: double stud wall with interior load bearing wall	Vented siding	10.5" cellulose in cavity, **R-37**	Fiberboard sheathing to exterior side of interior stud wall
Wall-11: 11" wide 2X6 stud wall with 2x3 exterior offset framing	Vented lap siding	5'5" cellulose in cavity + 4.5" closed cell spray foam on exterior, **R-46**	Exterior closed cell spray foam

Table of Foundation Types

Type	Foundation Wall Type	Finished or Unfinished	Location of Insulation	Type of Insulation	Climate
#1	8" Concrete	Unfinished	Interior	2" XPS slotted insulation + 2" foil-faced polyisocyanurate	Cold Climates
#2	8" Concrete	Unfinished	Interior	3.5" closed cell SPF (high density 2.0 pcf)	Cold Climates
#3	8" Concrete	Unfinished	Interior	6" open cell SPF (low density 0.5 pcf)	Cold Climate Zone 5
#3A	8" Concrete	Unfinished	Interior	6" open cell SPF (low density 0.5 pcf)	Cold Climate Zone 6
#3B	8" Concrete	Unfinished	Interior	6" open cell SPF (low density 0.5 pcf)	Cold Climate Zone 7
#4	8" Concrete with interior insulated 2x4 wall offset 2" from fdn wall	Finished	Interior	2" XPS + 3.5 unfaced fiberglass batts in cavity	Cold Climates
#5	8" Concrete with interior insulated 2x4 wall offset 2" from fdn wall	Finished	Interior	2" foil-faced polyisocyanurate + 3.5" cellulose in cavity	Cold Climates
#6	8" Concrete with interior insulated 2x4 wall offset 2.5" from fdn wall	Finished	Interior	6" open cell SPF (low density 0.5 pcf) in and behind cavity	Cold Climate Zone 5
#7	8" Concrete	Unfinished	Exterior	4" XPS	Cold Climates
#8	ThermoMass (2 - 4" concrete layers)	Unfinished	Middle of wall	4" XPS	Cold Climates
#9	ICF (8" concrete core)	Unfinished	Exterior and Interior	4" XPS	Cold Climates

Table of Crawlspace Types

Type	Vented or Unvented	Foundation Wall	Crawl Space Floor	Insulation	Climate
#1	Unvented	Brick veneer + 14" CMU	Polyethylene ground cover	4" XPS insulation internal to walls	Cold Climates
#2	Unvented	8" CMU foundation	2" concrete slab	4" rigid insulation internal to	Cold

				walls and 4” rigid insulation under slab	Climates
#3	Unvented	8” concrete foundation	Polyethylene ground cover	3.5” high density interior spray foam with spray on thermal barrier	Cold Climates
#4	Vented	Piers	No ground cover	6 1/3” high density spray foam in floor joists	Cold Climates

Table of Slab-on-Grade Types

Type	Slab Type	Insulation	Climate
SG Type #1A	Monolithic slab (slab with integrated grade beam) with brick veneer shelf	4” XPS under slab and on interior and exterior sides of integrated grade beam; 2” XPS below grade beam; 2” XPS horizontal frost protection	Cold Climates
SG Type #1B	Monolithic slab (slab with integrated grade beam) with brick veneer shelf	1” XPS on exterior side of integrated grade beam	Mixed Humid Climates
SG Type #2	Independent slab w/ concrete stem foundation walls	4” XPS on interior side of foundation wall; 4” XPS under slab	Cold Climates
SG Type #3	Independent slab w/ concrete stem foundation walls	4” XPS on exterior of foundation wall; 4” XPS under slab	Cold Climates

Table of Roof Assembly Types

Roof Type	Structure	Vented/ Unvented, Attic/Cathedral	Location of Insulation	Type of Insulation	Climate
#1	2x12 rafters	Vented, Attic	Perimeter and attic floor	Perimeter: 2” foil-faced polyisocyanurate + high density spray foam; Attic floor: 18” cellulose	Cold climates
#2	2x4 raised truss	Vented, Attic	Perimeter and attic floor	Perimeter: 6” high density spray foam; Attic floor: 10” cellulose over 3” high density spray foam	Cold climates
#3	2x12 rafters	Unvented, Cathedral	Above roof deck and in rafter cavities	Above roof deck: 4” foil-faced polyisocyanurate; Rafter cavities: 11 1/4” netted cellulose	Cold climates up to Zone 6
#4	2x10 rafters	Unvented, Attic	Above roof deck, perimeter, and in rafter cavities	Above roof deck: 4” foil-faced polyisocyanurate; Perimeter: 6” high density spray foam; Rafter cavities: netted cellulose	Cold climates up to Zone 6
#5	2x10 rafters	Unvented, Cathedral	In rafter cavities/perimeter and below rafters	Rafter cavities/perimeter: 9 1/4” high density spray Below rafters: 1” rigid insulation	Cold climates
#6	2x4 raised truss	Unvented, Attic	Under roof deck and at perimeter	Under roof deck/perimeter: 10” high density spray foam	Cold climates

Table of Retrofit Assembly Details

Drawing No.	Location of Window Flange Relative to Insulating Sheathing	Detail Title	Climate
Win-1	Interior side	Window Details	Cold
Win-2	Interior side	Window Installation Sequence	Cold
Win-3	Interior side	Window Trim Installation Sequence	Cold
Win-4	Interior side	Enclosure Assembly with Window Opening	Cold
Win-1A	Interior side	Window Details	Cold
Door-1	Interior side	Door Details	Cold
Door-2	Interior side	Door Installation Sequence	Cold
Door-3	Interior side	Door Trim Installation Sequence	Cold
Pen-1	Interior side	Penetration Details – Exterior Light	Cold
Pen-2	Interior side	Penetration Details – Electrical Box	Cold
Pen-3	Interior side	Penetration Details – Vent Pipe/Duct	Cold
Pen-4	Interior side	Penetration Details – Vent Pipe/Duct Installation Sequence	Cold
Win-1	Exterior side	Window Details	Cold
Win-2	Exterior side	Window Installation Sequence	Cold
Win-1A	Exterior side	Window Details	Cold
Door-1	Exterior side	Door Details	Cold
Door-2	Exterior side	Door Installation Sequence	Cold
Pen-1	Exterior side	Penetration Details – Exterior Light	Cold
Pen-2	Exterior side	Penetration Details – Electrical Box	Cold
Pen-3	Exterior side	Penetration Details – Vent Pipe/Duct	Cold
Pen-4	Exterior side	Penetration Details – Vent Pipe/Duct Installation Sequence	Cold

1.2.5.2. Advanced Framing Implementation

This report investigates the implementation of advanced framing in both production and prototype built homes built in a variety of climate regions across the USA. The current industry standard wall is being replaced by a 2×6 frame at 24 in. centers with single top plates, two-stud corners, no jack studs, no cripples and single headers (and in many cases no headers at all).

The advanced framing system is cheaper because it uses 5% to 10% less board feet of lumber, and it is faster because it uses 30% fewer pieces. It saves energy because it provides a 60% deeper cavity (which allows 60% more cavity insulation) and because it reduces the framing factor from 25% to 15%. Advanced framing can save energy, greenhouse gas emissions, and money if properly implemented. Through BSC's experience we have found that builders can save $1000 per house on advanced framing. To maximize cost savings and energy savings for the homeowner, the builder financial savings are best shifted to implementing more energy saving measures.

The following projects have implemented advanced framing in 2009:

Builder	Number of Homes

Ark Ventures, LLC	1
C.Nelson	7
Colter Construction	1
David Weekley Homes	77
Greencraft LLC.	5
Moser Builders	1
Project Home Again	32
Synergy Companies Construction LLC	1
Zeta Communities	1
Grand Total	126

In 2010 BSC will continue deployment of advanced framing where possible with its Building America partners. More detail about current and future work can be found in the full interim report, which is attached as an appendix.

Interim report (see appendix):

- Lstiburek, Joseph and Aaron Grin. "Advanced Framing Deployment – Interim Report" December 2009.

1.2.5.3. Planned Future Work

The following work is planned for FY10:

- "High R Attic Insulation: Raised Heel Roof Truss Systems and Knee Walls"

  Roof assemblies have aspects of their design that can reduce the overall effectiveness of the thermal enclosure. These aspects, while often ignored with respect to the overall performance of the attic or roof assembly lead to a reduction the performance of the thermal enclosure. In traditional vented attic assemblies, insulation levels at the exterior perimeter are often reduced where the truss or rafter bears on the exterior wall. Similarly, cathedral ceilings often run into space limitations due to the traditional available space for cavity insulation (and space for ventilation) created by the depth of rafter. Both systems also have additional concerns with air exfiltration which can be both and energy as well as a material durability concern for the assemblies.

  The intent is to develop cost effective means to create high R-Value attic and roof assemblies that achieve consistent insulation levels over the entire attic as well as increase the enclosure air tightness. The deliverable will be a research report that will examine the over thermal performance of the proposed assemblies as well as consider the specific construction and cost implications of the assemblies.

- "High R Windows Installations"

  We propose to develop installation details for High R-Value windows in high performance walls. Consideration will be given to factors affecting the window units themselves, such as frame sizes shapes as well as potential increases in weight from additional glass. Representative generic window profiles will be developed based on a review of current manufacturer's high R-Value window systems.

Integration of the windows in different high performance wall systems will be developed in order to maintain continuity of the water management system, air barrier, and thermal enclosure. The deliverable will be a series of isometric window installation sequences that illustrate the install of a high R-Value window in several high R-Value wall assemblies.

The details will be supplemented with case studies of actual installations discussing construction and installation, cost, and final performance of the windows.

- "Advanced Framing Deployment"

  BSC will work with builder partners to implement advanced framing on a large scale. From past experience, we know that it takes framing crews 5-10 houses to work efficiently with advanced framing methods. As part of this research task, BSC will conduct training and produce information resources. Anticipated resources include documentation of the material and labor savings, and an explanation of the energy efficiency benefits of this technology for different climate zones.

  BSC will also work as needed with local code officials to understand and overcome implementation issues.

- "Support for Foundations Working Group and Handbook"

  BSC will provide input and technical support for the Foundations Working Group activities and the production of a foundation manual being prepared by the group. BSC's work under this subtask will include supplemental research to address known knowledge gaps, possible input into the form and contents of the manual, and the production of drawings and other information. The specific support will be determined with the Foundations Working Group in early 2010.

1.3 Project Evaluation

The following sections evaluate the research project results based on performance benefits and the ability to develop performance specifications for advanced systems. References are made to the results from bench top tests, lab tests, tests in lab/research homes and energy simulations, which are included as an appendix to this report.

1.3.1. Source Energy Savings and Whole Building Benefits

Requirement:	*New whole house system solutions must provide demonstrated source energy and whole building performance benefits relative to current system solutions based on BA test and analysis results.*
Conclusion:	***Pass***

High R-value enclosures provide significant source energy savings and whole building benefits. BSC's research work aims to establish a set of recommended assemblies for that have approximately 50% greater thermal resistance under installed conditions. The work to date has demonstrated this for Cold Climate walls and has produced promising results for foundation, roof and retrofit assemblies.

As an example of this work, the High R-value Walls case study analysis (Part B: Prediction and Analysis) gave the following table summarizing the calculated "whole wall" R-values for walls examined in the study.

Table 16 : Summary of all calculated R-values

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8
1b	2x4 AF, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6
1a	2x6 AF, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4	
8b	2x6 AF, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4	
9	2x6 AF, 24"oc, 2" SPF and 3.5" cellulose	**17.5**	13.2	18.4	17.7
8a	2x6 AF, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5
2a	2x6 AF, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6	
3	2x6 AF, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8
12	2x6 AF, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1
10	Double stud with 2" 2.0 pcf foam, 7.5" cell.	**32.4**	15.9	36.2	28.5
2b	2x6 AF, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2
5	Truss wall 12" R43 cellulose	**36.5**	18.6	40.5	34.4
11	Offset frame wall with ext. spray foam	**37.1**	18.8	40.6	41.9

*AF - Advanced Framing

Walls listed below the lower line (4, 12, 10, 2b, 6b, 5, and 11) are considered to be high R-value assemblies appropriate for deployment in Building America research Prototype homes. Other walls in the study had high nominal R-values but are predicted to perform less effectively and would, therefore, not realize the whole house energy use reduction aimed for by the BA program.

Not all of the improvements in thermal performance can be secured by design choices – additional work was done to measure the influence of other factors, such as convective looping and air pressure differences. Another part of the work described in this report (Part C: Measurement) aims to more accurately measure the thermal performance of wall assemblies. The development of reliable measures of high R-value walls, including all heat transfer mechanisms, will allow for the adoption of new enclosure wall assemblies that reduce heat flow. This in turn can have a major benefit to the energy consumption of American homes.

Other whole building benefits will be realized with the development of high R-value enclosure technology. In particular, homeowners will benefit from increased thermal comfort (through better control of surface temperatures), homes that are quieter on both the inside and the outside (better sound insulation and airtightness), homes that can be heated or cooled with smaller, more efficient mechanical equipment (reduced enclosure loads and reduction of perimeter cold spots), and buildings that are more durable and healthier than houses typically built today (improved water management, resistance to interstitial condensation, and "vapor open" assemblies).

1.3.2. Performance-based Code Approval

Requirement:	*Must meet performance-based safety, health, and building code requirements for use in new homes.*
Conclusion:	***Pass***

All of the high R-value enclosure recommendations detailed under Part D: Implementation meet performance-based safety, health and building code requirements. We consider these enclosure assemblies ready for deployment in prototype research houses. Some BSC prototype houses have employed recommended enclosure assemblies in FY09. Further examination of some code-related issues is expected in FY10. These issues are described in sections below.

1.3.3. Prescriptive-based Code Approval

Requirement:	*Should meet prescriptive safety, health and building code requirements for use in new homes.*
Conclusion:	***Partial Pass***

Some of the enclosure assemblies have not yet been fully reviewed and do not meet all prescriptive requirements. However, the recommended high R-value wall assemblies detailed under Part D: Implementation have completed internal review and meet prescriptive safety, health and building code requirements for use in new homes, with some restrictions on cladding types and applicable wind zones. More discussion on research progress with these restrictions is discussed in Section 1.3.7 below. The following table summarizes the recommended wall assemblies:

Table of Recommended High-R Wall Types – Cold Climate

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier

Wall Type	Exterior finish	Insulation, Nominal R-Value	Air Barrier
Wall-02-1: 2X6 with 1.5" exterior insulating sheathing	Vented lap siding	5.5" cellulose in cavity + 1.5" foil-faced polyisocyanurate rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-2: 2X6 with 2" exterior insulating sheathing	Vinyl or aluminum siding	5.5" cellulose in cavity + 2" XPS rigid insulation, **R-29**	Airtight Drywall Approach
Wall-02-3: 2X6 with 4" exterior insulating sheathing	Vented lap siding	5.5" cellulose in cavity + 4" foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach
Wall-02-4: 2X6 with 4" exterior insulating sheathing	Wood shingles over ½" plywood nail base	5.5" cellulose in cavity + 4" foil-faced polyisocyanurate rigid insulation, **R-45**	Airtight Drywall Approach
Wall-04-1: double stud wall with interior load bearing wall	Vented siding	10.5" cellulose in cavity, **R-37**	Fiberboard sheathing to exterior side of interior stud wall
Wall-11: 11" wide 2X6 stud wall with 2x3 exterior offset framing	Vented lap siding	5'5" cellulose in cavity + 4.5" closed cell spray foam on exterior, **R-46**	Exterior closed cell spray foam

Several important building code considerations were identified and resolved.

First, the IRC provides specific prescriptive guidance on cladding attachment and allows attachment of cladding at 24" centers. A summary of the prescriptive requirements was developed as an "Information Sheet" for posting on BSC's website and for handout to builders of BA Prototype houses. This summary is repeated below.

> In the 2006 International Residential Code (IRC) cladding attachment requirements are covered in *Section R703 Exterior covering* with the majority of the requirements summarized in *Table R703.4 Weather-resistant siding attachment and minimum thickness*.
>
> When sheathings other than wood or wood structural panels are used (such as foam plastic insulating sheathing), the code requires that the cladding be fastened back to the studs. The stud spacing is not specifically stated in *Table R703.4 Weather-resistant siding attachment and minimum thickness* and therefore other sections of the code must be referenced for acceptability of stud spacing. This information is found in *Section R602.3.1 Stud size, height and spacing* in conjunction with *Table R602.3(5) Size, height and spacing of wood studs* listing that studs spaced at 24" centers are acceptable for certain walls.
>
> Depending on the type of cladding, thickness of cladding, and type and thickness of sheathing different fasteners may be required. The penetration depth of the fastener into the stud is the basic requirement. For most claddings the fastener length is specified since the cladding and sheathing thickness is known, a minimum penetration depth is assumed. Where the sheathing thickness is variable (such as with foam plastic insulating sheathing), the fastener size needs to take into account the siding thickness and thickness of sheathing and still provide a minimum of 1" to 1.5" penetration (depending on the cladding type) into the stud.
>
> *Table R703.4 Weather-resistant siding attachment and minimum thickness* is basically unchanged from the 2003 IRC except for the addition of fastener requirements for fiber cement siding over foam plastic sheathing. Where previously no direction was listed (a dash mark was listed in the box) the 2006 IRC now allows the fastening of fiber cement siding over foam plastic sheathing with the use of minimum 6d corrosion resistant nails with the provision that the nail length take into account the thickness of the sheathing a provide a minimum penetration of 1.5 inches into the stud framing.

In many cases furring strips are included in the design of the wall cladding to create a ventilation and drainage space behind the cladding. In this configuration it is often preferable to fasten the cladding to the furring strips instead of back to the studs. Unfortunately the code does not specifically cover this cladding system configuration so engineering may be required to design the cladding attachment to meet the cladding wind load requirements for the area.

Applicable Code Sections

2006 International Residential Code for One- and Two-Family Dwellings

* R602.3.1 Stud size, height and spacing

* Table R602.3.1 Size, height and spacing of wood studs

* R703 Exterior covering

* Table R703.4 Weather-resistant siding attachment and minimum thickness

Second, prescriptive requirements for vapor retarders with insulating sheathing were examined and the code issues summarized as follows:

In climate zones 1, 2, 3, 4A, and 4B a vapor retarder is not required regardless of the use of exterior insulation (*Section N1102.5 Moisture control – Exception 2*). In all other climate zones, the addition of insulation boards on the exterior of the assembly helps reduce the potential for wintertime condensation occurring in the wall assembly. If enough insulation is added to the outside, then a vapor retarder on the inside is not necessary. Also, it is good practice to allow a wall assembly to be able to dry to at least one side, and since many insulation boards can be classified as vapor retarders, removing the vapor retarder from the inside allows increased drying of the assembly to the inside and improves the performance of the wall. The code recognizes this and addresses it in *Section N1102.5 Moisture Control under Exception 3*, which allows for the vapor retarder to be removed "where other means to control condensation are provided." However this still requires some calculations to demonstrate that the potential for condensation is managed in the proposed design.

The current 2007 Supplement to the International Residential Code (IRC) has made some changes to the definition and use of vapor retarders. These changes provide some clarity on vapor retarders, and can be used as guidance.

So what actually is a "vapor retarder"? The current 2006 IRC describes a vapor retarder as a material that has a permeance rating of 1.0 perms or less (*Section R202 Vapor retarder*). This seems simple enough, but there is in reality a large variation in performance between a product with a 1.0 perm rating and a product with a 0.1 perm rating. To address this, the International Code Council (ICC) added a new definition to Chapter 2 of the 2007 Supplement to the IRC for Vapor retarder class.

The 2007 Supplement to the IRC currently defines vapor retarders under three classes:

Class I: 0.1 perm or less (Sheet polyethylene, non-perforated aluminium foil)

Class II: 0.1 perm <= 1.0 perm (Kraft faced fiberglass batts)

Class III: 1.0 perm <= 10 perm (Latex or enamel paint)

With the new definition for vapor retarder classes, new code language concerning the use for the new classes was also included. Class I and Class II vapor are needed to be installed on the warm in winter side of the insulation in Climate Zones 5, 6, 7, 8 and Marine 4 (*Section N1102.5 Vapor retarders*); however, Class III vapor retarders can now be used instead of Class I or II vapor retarders if the conditions of *Table N1102.5.1 Class III vapor retarders* (as listed below) are met.

Zone	Class III vapor retarders permitted for:
Marine 4	Vented cladding over OSB Vented cladding over plywood Vented cladding over fiberboard Vented cladding over gypsum Insulated sheathing with R-value >= 2.5 over 2x4 wall Insulated sheathing with R-value >= 3.75 over 2x6 wall
5	Vented cladding over OSB Vented cladding over plywood Vented cladding over fiberboard Vented cladding over gypsum Insulated sheathing with R-value >= 5 over 2x4 wall Insulated sheathing with R-value >= 7.5 over 2x6 wall
6	Vented cladding over fiberboard Vented cladding over gypsum Insulated sheathing with R-value >= 7.5 over 2x4 wall Insulated sheathing with R-value >= 11.25 over 2x6 wall
7 and 8	Insulated sheathing with R-value >= 10 over 2x4 wall Insulated sheathing with R-value >= 15 over 2x6 wall

Applicable Code Sections

2006 International Residential Code for One and Two-Family Dwellings

* R202 Vapor Retarder
* N1102.5 Moisture Control

2007 Supplement to the 2006 International Residential Code for One and Two-Family Dwellings

* R202 Vapor retarder Class
* N1102.5 Vapor retarders
* N1102.5.1 Class III vapor retarders
* N1102.5.2 Material vapor retarder class

Finally, for houses in wind zones less than 110 mph, BSC looked at wall bracing requirements for walls with insulating sheathing. The following information was developed:

Braced wall panels can be used instead of completely covering the entire building with plywood or OSB. While many types of braced wall panels are acceptable, the most common type of braced wall panels are: 1. A 4-foot wide sheet of plywood or OSB for outside walls and 2. Gypsum installed on interior walls. The various types of braced wall panels are described in *Section R602.10.3 Braced wall panel construction methods*. Standard braced wall panels need to a full 4 foot width with no cut outs from doors or window opening. Narrower panels can be used if the requirements of *Section R602.10.6 Alternate braced wall panels* are met.

A braced wall line and is made up of multiple braced wall panels on a wall. The number and location of the braced wall panels on a braced wall line depends on the wind speed, size and shape of the house, and number of stories. At minimum, braced wall panels are required at the corners and every 25 feet along the braced wall line; however the number may be increased depending on the shape and size of the house. This information can be found in *Table R602.10.1 Wall bracing*. This amount may need to be adjusted based on the weight of the roof assembly. The adjustment factors can be found in *Table R301.2.2.2.1 Wall bracing adjustment factors by roof covering dead load*.

Every house has multiple braced wall lines running in parallel directions. A braced wall line is commonly required every 35 feet; however there are some exceptions to this rule. Keep in mind that the braced wall lines must run in both directions on a house (front to back and side to side). The number and spacing of braced wall lines is given in *Section R602.10.1 Braced wall lines*.

Dwellings in wind zones greater than 110 mph are not covered under this section of the International Residential Code. In cases where the window zone is greater than 110 mph, the design and construction of the structural elements must be in accordance with accepted engineering practice (*Section R602.10.10 Design of structural elements*).

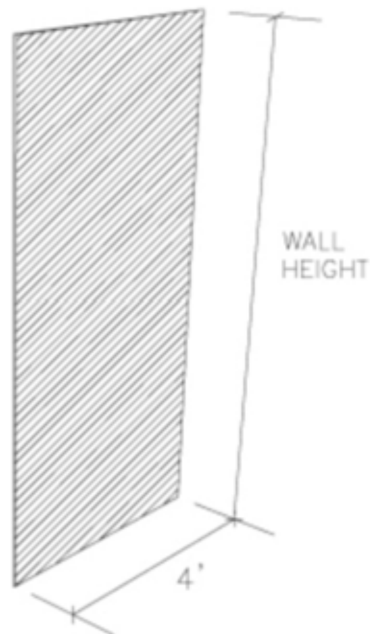

Figure 1: Braced wall panel

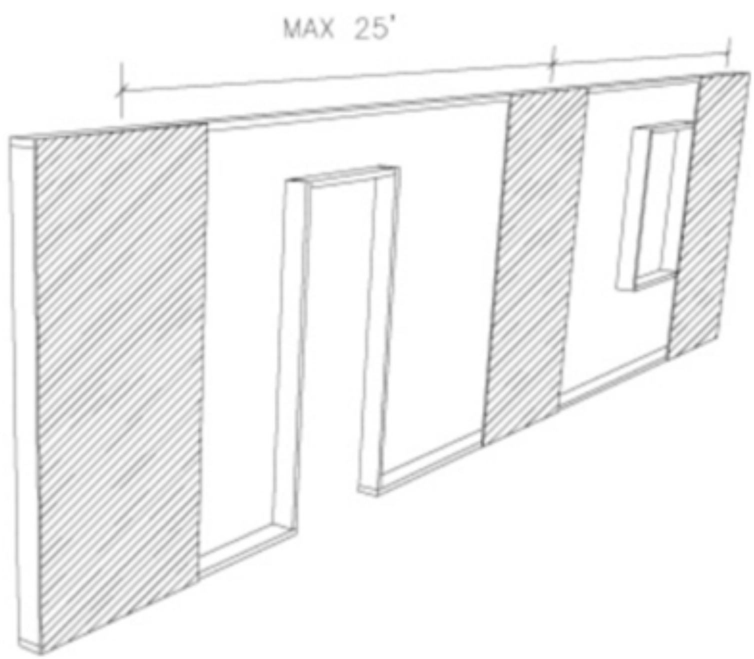

Figure 2: Braced wall line

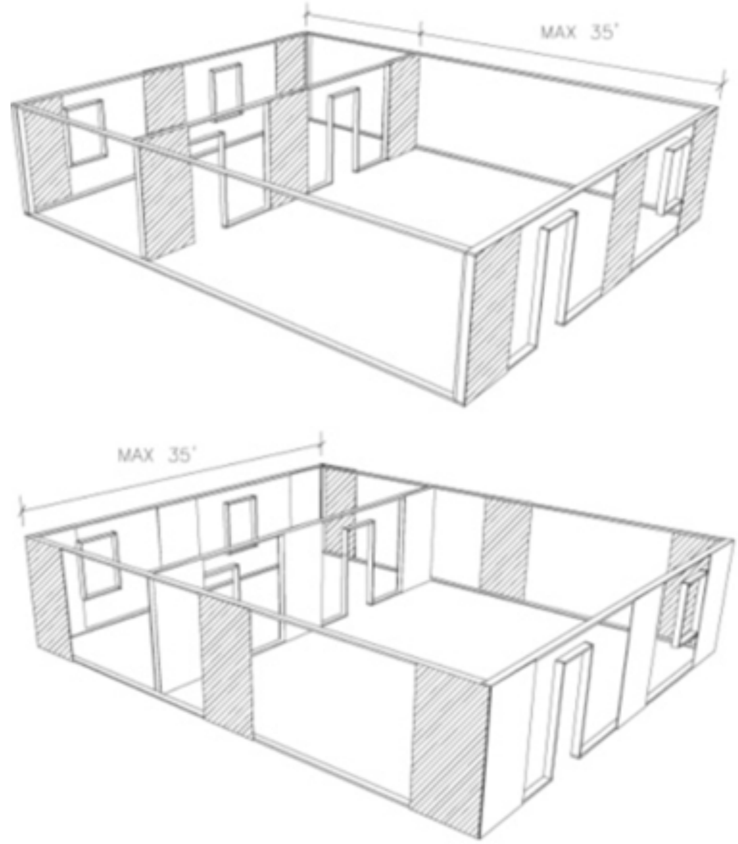

Figure 3: Braced wall lines spaced at 35 feet offsets in both directions

Applicable Code Sections

2006 International Residential Code for One- and Two-Family Dwellings

* R301.2.2.2.1 Weight of materials
* Table R301.2.2.2.1 Wall bracing adjustment factors by roof covering dead load
* R602.3 Design and construction
* R602.10 Wall bracing
* R602.10.1 Braced wall lines
* R602.10.3 Braced wall panel construction methods
* R602.10.10 Design of structural elements

Available Resources

* WFCM 110 mph Guide to Wood Construction in High Wind Areas
* WFCM section 3.4.4.2 Exterior Shear Walls

Some of the code issues that remain as limitations on the above recommended wall assemblies—mainly fastening certain types of cladding to furring strips, and the combustibility of foam insulations—are discussed in more detail in Section 1.3.7: Gaps Analysis below.

1.3.4. Cost Advantage

Requirement:	*Should provide strong potential for cost benefits relative to current systems within a whole building context.*
Conclusion:	***Pass***

Both the recommended High R-value wall assemblies and the roof, foundation, and retrofit assemblies still under review, provide strong potential for cost benefits relative to current systems when considered as part of the whole building.

Aside from the energy-savings-related cost reduction for homeowners described in Section 1.3.1 above, the proposed construction assemblies should provide for significant additional cost benefits. All of the assemblies developed for this research project have undergone a detailed thermal performance analysis. The assessment is intended to increase our understanding of physical characteristics (such as thermal bridging, susceptibility to convective air looping, resistance to infiltration/exfiltration, etc.) that degrade the performance of the assemblies. We have selected assemblies for our recommended list that will perform as close as possible to the nominal R-value of the insulating materials used – thereby providing the "best value" compared to similar wall assemblies designed and constructed in a manner that results in poorer performance.

For the completed set of wall assemblies recommendations, detail of this assessment can be found in "Building America Special Research Project—High-R Walls Case Study Analysis", which is attached to this report as an appendix.

1.3.5. Reliability Advantage

Requirement:	*Should meet reliability, durability, ease of operation, and net added value requirements for use in new homes.*
Conclusion:	***Pass***

Where possible, BSC has developed high R-value enclosure recommendations that are based on conventional technologies and existing products that offer the level of reliability that would be expected from assemblies with lower thermal performance. Durability assessments have be finished for wall assemblies and are being conducted for roof, foundation and retrofit assemblies, with the goal of providing recommended assemblies that both substantially increase the thermal performance of the enclosure and have less risk of moisture-related problems.

1.3.6. Manufacturer/Supplier/Builder Commitment

Requirement:	*Should have sufficient logistical support (warranty, supply, installation, maintenance support) to be used in prototype homes.*
Conclusion:	***Pass***

BSC has found that there is generally strong support for this research from both manufacturers and builders. There are some supply issues that have been identified as new enclosure assemblies are developed. Long shank screws suitable for the attachment of thick insulating sheathing, for example, were not found to be available "over-the-counter" at typical residential building supply stores, but were easily sourced in most locations from commercial roofing suppliers. We anticipate that supply issues such as these will be resolved an high R-value enclosures are more widely deployed.

1.3.7. Gaps Analysis

Requirement:	*Should include system's gaps analysis, lessons learned, and evaluation of major technical and market barriers to achieving the targeted performance level.*
Conclusion:	***Pass***

More detail will be added to our analysis of the major technical and market barriers as research work progresses. However, this research project has already identified a number of important barriers that must be addressed:

- **Attachment of various cladding materials over insulating sheathing.** Cladding attachment details are needed for re-cladding and over-cladding foam and other exterior insulating sheathings. A table of values for 1x4 furring connections installed over various thicknesses of foam sheathings to support fiber cement and wood siding needs to be developed. This needs to be done for masonry block and concrete walls. Values are needed for 2 to 10 inch thick insulating sheathings under a variety of cladding systems.

- **Fire-testing of high R-value assemblies with foam sheathing.** For the fire testing of assemblies the base case framing is always 2x6. Sometimes it will be on 24-inch centers - most of the time it will be on 16-inch centers. Sometimes it will be single top plate - most of the time it will be double top plate. The primary test will be 24-inch centers and single top plate. The others will not need to be tested, as they are more conservative.

  The thickness of the insulating sheathing should be 1.5 inches of polyisocyanurate. (Sometimes it will be 1 inch of polyisocyanurate so this should be tested as well).

  The primary test should test 2x6 framing at 24 inch centers with single top plates and 1.5 inches of polyisocyanurate.

  Sometimes - probably at least 40 percent of the opaque area of the wall - we will need 1/2 inch OSB for shear. So we will need an acceptance for a 2x6 wall at 24-inch centers with single top plates and 1/2 inch OSB covered with 1-inch polyisocyanurate. Sometimes the OSB will only be covered with 1/2 inch of polyisocyanurate.

  The wall cavity insulation should be damp spray cellulose. Interior lining should be 5/8 Type X fire rated gypsum board.

  For the fire testing proposed the goal is approvals for both 1.5-inch and 1-inch polyisocyanurate over 2x6 advanced framing and 2x6 standard framing. Cavities should be insulated with cellulose with interior linings consisting of 5/8 inch Type X fire rated gypsum board. The shear wall versions of these assemblies also need to be tested (that means a wall with 1 inch polyisocyanurate and 1/2 inch OSB and another wall with 1/2 inch polyisocyanurate and 1/2 inch OSB).

For the structural testing a table of single headers for window and door openings needs to be developed in a building code compatible version to make it easy on a prescriptive basis to do this piece of the advanced framing package.

- **Use of combustable foam insulation in exposed applications.** High R-value enclosures require increased levels of insulation in areas that are often poorly insulated such as attics, crawlspaces and basements. The building code requires a thermal barrier for foam insulations installed in these areas in any case that the space is also accessible to the occupants. Current thermal barrier options are often expensive or difficult to apply. Many production builders, in particular, need options for insulation in exposed areas that they wish to leave unfinished at the time of sale. There is a cost hurdle to overcome here.

- **Wind design requirements impact high R-**value construction. Wind design guidelines in some areas of the country require modifications to current high R-value enclosure recommendations. These modifications need to be explored in more detail.

- **Understanding the influence of airflow on heat transfer.** Observing the commissioning and calibration of BSC's precision calibrated hot box, it was learned that quantifying the heat flow resistance of walls is much more than just R-value. Although there has been research conducted in the past, there is still no clear single performance metric that can be used to communicate high performance walls to designers, code officials or owners. Proving that the performance of the new test apparatus can meet the demanding targets set is not yet complete.

  The influence of airflow within and through building enclosures on heat transfer is significant, much more significant than for standard enclosures. For many high R-value walls, basements, and roofs the proportion of heat flow due to airflow effects increases as R-value increases. For wall and roof assemblies with R-values in the order of 30 to 60, airflow affects can dominate performance, whereas for traditional walls (R-10 to R-15 true r-value) the impacts were small enough they could be ignored.

  Higher airtightness standards for both whole buildings and assemblies need to be imposed for high R-value enclosures. Airtightness targets that approach 1.0 l/s/m2@75 Pa of enclosure area for total building airtightness should be sought for homes that use very high R-value walls and roofs (e.g. R-40/R-60).

  The interaction of airflow and heat transfer is poorly understood. There appears to be a real impact, and for accurate assessments heat flow due to conduction and heat flow due to through-enclosure convection cannot simply be added. However, the precise interaction has not been experimentally quantified and is likely in the order of more than 10% impact for high R enclosures.

  Airflow within enclosures influence heat flow in all walls. However, small defects and a limited amount of wind washing can be tolerated in enclosures with R-values of 10 to 20 without serious reductions in performance. For high R-value enclosures, even small, perhaps even unavoidable defects, can begin to have a more significant influence on heat flow for high R-value enclosures. Hence, techniques to reduce the impact of these mechanisms need to be implemented. For example, the use of wind washing barriers, multiple layers of insulation and insulation with higher resistance to airflow may be required.

In addition, several minor barriers were noted:

- **Impact of increased wall thickness.** For most high R-value assemblies, the additional insulation material increases the thickness of the exterior wall. For builders, this may interfere with interior space plans or, because of typically very tight fit between house and lot, impact the entire community plan. For new house designs, this additional thickness can likely be accommodated with minimal difficulty but for existing house plans in use by production builders, a modification to the exterior wall is a major change.

- **Global warming potential of insulation materials.** As homeowners become more attuned to the global warming potential of the products that they buy, alternates for many commonly used insulation materials must be found.

- **First or capital cost of building high R-value enclosures.** The initial cost of high R-value enclosures can be significant. Our research has focused on the development of enclosure systems that will meet the BA neutral cost criteria but several of the gaps above need to be addressed in order to bring the first cost down for the builder. Changing thermal resistance requirements in building codes reduce the effective cost to the builder and pass the same amount on to the homeowner – who will benefit from the energy savings of these measures – but may also be faced with a higher purchase price.

- **Availability of new insulation materials.** Not all of the insulation materials that are listed in BSC recommendations are available in all regions. For example, it is currently difficult to get damp sprayed cellulose in some areas and SPF is hard to get in other areas. This situation is expected to change slowly but should be monitored.

1.4 Conclusions/Remarks

The BSC Industry Team has determined that a 50 percent improvement in the thermal resistance of the exterior wall, roof/ceiling and foundation assemblies must be achieved with a reduction in material and labor costs in order to meet the Building America Program mid term objective to reduce whole-house energy use in new homes by an average of 50 percent by 2015.

In addition, other whole building benefits will be realized with the development of high R-value enclosure technology. In particular, homeowners will benefit from increased thermal comfort (through better control of surface temperatures), homes that are quieter on both the inside and the outside (better sound insulation and airtightness), homes that can be heated or cooled with smaller, more efficient mechanical equipment (reduced enclosure loads and reduction of perimeter cold spots), and buildings that are more durable and healthier than houses typically built today (improved water management, resistance to interstitial condensation, and "vapor open" assemblies).

BSC has produced final recommendations for six high R-value wall assemblies, including details for windows, doors and enclosure penetrations. These recommendations are accompanied by building science notes on thermal performance, durability, cost and constructability, presented as two-page illustrated case studies. In addition, BSC is reviewing and analyzing details for high R-value foundation, roof and retrofit assemblies. These work products are supported by fundamental research into the thermal performance of materials and systems, as well as the known physical heat flow mechanisms (particularly natural and forced convection) and operating conditions that influence thermal performance.

Detailed descriptions of work planned for FY10 can be found at the end of each section of this report. As an overview, BSC will conduct additional analysis of roof, foundation and retrofit assemblies and will report on the measurement of full wall assemblies. High R-value enclosure drawings and details that are currently under review will be modified to reflect information gained from these and other research subprojects. Enclosure recommendations applicable to all climate zones will be developed.