Design Challenges of the NIST Net Zero Energy Residential Test Facility

Research Report - 1401

September 2014

Betsty Pettit, FAIA and Cathy Gates, AIA Building Science Corporation with Hunter Fanney, Ph.D. and William M. Healy, Ph.D.

Abstract:

Trends in the United States and throughout the world have motivated builders to build low energy use and environmentally friendly homes. As materials and equipment have improved, energy reduction as a goal has increasingly been replaced with the goal of net-zero energy use. But the general approach to building energy efficient homes that has been recommended has always been the same – namely that the primary goal is to meet homeowners' desired way-of-life while reducing energy use through available technologies and methods within the homeowner's means. Then, on-site generation of energy is simply an alternative, clean and renewable source for the energy required after energy consumption has been reduced as much as is feasible.

This approach to achieving net-zero energy homes is reflected in the ten general principles for the design of net-zero energy capable houses that are presented and discussed in the first part of this paper. In the second part of the paper, specific strategies and details are described that were used for the design of the Net Zero Energy Residential Test Facility (NZERTF), a NIST laboratory in the form of a typical residence for a family of four that has been constructed on the NIST campus in Gaithersburg, MD. This facility provides a concrete example of a net-zero energy capable house for which the development of the design is consistent with the ten principles.

NIST Technical Note

Design Challenges of the NIST Net Zero Energy Residential Test Facility

Betsy Pettit, FAIA, Cathy Gates, AIA,
A. Hunter Fanney, Ph.D., William M. Healy, Ph.D.

National Institute of
Standards and Technology
U.S. Department of Commerce

NIST Technical Note

Design Challenges of the NIST Net Zero Energy Residential Test Facility

Betsy Pettit, FAIA and Cathy Gates, AIA
Building Science Corporation

A. Hunter Fanney, Ph.D. and William M. Healy, Ph.D.
Energy and Environment Division
Engineering Laboratory

September 2014

U.S. Department of Commerce

National Institute of Standards and Technology

Abstract

Trends in the United States and throughout the world have motivated builders to build low energy use and environmentally friendly homes. As materials and equipment have improved, energy reduction as a goal has increasingly been replaced with the goal of net-zero energy use. But the general approach to building energy efficient homes that has been recommended has always been the same – namely that the primary goal is to meet homeowners' desired way-of-life while reducing energy use through available technologies and methods within the homeowner's means. Then, on-site generation of energy is simply an alternative, clean and renewable source for the energy required after energy consumption has been reduced as much as is feasible.

This approach to achieving net-zero energy homes is reflected in the ten general principles for the design of net-zero energy capable houses that are presented and discussed in the first part of this paper. In the second part of the paper, specific strategies and details are described that were used for the design of the Net Zero Energy Residential Test Facility (NZERTF), a NIST laboratory in the form of a typical residence for a family of four that has been constructed on the NIST campus in Gaithersburg, MD. This facility provides a concrete example of a net-zero energy capable house for which the development of the design is consistent with the ten principles.

Keywords

Net-zero energy residential design, high performance enclosure, energy efficiency

Disclaimer

Certain trade names and company products are mentioned in the text in order to adequately specify the technical procedures and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in metric units first, followed by the corresponding values in U.S. customary units within parentheses.

Author Information

Betsy Pettit, FAIA
Principal
Building Science Corporation
30 Forest Street
Somerville, MA 02143
978-589-5100
betsy@buildingscience.com

Cathy Gates, AIA
Project Architect

A. Hunter Fanney, Ph.D.
Senior Research Scientist, Energy and Environment Division
National Institute of Standards and Technology
100 Bureau Dr.
Gaithersburg, MD 20899

William M. Healy, Ph.D.
Leader, Heat Transfer and Alternative Energy Systems Group
National Institute of Standards and Technology
100 Bureau Dr.
Gaithersburg, MD 20899

Contents

List of Acronyms

ARRA	American Recovery and Reinvestment Act of 2009
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSC	Building Science Corporation
CCT	Correlated color temperature
CEE	Consortium for Energy Efficiency
CFL	Compact fluorescent lamp
cfm	Cubic feet per minute
CRI	Color rendering index
DOE	United States Department of Energy
ECM	Electronically commutated motor
EF	Energy Factor
EgUSA	EnergyGauge USA
ERV	Energy (or enthalpy) recovery ventilator
FMEP	Fire protection, mechanical, electrical and plumbing
FSC	Forest Stewardship Council
gpm	Gallons per minute
gpf	Gallons per flush
HRV	Heat recovery ventilator
HSPF	Heating seasonal performance factor
HVAC	Heating, ventilation and air conditioning
HVI	Home Ventilating Institute
HWPW	Hardwood plywood
IAQ	Indoor air quality
IECC	International Energy Conservation Code
in. w.g.	Inch water gauge

L/f	Liters per flush
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
LSL	Laminated strand lumber
MDF	Medium density fiberboard
MEF	Modified Energy Factor
MEL	Miscellaneous electric load
MEP	Mechanical, electrical, and plumbing
MERV	Minimum Efficiency Reporting Value
NAF	No-added formaldehyde
NIST	National Institute of Standards and Technology
NZERTF	Net Zero Energy Residential Test Facility
o.c.	on center
OSB	Oriented strand board
Rhvac	Residential HVAC (software from EliteSoft)
SEER	Seasonal Energy Efficiency Ratio
SHGC	Solar Heat Gain Coefficient
UF	Urea formaldehyde
UFAS	Uniform Federal Accessibility Standards
U.S.	United States
VOC	Volatile organic compound
WF	Water Factor
XPS	Extruded polystyrene

List of Figures

List of Tables

1 Introduction

1.1 Background and Purpose

In 2009, the National Institute of Standards and Technology (NIST) received American Recovery and Reinvestment Act funding for the construction of a net zero energy residential test facility (NZERTF) on the NIST Campus in Gaithersburg MD. The facility was to be constructed as a typical residence for a family of four that could be demonstrated to achieve net-zero site energy use on an annual basis. Net-zero energy use was to be accomplished through the combination of low energy loads due to a high performance enclosure, efficient mechanical systems, and low energy fixtures and appliances in combination with site-generated energy using roof-mounted solar panels. Following the demonstration of net-zero site energy use, the facility is to be used by NIST's Energy and Environment Division as a research laboratory to test and measure residential energy technologies, indoor environmental quality, materials, and other aspects of sustainable performance in a realistic context.

Building Science Corporation (BSC), a building science consulting and architecture firm, has been researching and designing durable, healthy, and energy efficient homes for 20 years and is one of the original teams in the U.S. Department of Energy's Building America program[1]. During this time, BSC has developed proven methods for construction of high performance enclosures and a practical approach to design for low energy homes. Using this experience and expertise, BSC worked with NIST to develop the architectural and mechanical design of the NZERTF. BSC's work was partially funded by the Building America program.

The purpose of this report is to describe a general approach to the design of new, low energy, net-zero capable homes and then to describe the specific strategies used in the architectural and Mechanical/Electrical/Plumbing (MEP) design of the NZERTF that promote low energy use, good indoor air quality, durability, minimal environmental impact, and net-zero energy capability.

1.2 Approach

Trends in the United States and throughout the world have motivated builders to build low energy use, environmentally friendly and affordable, or at least more economical, homes. As materials and equipment have improved, energy reduction as a goal has increasingly been replaced with the goal of net-zero energy use. But the general approach that is recommended has always been the same. This is reflected in the general principles that are enumerated in the first part of this report – namely that reduction of energy use through means that are consistent with the homeowner's way of life and available technologies is the primary goal; on-site generation of energy is simply an alternative, clean and renewable source for the energy after energy consumption has been reduced as much as is feasible.

The second part of the report explains the strategies and details that were included in the design of the NZERTF specifically to promote energy efficiency and durability of the various components and systems. The uniqueness of the NZERTF project, including government procurement and a construction process that restricts communication between the contractor and the architect, and the fact that construction of low energy use homes requires non-standard residential techniques and processes meant that more design detail and explanation was needed

[1] http://www.eere.energy_gov/buildings/building_america

than is typical for residential construction. As such, an important component of the NZERTF design was to promote design communication by including sufficient design detail information in the construction set to indicate the adjustments to standard practice that are needed in the construction of low energy use homes.[2]

2 General Design Approach for a Net-Zero Energy House

2.1 What is a net-zero energy house?

A zero energy house is one in which all energy needs of the house are met using energy that is generated on-site using renewable sources. A zero energy house is independent of all off-site energy sources and must have the capability to harvest and store energy on the site. Most homeowners do not have the resources to meet these criteria, i.e., access to on-site clean and renewable energy sources, sufficient energy storage capacity, and low enough energy use on a continuing basis. On the other hand, a net-zero energy house is one in which the total amount of energy consumed in a year is less than or equal to the total amount of energy generated on-site during that year. While this still requires on-site energy generation, a net-zero energy house is connected to the electrical grid and the grid acts as the "storage" for the site-generated energy that is not immediately consumed.

While meeting the goal of net-zero energy is less difficult than the more stringent zero energy goal, it still requires a significant energy reduction effort. Reduction of energy consumption by houses has been a topic of research for decades but has received more attention recently as the environmental impact of continued and growing use of fossil fuels becomes evident. New building materials and building techniques as well as availability of more efficient equipment and appliances have made construction of low energy houses possible though progress has been somewhat offset by increasing house sizes and the extensive use of electronic devices in homes.[3] Nevertheless, many low energy houses are being built and there are a number of case studies that demonstrate that net-zero energy use is being achieved.[4]

For a low energy house, a significant portion of the total annual energy consumption can be attributed to miscellaneous electric loads (MELs), also called plug loads. The energy consumption of MELs is primarily a function of the activities of the occupants of the house rather than the low energy characteristics of the house. For this reason, it is more accurate to refer to the design of a new house as being net-zero energy capable rather than being net-zero energy.

The term "net-zero energy" as used in this paper could refer to either net-zero site energy or to net-zero source energy.[5] Energy use reduction is the goal in either case, but the calculation used to determine energy consumption for site energy is based only on energy use at the site whereas source energy use takes into account the energy used to generate and to deliver energy to the site

[2] Lukachko (2011).
[3] Brown, Richard et al (2006).
[4] Ueno, K. et al (2013).
[5] Torcellini, P. et al (2006).

as well as what is used at the site. Source energy consumption more accurately reflects the environmental impact of energy use.[6]

2.2 Ten Principles for Design of a Net-Zero Energy Capable House

The overall approach for designing a net-zero energy capable house is to first incorporate as many energy reducing techniques as are economically and technically feasible and appropriate for the project. The next step is to do a thorough energy use analysis to project total annual energy consumption, revisiting earlier decisions and making adjustments as needed to get the projected consumption as low as possible. Finally, enough on-site renewable energy is provided to exceed the projected annual energy consumption. These steps would conventionally be done using weather conditions in a typical year, appreciating that deviations from that typical year could make the goal of achieving net-zero operation either more or less difficult.

It should be noted that this approach does not start by calculating the maximum potential for renewable energy generated in a year and then designing with the goal of keeping annual energy consumption below that amount. Instead, the primary goal is to reduce energy use as much as possible. The on-site renewable energy reduces, but does not eliminate, the dependence on external energy sources since electricity from the grid is used at those times when the energy needed within the home exceeds the energy being generated. Therefore reducing energy consumption remains the most important factor.

The ten principles described in this section are consistent with the approach of minimum energy consumption and using renewables to meet the annual energy requirements. They are derived from Building Science Corporation (BSC)'s continuing research and experience with low energy houses, much of which has been done in conjunction with the U.S. Department of Energy's Building America program.

The design and construction of a net-zero energy capable house requires a team effort. The capabilities needed within the team include owner, architect, building contractor, building scientist, structural consultant, MEP professional, energy analyst, renewables consultant, and landscape designer. With the exception of the owner, all team members should have experience with low energy house design and construction. Design and construction of a net-zero energy capable house differs from, and is less forgiving than, standard residential design and construction.

2.2.1 Principle 1: Design for comfort and function

While it may seem strange that the first principle for a net-zero energy house design does not mention energy use at all, a house that does not meet the comfort level and functions needed by the occupants will not be used or maintained in the manner intended. As a result, the energy use assumptions made during the design will be invalid. The design should strive to meet these requirements with as little energy use as possible.

For example, the placement of windows can enhance comfort level without using any energy. Operable windows can be arranged to provide airflow by natural ventilation when neither heating nor cooling is needed. During the winter, sunlight through south-facing windows can enhance comfort to occupants through radiant heat transfer. However, these windows could also

[6] Ueno, K. and Straube, J. (2010).

cause overheating in the summer (and thus increased energy use to maintain comfort) so some means of shading of the windows, such as appropriately sized overhangs, would be needed.

Because of this first principle, tradeoffs may be needed between a design of the smallest, most compact home layout possible and a more expansive structure that better meets the living style of the occupants. With careful orientation of the building and layout of space, with a high performance building enclosure and with high efficiency HVAC systems and appliances, the energy use can be kept low even for a more expansive building form. While small and compact is a good energy reduction technique, if it doesn't meet the needs of the occupants, additions will soon be made which will increase the floor and surface area, increase energy use and require further adjustments if net-zero energy use is still to be met.

In heating or cooling dominated climate zones, delivery of heated or cooled air to the living spaces in a consistent manner is a major factor for comfort and actual energy use. If some living space is felt to be too hot, too cold or too stuffy, adjustments will be made by the occupants (for example, leaving windows open or continually adjusting the thermostat or ventilation controls) that will undermine the efficiency of the enclosure or HVAC design.

A house can be designed and built to be net-zero energy capable, but ultimately it is the occupants' use of the house, generally driven by their comfort and functional needs, as well as the way that the house is maintained that determines whether the net-zero energy goal is met.

2.2.2 Principle 2: Establish an airtight building enclosure

The building enclosure separates the indoors from the outdoors. Therefore it must provide for airflow control as well as water, vapor and thermal control. The design of a high performance enclosure, as is required for a net-zero energy capable house, must clearly specify how these functions are to be provided.

Uncontrolled air leakage across the enclosure can be responsible for much of the energy use for heating/cooling of a house as well as being the primary source of moisture within the structure.[7] Airtightness of the enclosure is one of the most important requirements of a low energy house. Airtightness is provided by the airflow control system of the enclosure. This is a continuous system of air impermeable materials and building components (such as windows and doors) that separates the conditioned space of the house from unconditioned air and from contact with the ground. The effectiveness of the airflow control system of a house is usually measured in terms of leakage rate (Q_{50}) or air changes per hour (with units of h^{-1}) measured under a fan pressurization test with a 50 Pa pressure differential between the inside and outside air. Building Science Corporation set the target airtightness for the NZERTF at 1.5 h^{-1}.

An effective airflow control system is one that is durable and is simple to construct. For a house with a conditioned attic and a conditioned basement, the boundary between conditioned and unconditioned space is the same as the exterior of the house. In this case, wrapping an air barrier membrane completely and continuously around the exterior sheathing of the roof and walls creates a very effective airflow control system provided there is appropriate air sealing to the foundation and at the windows, doors and all wall/roof penetrations. Inclusion of the basement and attic in conditioned space has additional advantages. Location of mechanical equipment and

[7] Straube, J. (2008).

ductwork in the conditioned space reduces wasted energy. Conditioned attic and basement space is more useful, even if just for storage. And an unconditioned basement can increase the likelihood of indoor air quality and moisture problems. If the house is airtight and well insulated, the overall reduction in wasted energy consumption will generally compensate for the increased total volume of conditioned space.

If the attic or the basement is not conditioned, or if there is an attached garage, it is more difficult to establish a sufficiently tight air control layer system since components of the airflow control layer must be connected through the discrete structural elements of the enclosure. In these cases, it may be more effective to establish the air control layer system on the interior side of the enclosure using a method called the "airtight drywall approach."[8] This method requires very careful attention to detailing, taping and caulking in order to create a continuous air control layer system around the entire conditioned interior, but it is effective when done correctly.

While airtightness alone will not achieve net-zero energy use, it is one of the more effective ways to reduce excess energy consumption. Other benefits of airtightness include improved durability of the wall materials due to better moisture control and improved comfort due to reduced drafting and better control of the source of incoming air and any contaminants it may bring into the building.

2.2.3 Principle 3: Provide controlled ventilation

All buildings require ventilation – the purposeful, controlled flow of outside air into conditioned space. ASHRAE Standard 62.2 "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings" specifies the amount of ventilation that the system should support based on the size of the house and the number of bedrooms. One method of meeting ASHRAE Standard 62.2 is through the use of an "exhaust-only" ventilation system. In this type of system, air is removed from the house using fans which exhaust air from the baths and kitchen to the outside; this creates a pressure differential forcing outside air to enter the house through any air infiltration paths that exist in the enclosure. From an energy use standpoint, this approach is not optimal since conditioned air is exhausted from the house. From an interior air quality standpoint, this approach is not optimal since the unfiltered outside air enters through unintended and potentially contaminated passageways in the building enclosure.

An airtight, high performance enclosure works best with a balanced ventilation system – one that mechanically controls and balances the flow of both the supply air and the exhaust air. By controlling the path of the supply air, the incoming air can be filtered and distributed appropriately within the house. Many balanced systems also perform heat exchange between the streams of incoming and outgoing air. The heat exchange reduces the excess energy use caused by exhausting conditioned air and bringing unconditioned air directly into the interior.

There are two types of balanced air systems with heat exchange: an HRV (heat recovery ventilator) system that exchanges heat between the supply and exhaust air streams and an ERV (energy or enthalpy recovery ventilator) system that exchanges heat and moisture between the air streams. While these systems provide some energy recovery, they also require energy to operate

[8] Building Science Corporation (2009a).

the fans, so it is important to specify a properly sized system with a highly efficient and quiet fan.

There are a variety of ways to configure a balanced ventilation system. Three options typically considered for a low energy house include integration with the central air system, integration with the bath exhaust system, or independent installation with a dedicated duct system.[9] Design, installation, and commissioning of these systems must be done by an HVAC professional who is familiar with the systems and with low energy houses.

BSC typically commissions the ventilation system to provide about half of the ASHRAE 62.2-specified rate for normal use. BSC also believes that the controls should include a higher setting that allows the installed system to be run at the ASHRAE 62.2-specified rate. If the ventilation system is part of the bathroom exhaust system, a timed boost switch is needed in the bathroom. But perhaps the most important requirement is that the controls be simple and easy to understand and that the occupants fully understand the intended use of the system and how changes to that will impact air quality and energy use.

For a very tight house, the operation of the kitchen range hood, the clothes dryer or other exhaust devices that are not integrated with the ventilation system can cause some depressurization of the house. In this case, makeup supply air will need to be provided when any of these devices are operating.

It is recommended that a passive radon mitigation system be installed in all tight houses that have basements or slab-on-grade floors. This is a sub-slab ventilation system with a vent stack extending up through the roof creating a negative pressure zone under the slab so that soil gas is vented out. If needed, a fan can be added to the system in the future.[10]

2.2.4 Principle 4: Install insulation that exceeds current energy code requirements

While airtightness reduces direct loss of conditioned air by infiltration through the enclosure, insulation resists transfer of heat by conduction through the enclosure. The thermal control system of the enclosure consists of all those materials that are installed to control the transfer of heat through the enclosure. Resistance to heat flow is usually quantified in terms of R-value. When comparing two materials, if the same amount of the two materials is used, heat transfer through the material with the larger R-value will be less than that through the material with the smaller R-value.

For houses using standard residential construction techniques, exterior wall insulation is applied in the bays between the framing members. Since walls are composed of a combination of materials, some of which are highly conductive, the overall R-value of the wall is considerably less than that of the insulation. For example, a 38 mm x 140 mm (2x6) wall framed at 406 mm (16 in.) on center (o.c.) with an R-value of 3.3 $m^2 \cdot K/W$ (19 $ft^2 \cdot h \cdot {}^\circ F/Btu$) insulation installed in the framing bays has an overall wall insulation R-value of 2.4 $m^2 \cdot K/W$ (13.7 $ft^2 \cdot h \cdot {}^\circ F/Btu$).[11] This takes into account not only the R-values of all materials in the wall but also the effect of thermal bridging that the framing introduces through the walls.

---

9 Building Science Corporation (2013).
10 http://www.epa.gov/radon/pdfs/buildradonout.pdf
11 Building Science Corporation (2009b).

Use of continuous insulation in addition to the framing bay insulation is recommended for high performance enclosures to reduce thermal bridging, especially in a heating dominated climate. This can be accomplished by applying a continuous layer of insulation to the exterior side of the walls or to the interior side of the walls, or by construction of a double wall so that the framing does not extend completely through the wall. Similarly, minimizing thermal bridging through the roof (or attic floor) framing can be accomplished by applying a continuous layer of insulation to either the exterior or interior side of the assembly. If it is applied to the interior, special construction techniques may be needed to provide sufficient depth along the eave for the insulation.

The 2012 International Energy Conservation Code (IECC) (International Code Council, 2012) for residences specifies minimum performance requirements for the enclosure based on the climate region in which the house is located. In general, the minimum R-values specified by the IECC code are not consistent with a high performance enclosure. Instead, high performance enclosures should use as much insulation as is possible (exceeding the IECC requirements), include continuous insulation to reduce thermal bridging, and install the insulation so that there are no internal air gaps (and so that the insulation will not shift or pull away to create air gaps over time). The latter requirement is to prevent convective looping within the insulation that can undermine its thermal resistance function.

Windows are the weakest component in the thermal control layer of the building enclosure because of the low R-value of glazing. However, windows are important for the comfort and function of the house (e.g., natural lighting and views). Where possible, the size and number of windows in locations that contribute the most to heating and cooling loads should be minimized. The most important characteristics of the windows are an R-value of at least 0.88 $m^2 \cdot K/W$ (5 $ft^2 \cdot h \cdot {}^\circ F/Btu$) (higher in heating dominated climates), air and water tightness, and installation in a way that supports continuity of the airflow, water, and thermal control systems of the enclosure.

Similar to the airflow control system, the thermal control system is located along the boundary between the conditioned and unconditioned air. As with the airflow control system, connections between components of the system must be detailed carefully so that the control function is provided continuously. While a discontinuity in the airflow control system results in direct loss of conditioned air through air infiltration, a discontinuity in the thermal control system results in reduced overall resistance to heat transfer because of thermal bridging. In either case, the discontinuity causes excess energy use to maintain the interior conditioning and may contribute to potential envelope moisture problems.

2.2.5 Principle 5: Establish water and moisture control for the building enclosure

There are many aspects of water and moisture control required for any building (see Figure 1). The site must be graded to drain surface water away from the foundation wall of the building; groundwater must be kept away from the foundation and footings; the exterior of the building must be designed to drain water off of, and away from, the building; the building enclosure must have a water control system which reduces the likelihood of water from penetrating any further into the enclosure and redirects it to the outside, usually via flashing; and, any water or moisture that does manage to get into the enclosure must be able to dry. Failure to provide for these conditions will ultimately damage the building structure and materials and contribute to poor indoor air quality.

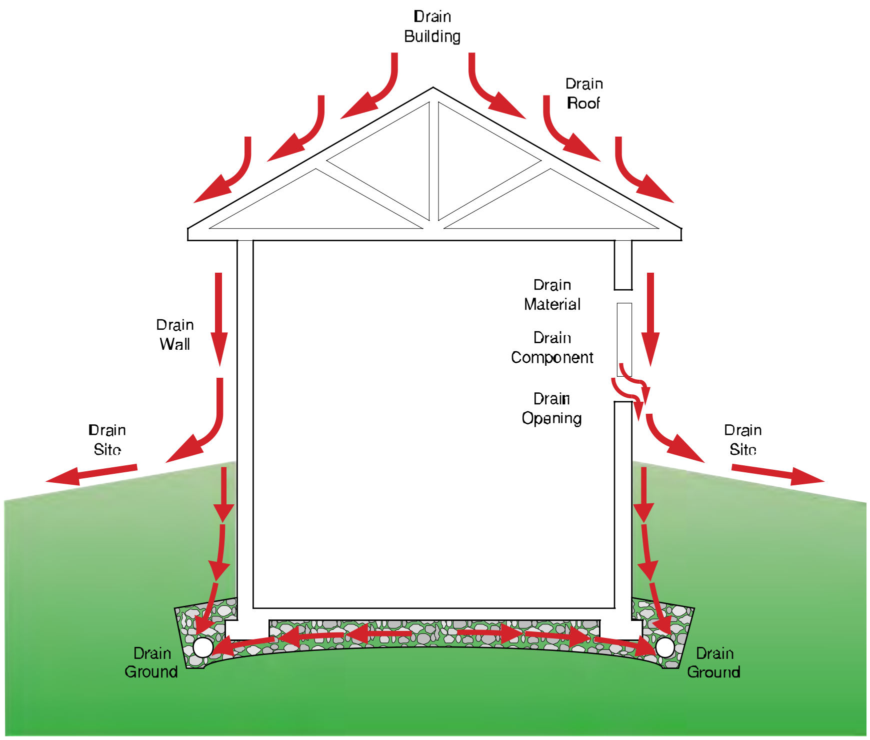


Figure 1: Fundamental Rainwater Control

While these requirements apply to all buildings, the design and implementation of the water control system of the enclosure and the ability for moisture in the enclosure to dry need more attention for a high performance enclosure. Due to the airtightness, type of materials, and thickness of a high performance enclosure, it cannot be assumed that water or moisture that gets into the enclosure will be able to dry. The design of the enclosure must minimize the potential for water getting past the water control system but also provide specific support for drying of any water or moisture that does get in.

The water control system for the roof and walls of a house is usually provided by a water control layer (e.g., building wrap or membrane) located just behind the cladding or roofing that is interconnected with flashings, window and door installations, and other penetration drainage mechanisms. All connections between components of the water control system must be shingle-lapped so that water does not get behind the water control layer as it flows down. If tape is used on the water control layer, it must be tightly adhered to the surface; any "fish-mouthing" at the top edge of the tape will collect rather than shed water, ultimately allowing water through the water control layer. With the water control layer directly behind the wall cladding, there needs to be a gap between the cladding and the water control layer sufficient to allow drainage.

Provision for drying of the wall depends on the design of the high performance enclosure. For example, if drying to the exterior is prevented by the presence of vapor impermeable materials on the exterior, such as insulating sheathing applied over the structural sheathing, there must be sufficient vapor permeability of the materials to the interior side of the sheathing to allow drying. Since this vapor permeability will also allow vapor from the interior to enter the enclosure, an analysis must be made to verify that the amount of exterior insulation is sufficient to keep the structural sheathing warm enough to minimize the risk of condensation.[12]

2.2.6 Principle 6: Configure building on site to maximize renewable energy potential

To achieve a net-zero energy house, clean and renewable energy must be generated on site. This is usually in the form of solar energy systems, but it could also be a ground source heat exchange loop, wind or water power, or some type of biomass. The site layout and the orientation and form of the house should take into account plans for the inclusion and possible future addition of renewables.

For solar energy, the location on the site with the largest unshaded southern exposure needs to be reserved for the solar renewables. For photovoltaics, this location may be used for a ground-mounted array of panels or for a roof-mounted array on a south facing sloped roof of the house or of an outbuilding such as a garage; for solar thermal, the panels should be placed as close to the point of use as possible to minimize heat loss and frictional losses in the pipes between the panels and the end use. When using a south facing roof for solar panels, it is best if the slope of the roof is within the optimal range recommended for solar panels in the region, which is typically the same as the latitude of the site[13]; in this case the panels can be laid flat on the roof which will maximize the number of panels that can be installed as well as their efficiency. If the site is large, a site survey and shade analysis may be useful in determining the optimal location for the solar array. For a small site, the best solution is to simply incorporate as much unshaded south facing roof surface as possible; Figure 2 shows one such installation in which the entirety of the available roof is used for solar panels.

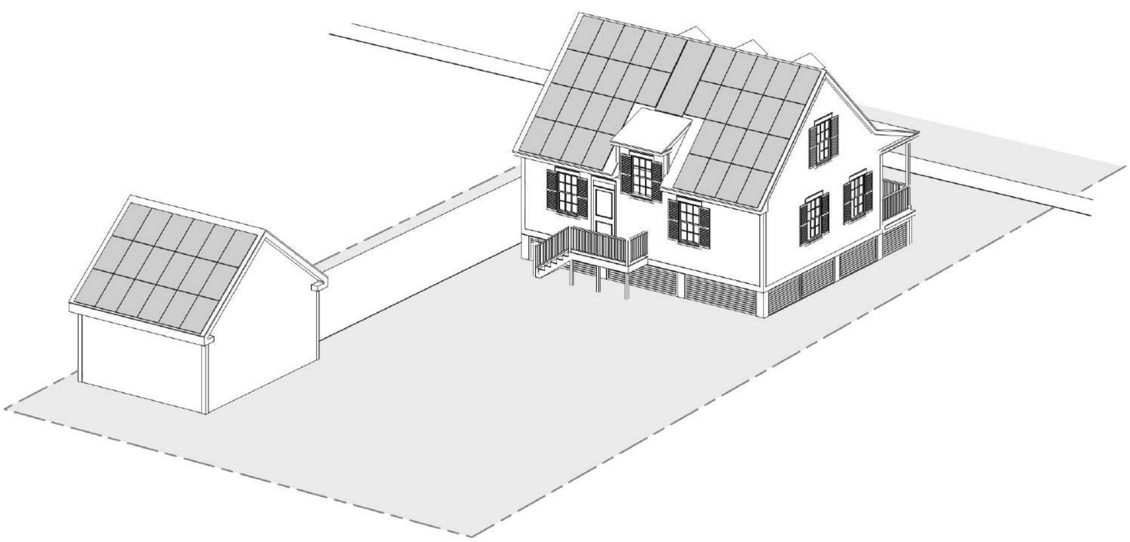


Figure 2: Solar Panel Distribution on a Small North-Facing Lot

[12] Lstiburek, J. (2008a).

[13] U.S. Department of Energy, "Installing and Maintaining a Home Solar Electric System" http://energy.gov/energysaver/articles/installing-and-maintaining-home-solar-electric-system. Last accessed August 26, 2014.

Passive solar energy can be collected and transferred into the house by placing windows on the southern exposure of the house. However, too much exposed southern glazing can cause overheating in the summer and even in the winter. Therefore, careful sizing and placement of the windows and design of overhangs or other shading methods are needed in order for this solar energy strategy to actually reduce net energy use.

For wind power or a ground source heat exchange loop, the location of the renewable equipment depends on other site features such as soil type or predominant wind direction. Thus a general layout of the renewables equipment on the site will inform the options for the placement and orientation of the house.

In addition to orienting or placing the new house in a location that is compatible with provision of the renewable energy source, orientation for other energy reduction strategies appropriate for the climate region should be considered. For example, the orientation, layout and form of the house should be arranged to take advantage of daylighting, to support passive solar heating, to avoid unwanted solar heat gain, and to create unconditioned or semi-conditioned living space such as a three-season porch.

2.2.7 Principle 7: Select efficient mechanical equipment

For standard residential construction, heating and cooling typically consumes more than half of the annual energy use in most climates. With a high performance enclosure, the heating and cooling load is significantly reduced and accounts for a smaller part of the total energy consumption. For example, for a BSC case study of a net-zero energy capable house design in a heating dominated climate, the source energy consumption for heating and cooling accounted for more than 54 % of the total annual source energy use if standard construction were to be used. (Building Science Corporation, 2010a) However, with a high performance enclosure, the heating and cooling source energy use was reduced to 25 % of the total (see Figure 3).

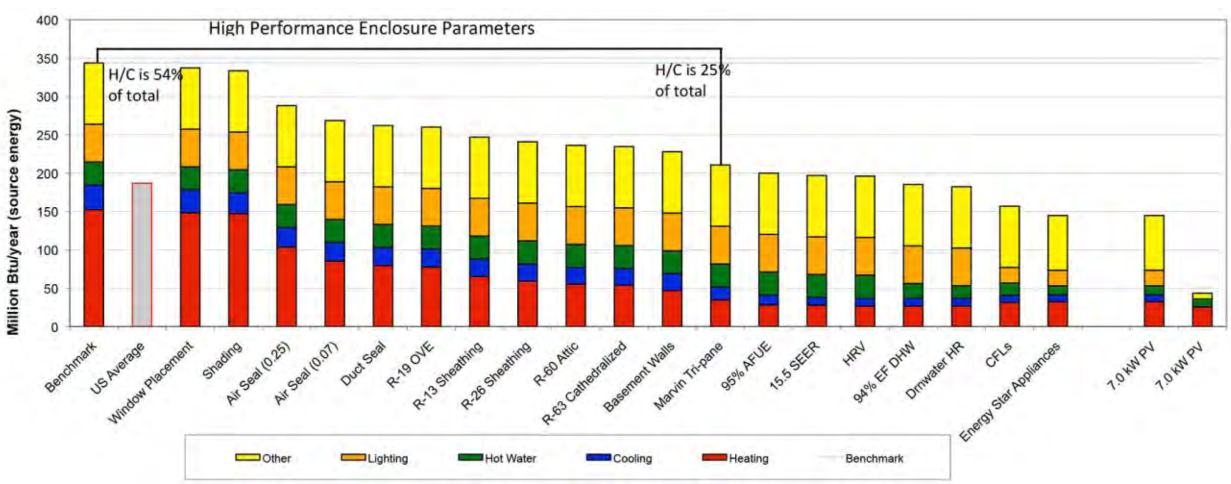


Figure 3: Parametric Study for Concord Cape Prototype; taken from Building Science Corporation (2010a)[14]

With the smaller heating and cooling loads of a high performance enclosure, smaller and more efficient mechanical equipment can be selected to further reduce energy use. Options for highly

[14] Building Science Corporation (2010a).

efficient forced air heating and cooling include an efficient furnace for heat and an efficient heat pump for cooling; an efficient heat pump for central air heating and cooling; or one or more mini-split air source heat pumps for both heating and cooling. A hydro-air system with a sealed combustion high efficiency gas boiler may also be an efficient heating solution. It is important that the heating and cooling system not be oversized since, in most cases, that will reduce the overall efficiency of the system. For a small house with very low heating and cooling loads, use of a mini-split system may be the only system that is small enough. The most important characteristics are that the system be efficient, be sized correctly, and be installed, operated, and maintained in a way that is consistent with the capabilities of the system.

Even though electricity is generated on site for a net-zero energy capable house, an all-electric system may not provide the most energy efficient solution. If natural gas is available at the site, the use of an efficient sealed combustion gas rather than electric furnace or boiler may result in lower source energy consumption.

Traditionally, dehumidification of living space has been assumed to be adequately provided by the air cooling system. However, with the reduced cooling load of a high performance enclosure, the cooling system may not run long enough to provide adequate dehumidification. Therefore, supplemental dehumidification should be considered in climates that require cooling.[15]

All ductwork and mechanical equipment should be located in conditioned space; otherwise it is any leakage or heat transfer leads to wasted energy. In addition, supply trunks should be insulated and all ductwork should be sealed so that conditioned air is delivered as designed. Hot water heat loss is reduced by insulating the pipes and by placing all hot water use in the same general section of the house. Energy efficient options for hot water heating include a gas water heater, a solar hot water system with gas or heat pump backup, or gas or electric tankless systems. Any gas space and water heating appliance used must have sealed combustion.

All of the energy efficient mechanical systems should be designed, installed, and commissioned by an HVAC professional who is familiar with the specified systems and with low energy houses. Controls for the equipment need to be straightforward and fully explained to the occupants.

2.2.8 Principle 8: Select efficient lighting layout, fixtures and appliances

The best way to keep energy consumption of interior lighting low is to design a lighting system that meets, but does not exceed, the needs of the occupants. The design should clearly distinguish between ambient lighting, task lighting, and accent lighting based on the functions to be performed at particular locations within the house. The ambient lighting level can be quite low. The building orientation, room layout and window placement should maximize useful daylighting in those areas that are used during the day. High efficiency, Energy Star qualified lighting fixtures with fluorescent or LED lamps that provide high quality light should be specified. And finally, lighting controls should be convenient and simple.

The refrigerator, dishwasher, and clothes washer should be Energy Star certified. All appliance selection should also take into account the posted energy use ratings to determine how the different products available will contribute to energy consumption. Less energy will be used if

[15] Building Science Corporation (2009c).

the appliances selected adequately meet the occupants' requirements but do not exceed what is needed in size or in function. If natural gas is available at the site, selection of gas appliances may result in lower source energy use.

In general, integrated home control and monitoring systems are not needed for a low energy house. Inclusion of any such system should be based on the expectations of the occupants rather than installed as an energy reduction strategy.

2.2.9 Principle 9: Use energy modeling to further reduce and project total energy use and to size on-site renewables

While energy modeling or other forms of energy use projection will have been used to make decisions throughout the design, the primary focus up to this point has been selecting reasonable low energy use strategies and meeting the requirements of the occupants. The next step is to perform a thorough and detailed analysis of the projected energy loads and energy consumption.

The energy modeling method needs to be detailed enough to accurately reflect the important characteristics of the location, the site, the enclosure and the layout of the house, to calculate and categorize loads (heating, cooling, hot water, etc.), to size mechanical equipment, and to project and categorize energy consumption on daily, monthly, and yearly bases. Methods to effectively model newer energy saving technologies such as tankless water heaters, solar thermal with a backup water heater and geothermal systems are also needed. Using the information generated by the analysis, additional energy reduction can be explored or tradeoffs between other possible strategies can be considered.

After the energy use has been reduced as far as is possible within the constraints of the project, the size and layout of the on-site renewable energy can be finalized. If there is sufficient potential for the on-site renewable energy to exceed the final projected annual energy consumption, the designed house will be net-zero energy capable. Whether the house meets the goal of net-zero energy or not will depend upon the future actions of the occupants.

2.2.10 Principle 10: Include coordination and commissioning of systems in the project plans

The construction techniques required for a high performance enclosure have some important differences from those used for standard residential construction. Similarly, the mechanical equipment specified for a low energy house differs from standard equipment. If the building enclosure is not built correctly or the mechanical equipment is not installed and commissioned correctly, not only will the house fail to be low energy but it will also be very uncomfortable. Therefore, the project plans and documents must be very specific about construction techniques, testing and verification to be performed and commissioning required of all systems including the renewables.

The best results will be obtained if everyone on the team understands the goals of the project, the reasons that particular techniques and tests were specified, and the operational parameters that need to be met by the specified equipment.

3. Design of the NZERTF

All of the principles described in Section 2 were applied to develop the strategies for reaching the net-zero energy goal during the design of the NZERTF. The following sections describe how the resulting design incorporates and supports specific energy reducing techniques to be net-zero energy capable.

3.1 Overview of Design of NZERTF

This section covers the background, general requirements and design decisions made about the form and layout of the house.

3.1.1 Purpose and General Requirements

In the fall of 2009, the Energy and Environment Division of NIST's Engineering Laboratory began to work with BSC to design a high performance, net-zero energy capable house to be located on NIST's Gaithersburg, MD campus for use as a research and test facility. The style and size of the house was to be a typical residence that might be built in the local suburban area for a family of four. The house is to be used as a demonstration home for the first year following completion to show that net-zero energy use can be met using roof-mounted photovoltaics while still maintaining the aesthetics and life style typical for homes in the surrounding area and delivering indoor environmental quality that meets or exceeds that in typical homes. During the demonstration phase, energy use is to be tracked for a simulated family of four "occupying" the house using techniques developed by the NIST researchers. Following the demonstration phase, the house is to be used by the NIST researchers as a measurement science laboratory to develop and assess performance metrics and evaluate current and emerging systems for net-zero energy homes.

3.1.2 The NZERTF Site

Gaithersburg, MD is in climate zone 4A (Mixed Humid). The general criteria for this climate zone are as follows: more than 508 mm (20 inches) annual precipitation, less than or equal to 4500 cooling degree days at 10 ^{o}C (50 ^{o}F) basis and less than or equal to 5400 heating degree days at 18 ^{o}C (65 ^{o}F) basis. While the heating load often predominates in a Mixed Humid climate, the cooling and humidity loads are also significant.

The site for the house is a large south-facing lot that rises about 3 m (10 ft) above the road within the first 30.5 m (100 ft). The slope is less steep in the other directions. There are mature trees along the east and west edges of the site. Since solar energy is to be used to meet the net-zero energy goal, shading studies of the site were performed by NIST. It was determined that the best location for capturing solar energy would be just north and west of the crest of the hill. Use of this location required that several plum trees to the south and southwest be relocated to other parts of the campus, but all of the mature trees aligning the site to the east and west could remain. While these trees provide some obstruction of view from the east and west, the site – and therefore the house – is clearly visible from both the south and the north (see Figure 4).

Figure 4: NZERTF Site Plan

Electricity, communication cable, natural gas, water, sewer, and storm drainage are available at the site. During the demonstration phase, the house is to be configured as an all-electric house. Following that, natural gas equipment will be used, so gas lines were brought to the house and capped for future use. In addition to the solar energy, geothermal energy is planned for use after the demonstration phase so three types of geothermal loops were installed to the south, to the northwest and to the north of the house and capped for future use.

3.1.3 House Design Decisions for Net Zero Goals

The design of the house is based on a modern, enlarged Dutch Colonial style with a full unfinished basement, a first floor with a side extension to the east for additional living space, and a nearly full second floor with front and rear shed dormers (see Figure 5). Porches on the front and back of the house provide additional living space during the shoulder seasons and add exterior features to the two most visible sides of the house. The interior of the house includes a typical modern kitchen at the rear with adjacent dining area, a living room at the front, a master bedroom suite on the second floor, three additional bedrooms one of which is on the first floor and can be used as an office, and three full bathrooms. The total interior living space is about 250 m^2 (2700 ft^2). This style of house with a similar interior layout can be found throughout the mid-Atlantic region as well as in New England.

Figure 5: 3-D Rendering of NZERTF from SSE

3.1.3.1 Exterior Design

In this section, general design decisions about the exterior that were made specifically to address energy efficiency and/or durability of the house are described.

House Form and Orientation

The relatively compact footprint and volume of the house contributes to energy efficiency primarily because of a low surface area to volume ratio. Even though this type of house can accommodate nearly a full second floor, the roof configuration lowers the overall profile of the house and reduces the exposed wall surface area.

With solar energy as the renewable energy source, a south-facing sloped surface is needed on which photovoltaic panels can be mounted. The 4:12 sloped roof of the shed dormer across the front of the house provides a fully unshaded surface for the solar panels. The roof of the porch (also 4:12) can be used for this purpose as well. While this slope is not ideal from the perspective of optimizing solar production, it represents a typical configuration in residential construction.

The south-facing roof of the detached garage, that is located to the west side of the house, provides additional space for solar panels. For the demonstration phase, the garage roof is not to be used for photovoltaics; but should additional or alternative solar panels be needed for research purposes, the 9.5:12 sloped garage roof could be used.

Location, Type and Size of Windows

With the house placed on the site to maximize sun exposure, techniques for controlling solar heat gain were considered while determining the number, location and size of the windows. Table 1 shows the distribution of the total window area over the exterior walls.

	North	South	East	West	Total
Surface area of exterior wall	71.3 m^2 (767 ft^2)	71.3 m^2 (767 ft^2)	83.7 m^2 (901 ft^2)	83.7 m^2 (901 ft^2)	310 m^2 (3,336 ft^2)
Total area of glazing	11.7 m^2 (126 ft^2)	16.5 m^2 (178 ft^2)	6.2 m^2 (67 ft^2)	4.2 m^2 (45 ft^2)	38.6 m^2 (416 ft^2)
% glazing of surface area	16.4 %	23.2 %	7.4 %	5 %	12.5 %

Table 1: Exterior Window Distribution

In a mixed-humid climate, solar gain through south-facing windows can lower the heating load during the winter but increase the cooling load in the summer. The general guideline in this climate is to place south-facing windows so that they are fully blocked in the summer to prevent solar heat gain but exposed to allow solar heat gain in the winter. For the NZERTF design, there is more glazing on the south facade than on any other side. The windows on the 2nd floor and in the living area extension to the east are directly below an overhang; the depth of overhang is designed so that the summer sun at its solstice is totally blocked by the overhang whereas the winter sun at its solstice reaches the entire window. The first floor south-facing windows along the main section of the house (about 44 % of the south-facing glazing) are fully shaded in the summer by the roof of the front porch; during the winter, about 50 % of that glazing is unshaded (see Figure 6).

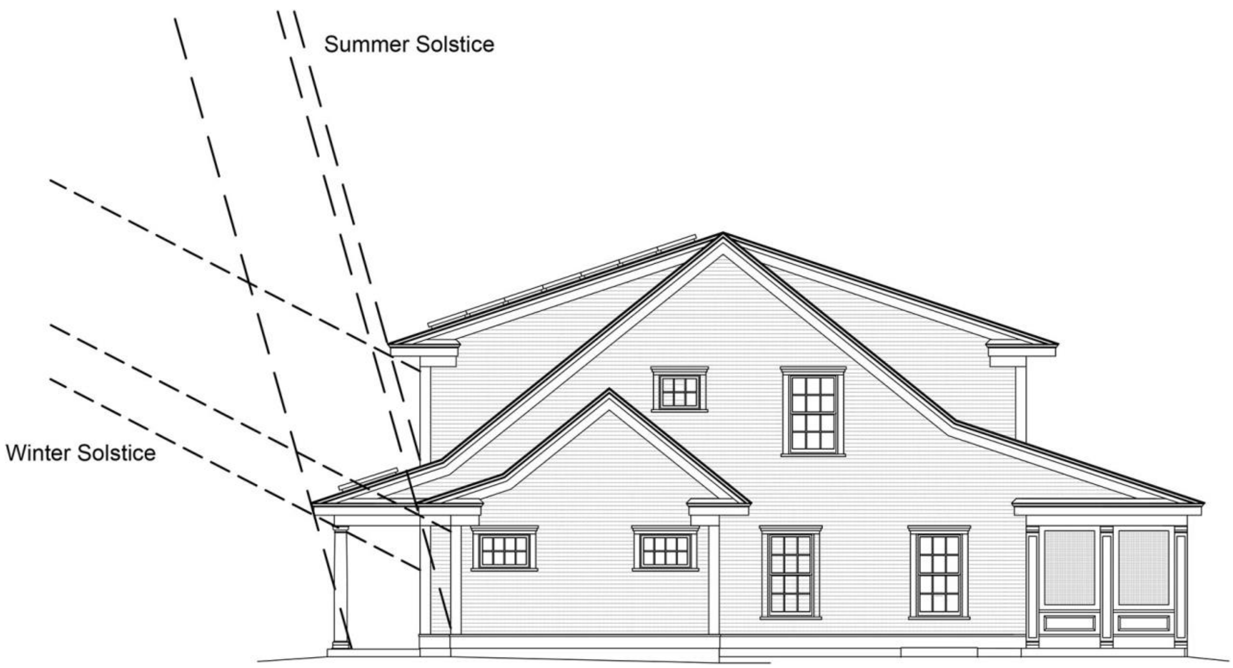


Figure 6: East Elevation with Summer & Winter Solstice

Because of the deep front porch, the full potential of solar heat gain during the winter of the first floor south-facing windows is not realized. However, the front porch provides a number of other benefits: aesthetically, the porch roof connects to the main gable roof and extends it forward from the base of the front shed dormer so that the house appears less tall when viewed from the road below; the shaded porch provides an extended living space during temperate weather; and the porch roof provides additional south-facing roof area for installation of solar panels. Since the house design only has a minimal amount of interior surfaces with thermal mass (mainly tile and drywall) a tradeoff was made in favor of the benefits provided by the porch roof versus the maximum solar heat gain that could be obtained in the winter through the four first floor front windows at the porch.

Sunlight coming in through the glazing on the east and west contributes to the passive solar gain of the building enclosure during the winter; unshaded east and west facing glazing adds to the cooling load with unwanted solar heat gain during the summer. For the east and west sides, glazing is only about 7.4 % and 5 % respectively of the surface area. Windows on the north side contribute to the heating load during the winter because of the relatively low thermal resistance of glazing. About 16.4 % of the north facing wall is glazing but nearly one-third of that is the patio door leading to the screen porch and thus is somewhat protected from exterior conditions. This conservative use of glazing is consistent with the style of the house and the low energy use goal but is sufficient to provide natural lighting and ventilation for the interior where needed as is described later.

All windows are double hung except where interior or exterior conditions require a shortened window in which case awning windows were specified. One low energy use strategy would have been to use only casement and awning windows since these are generally more airtight than double hung windows. This approach was not used for the NZERTF since that would not be typical for a house of this style.

3.1.3.2 Interior Design

This section describes general interior house design decisions that were made specifically to address energy efficiency of the house.

Room Layout and Window Distribution

The main section of the floor plan of the NZERTF is approximately square. The living spaces and bedrooms were placed in corners of the plan with the circulation occurring in the center (see Figure 7). With this layout, all rooms have windows on at least two adjacent sides. Since all windows are operable, this supports the use of natural ventilation as an option both within the individual rooms and, if room doors are open, for the entire house when the weather is appropriate. An advantage of a double hung window is that airflow can come from the bottom or the top. Lowering the top sash allows for natural ventilation while still providing privacy.

The window arrangement also provides daylighting in the living areas throughout the day. In the second floor bedrooms, most of the daylighting is provided by the north- or south-facing windows because the east or west windows are located in alcoves which limit the range of the natural light.

Figure 7: First Floor (left) and Second Floor (right) Plans

It was a tradition in old New England houses that the front of the house face south and the kitchen, as a source of heat, be on the north; with this arrangement the kitchen augments the heat in the winter and avoids overheating in the summer.[16] While modern kitchen appliances minimize this effect, there is still some validity to this reason for placing the kitchen on the north side. But more beneficially, with this location the kitchen has the best natural lighting because light from the north does not produce glare and is even throughout the day.

The layout of the house was arranged so that all bathrooms, the kitchen and the laundry are in the same quadrant of the house – the northwest quadrant. Since the hot water heater is also located in the northwest quadrant of the basement, this simplifies the plumbing and minimizes the length (and heat loss) of the water lines.

Conditioned Attic and Basement

Since both the attic and the basement were to contain mechanical equipment, they were both included in the conditioned space. Heating, cooling, ventilation, and hot water equipment as well as ductwork are located in the basement. The inverters for the solar panels and some ductwork are located in the attic. The basement is actively conditioned with supply diffusers whereas the attic is conditioned through transfer vents between the 2nd floor and the attic.

Built-in Chases for Ducts

To support future research efforts, a large amount of ductwork must run between the basement and rest of the house. To provide space for vertical ductwork, the interior design included several chases integrated as design elements. Thickened walls were designed between the entry hall and the living room, between the entry hall and the back of the house, and between the living room and the dining area to create formal entries to the spaces while providing ductwork chases from the basement to the 2nd floor. Similarly, two "columns" on either end of a room divider between the kitchen and the dining area function as chases up to the 2nd floor. There is also a hidden chase

[16] Brown, G.Z. and DeKay, Mark (2001), p. 145.

connecting the basement to the attic through "dead space" behind the hall walls on the first and second floors.

In addition to the chases, the wall between the kitchen and the 1st floor bathroom was widened to a 38 mm x 140 mm (2x6) partition to provide more space for ductwork and plumbing in that wall.

3.1.4 Additional special requirements

In many ways, the NZERTF was designed as a typical net-zero energy capable house. However there were some additional requirements that required special attention during design as described in this section.

3.1.4.1 Accessibility

The house was designed so that all entrances and all movement through the first floor are barrier-free based on the Uniform Federal Accessibility Standards (UFAS) (Code of Federal Regulations, 1997) and so that the first floor bathroom is accessible. In addition, access to the garage was designed to be barrier free.

Both the staircase to the basement and the main interior staircase were designed to be wide enough and to have adequate wall support for future stair lifts. To permit access to the stair lift to the basement, the opening at the top of the basement stair would need to be widened to the full width of the basement staircase. Also, the closet at the top of the main staircase would need to be opened to provide a storage place for the stair lift when not in use. Since these openings are within a bearing wall, the structure was designed to span across them so that this adaptation can be made in the future without requiring structural changes.

3.1.4.2 Support for research

In addition to the systems installed for use during the demonstration phase, support was provided for future systems including duplicate ductwork for the central air system run-outs for an alternative air distribution system; ductwork for a future ducted 2-1 multi-split system; tubing for future radiant floor heating in the basement slab; capability for two central air handlers to be in place concurrently. Also, ductwork for a future high velocity cooling system was installed using a design provided by NIST.

The design of the electrical system was required to provide several independent systems – one for normal household use only, one for garage use, and one for instrumentation and monitoring. Only electricity for normal household use is subject to the net-zero energy use requirement.

3.1.4.3 Made in USA

Because the construction costs were funded by ARRA, a "Buy American" provision applied to the project. NIST's implementation of this provision required that all products delivered to the site have documented proof that they were manufactured in the U.S. Exceptions to this requirement were allowed only if it could be demonstrated that no U.S.-made product could be substituted and still deliver the function and energy use parameters required to meet the net-zero energy goal.

3.1.4.4 LEED for Homes Certification

The building was to be LEED Certified under the LEED for Homes 2008 standard. During the design phase, it was determined that LEED for Homes Platinum would be achievable. This added certain requirements that were not related to the net-zero energy goal, but contribute to sustainable practice.

3.1.4.5 NIST-provided Indoor Air Quality (IAQ) Specification

As part of the NIST research effort associated with the NZERTF performance, the indoor air will be monitored for volatile organic compounds (VOC) and aldehyde levels. In support of this effort, specific restrictions were provided by NIST for the contents of products used in the building's construction. The products to which these restrictions applied include structural wood products, adhesives and sealants, interior wood-based products, interior paints and other coatings, interior-side insulation, cabinetry and wallboard. These restrictions were stricter and more specific than those in LEED for Homes.

3.2 Structure Design Decisions for Net Zero Goal

The structure for the NZERTF is typical of conventional construction but there were several structural design decisions made specifically to improve energy efficiency or to support a specific NZERTF requirement. These are described in the following sections.

3.2.1 Advanced Framing

The framing uses an approach often referred to as "advanced framing."[17] This technique replaces the standard 406 mm (16 in.) on center (o.c.) 38 mm x 89 mm (2x4) or 38 mm x 140 mm (2x6) construction with 38 mm x 140 mm (2x6) framing at 610 mm (24 in.) o.c. along with single top plates, 2-stud corners, single headers in bearing walls, no headers in non-bearing walls, no blocking at partition walls, no jack studs and no cripples. Rafters and floor joists are also installed at 610 mm (24 in.) o.c. rather than the standard 406 mm (16 in.) o.c. Use of advanced framing reduces the amount of wood that is required and increases the volume of cavity space so that more cavity insulation can be installed. For the NZERTF, all interior partitions, as well as the center east-west load-bearing wall, were also framed at 610 mm (24 in.) o.c. This provides slightly more space within the interior walls that can be used for ductwork or other equipment.

For some implementations of advanced framing, the exterior plywood or oriented strand board (OSB) sheathing of standard construction is also eliminated except where required as shear panels. However, for the NZERTF, plywood sheathing was applied to all of the framing. Because of the wind exposure design criteria for the NZERTF site, the wall sheathing is needed to resist the roof uplift. Since plywood is not available in sheets that are long enough to span from the sole plate to the top plate, horizontal blocking was added to the wall framing where needed to secure the ends of the plywood sheets as required to resist the uplift.

Wall framing elevations for all exterior walls and for the interior bearing wall were developed during design and included in the NZERTF construction set. These elevations show the location and size of every framing element and sheathing panel and indicate the size of the header in those places where a header is needed. Also included in the construction set are 3-dimensional drawings showing the advanced framing details. The details for the 2-stud corners and the termination of partition walls demonstrate the use of drywall clips to attach the interior gypsum wallboard (see Figure 8).

---

[17] Lstiburek, J. (2010).

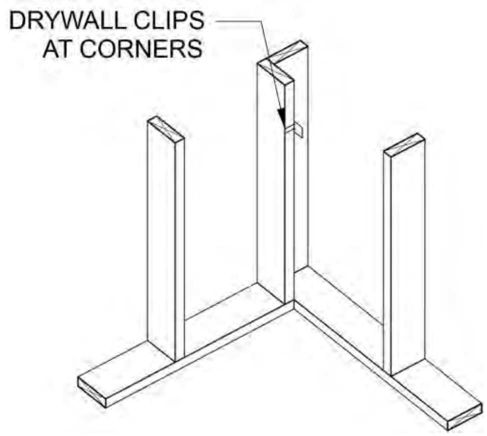


Figure 8: Advanced Framing: Bottom of 2-Stud Corner (from Construction Set)

While 610 mm (24 in.) o.c. framing is acceptable for supporting interior gypsum wallboard, it is preferable to have 406 mm (16 in.) o.c. support for tile backer board because of the potential weight of the tile. For the NZERTF, 406 mm (16 in.) o.c. interior-side horizontal ladder blocking was added to the exterior wall framing in those areas where there was to be tile on the interior.

3.2.2 Open-Web Floor Trusses

To accommodate the layout of the ductwork, as well as to make it easier to add cabling and wiring in the future, 356 mm (14 in.) deep open-web wood trusses were specified for the 1st and 2nd floor joists. Several removable access panels were called for in the 1st floor ceiling and on the 2nd floor (in closet floors) so that the NIST researchers would have access to the space below the floor. The basement ceiling trusses are left exposed for the same purpose.

Using the duct layout and duct sizes, BSC designed the web pattern of the open-web trusses so that the ducts could pass through the trusses where called for in the layout. The nine truss types and the type of each floor joist were specified in the construction drawings. Figure 9 shows one of the truss types and indicates where ducts are to pass through the truss.

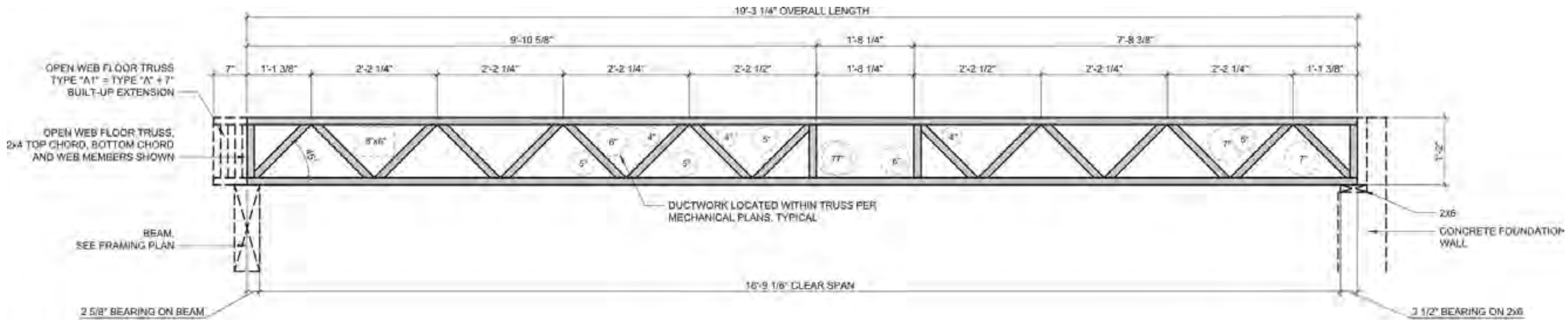


Figure 9: Truss Type A (from Construction Set)

The basement duct layout was designed so that all of the basement ductwork could be installed either within or directly below the trusses to maintain a basement head height no lower than the east-west structural beam at 2.3 m (7 ft, 6 in.).

3.2.3 Roof Structure

Although the house is designed to have generous overhangs, the laminated strand lumber (LSL) roof rafters do not extend beyond the wall but instead terminate at the outer edge of the exterior wall framing. Therefore, when the plywood sheathing is applied over the wall and roof framing, the roof sheathing and the wall sheathing meet to form an edge or corner. As is described later, this allows the air barrier membrane for the roof to be continuously lapped from the roof sheathing down onto the wall air barrier membrane so that there is no air leakage at the roof/wall intersection. Later in the construction sequence, a separate cantilevered structure for the roof overhangs was attached to the roof structure from above and embedded in the layers of insulating sheathing that are applied over the roof structure.

3.2.4 Top of Foundation Wall

In order to have accessible entrances, the first floor elevation needs to be the same as the elevation at the exterior of the entry doors. Rather than have the first floor joist extend over the foundation wall, which would put the first floor elevation 356 mm (14 in.) above the foundation wall and 508 mm (20 in.) above grade, the top of the foundation wall was designed to have a shelf and stem wall; the 356 mm (14 in.) deep shelf supports the floor joist while the exterior wall is supported by the stem wall. Using this approach, the first floor elevation is only 152 mm (6 in.) above the exterior grade and meets the elevation of the exterior surface at the three entrances.

A disadvantage of this approach is that it creates a thermal bridge through the concrete stem wall up to the exterior wall framing since the floor joist does not separate the concrete foundation wall from the exterior wall framing. To reduce the effect of the thermal bridge, the NZERTF design called for a layer of exterior insulation to be applied to the exterior face of the upper part of the foundation wall extending to below grade (see Figure 10). The exterior insulation is protected above grade by an aluminum coil stock cover.

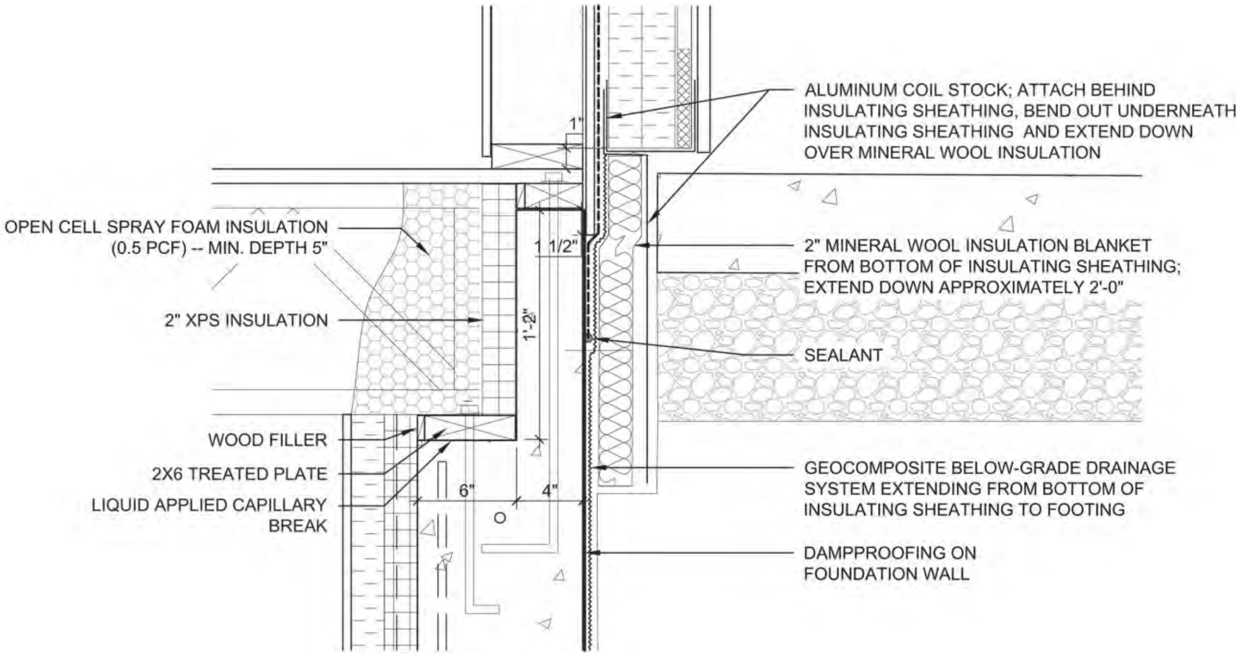


Figure 10: Top of Foundation Wall (from Construction Set)

3.3 Building Enclosure Design for NZERTF

The design of the building enclosure is the single most important factor in the design of a high performance building since this is the only contribution that the building itself can make towards controlling energy use. The design specifies all layers and materials that make up the physical separation between inside and outside. In particular, the enclosure design must include the design of the four control systems required of the enclosure: liquid water, airflow, water vapor, and thermal.

The water and vapor control systems are required for the durability of the enclosure. The airflow and thermal control systems reduce heat transfer between the interior and the exterior and thus control much of the heating and cooling load of the house. The basic approach to the building enclosure design for the NZERTF was to clearly specify each of the control layers for each component of the enclosure and then to design the details of the connections between components to create continuous and complete systems for each control function.

Insulation is the primary material in the thermal control system. The thermal resistance of the installed insulation as quantified by the R-value is the most widely used measure of heat loss through the enclosure. Achieving high R-values is a necessary part of any high performance enclosure design strategy. The following table shows the design R-values of the installed insulation for the NZERTF. For comparison, the table also shows the minimum prescriptive R-values by component required by the 2012 IECC for residences in Zone 4A. For the above grade components, the R-values for the NZERTF are nearly two times that called for by the prescriptive 2012 IECC.

	Sub-Slab	Fdn Wall	Ext Wall	Windows	Roof
Prescriptive 2012 IECC nominal R-value [m^2·K/W (ft^2·h·°F/Btu)]	1.8 (10)	1.8 (10)	3.5 (20)	0.5 (2.8)	6.7 (38)
NZERTF nominal R-value [m^2·K/W (ft^2·h·°F/Btu)]	1.8 (10)	4.1 (23)	7.9 (45)	0.9 (5.2)	12.7 (72)

Table 2: Insulation R-values by Component

More than half of the installed above-grade insulation is applied to the exterior side of the structure. Unlike cavity insulation, which is interrupted by framing, the full R-value of exterior insulation contributes to the installed R-value of the component, which illustrates one benefit of a continuous thermal control layer. Continuity of each of the control layers is important for the performance of the enclosure. A break in the water control system can allow water into the assembly. A break in the airflow control system allows air to flow through the assembly taking heat and moisture with it. A break in the vapor control system can result in condensation forming within the assembly. A break in the thermal control system creates a thermal bridge.

The NZERTF building section in Figure 11 shows the building enclosure components, the nominal R-value of the components and, except for the window and door, the primary location of the water, airflow, vapor and thermal control functions for each component.

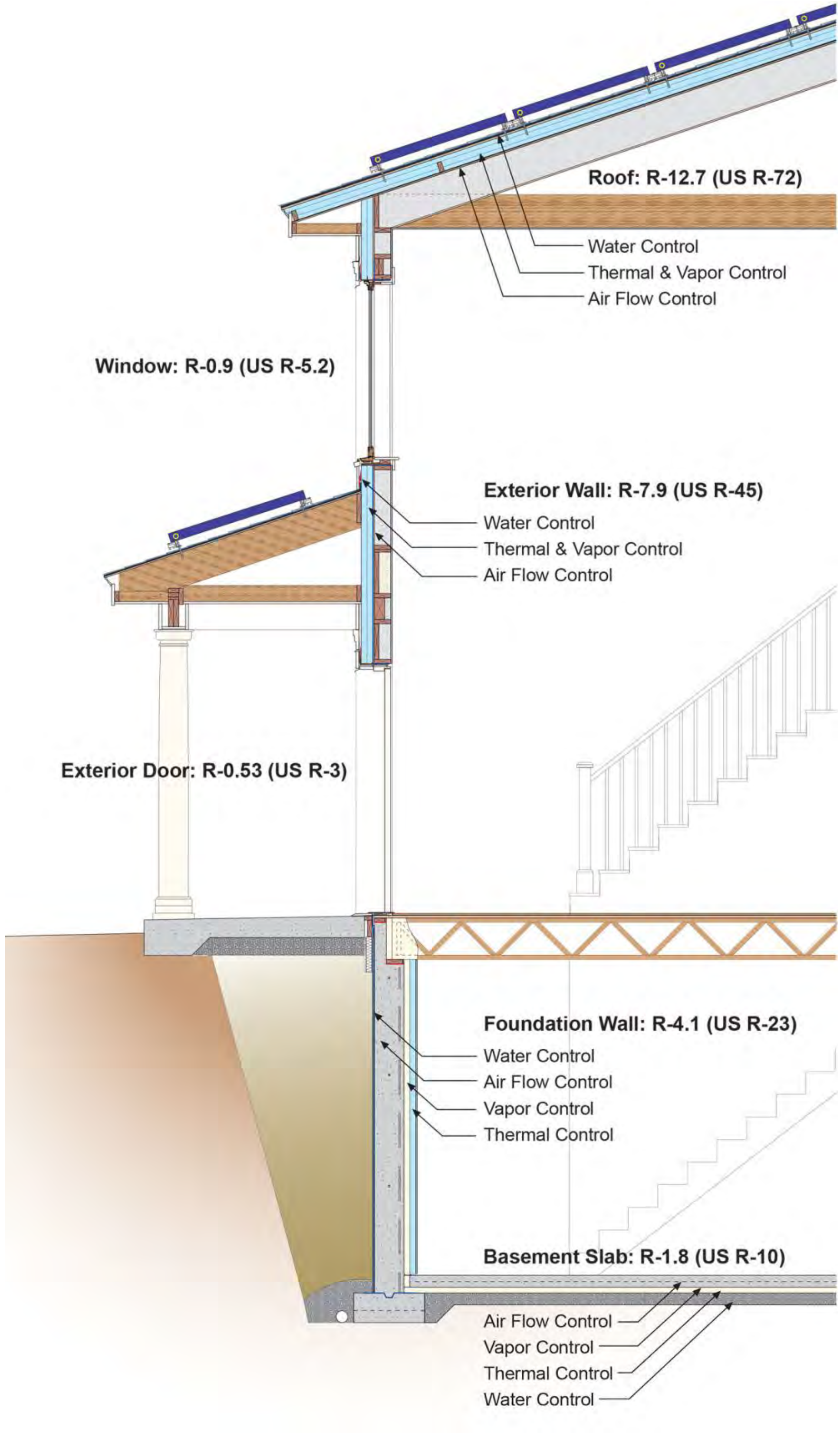


Figure 11: Building Enclosure Components with Nominal R-value in $m^2{\cdot}K/W$ ($ft^2{\cdot}h{\cdot}°F/Btu$)

The following sections describe the design decisions and details specific to the high performance requirements of the components of the NZERTF building enclosure.

3.3.1 Wall and Roof Enclosure Design

In an article published in 2008, J. Lstiburek explains that the "perfect wall" (and similarly the "perfect roof") is one which consists of layers for water control, airflow control, vapor control and thermal control all applied to the exterior side of the framing. The wall and roof enclosure design for the NZERTF are instances of the "perfect wall." [18]

The material layers of the NZERTF wall assembly from exterior to interior are as follows:

- fiber cement lap siding with venting/drainage gap behind,
- two layers of foil-faced polyisocyanurate insulating sheathing with seams staggered and outer seams taped (water, thermal and vapor control),
- fully-adhered air barrier membrane (rubberized asphalt integrally bonded to high density cross laminated polyethylene film) applied to the plywood sheathing (airflow control),
- plywood sheathing,
- cellulose cavity insulation (additional thermal control),
- interior gypsum wallboard with latex paint.

These layers can be seen in the exterior wall section shown in Figure 12.

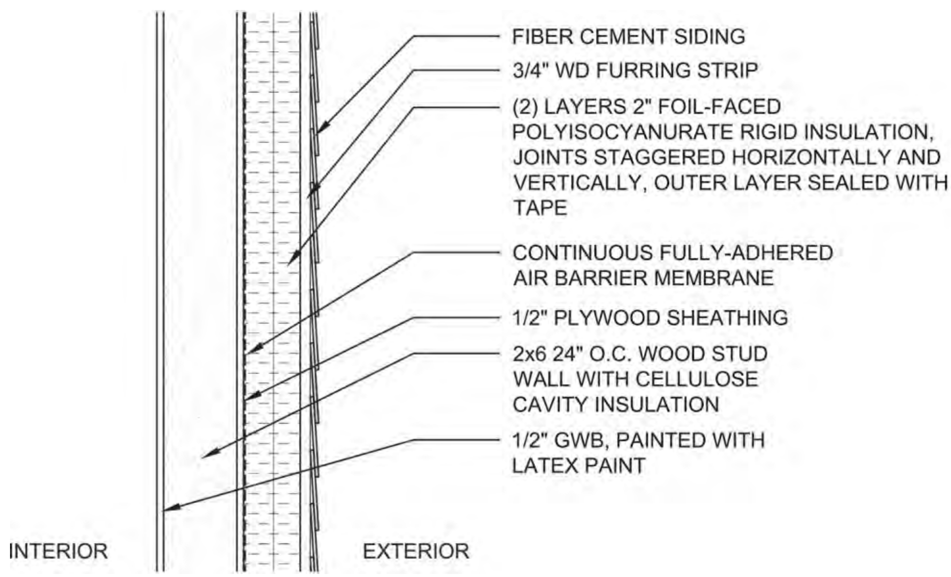


Figure 12: NZERTF Exterior Wall Section (from Construction Set)

Along the rim joist of the first and second floor framing, it is not feasible to use cellulose insulation for the cavity insulation, so open cell spray polyurethane foam replaces the cellulose to maintain the insulation level across those sections of the exterior wall.

[18] Lstiburek, J. (2008b).

The venting/drainage gap behind the cladding is required so that any rainwater that gets behind the cladding can drain down the water control layer until it is redirected to the outside by flashing or transferred to another part of the water control system. This gap also assists in drying the backside of the cladding. For the NZERTF design, the gap is created by the vertical wood furring strips that attach the insulating sheathing to the wall framing and serve as nailers for the cladding. During construction of the NZERTF, it was observed that nailers were needed at the sloped base of some of the walls for cladding attachment, but these could potentially block the drainage and venting functions of the furring strips. To ensure that the drainage function was still provided, the design was modified to include a space between the bottom of the furring strips and the sloped nailer so water can drain out along the top of the sloped nailer.

The material layers of the NZERTF roof assembly from exterior to interior are as follows:

- asphalt roof shingles,
- fully adhered roof membrane water control; rubberized asphalt integrally bonded to high density cross laminated polyethylene film) for water control over plywood roof sheathing,
- three layers of foil-faced polyisocyanurate insulating sheathing with seams staggered and taped on the middle layer (thermal and vapor control),
- fully-adhered air barrier membrane (rubberized asphalt integrally bonded to high density cross laminated polyethylene film) for airflow control applied to plywood sheathing,
- plywood sheathing over rafters,
- cellulose cavity insulation (additional thermal control),
- interior gypsum wallboard with seams taped (in attic).

These layers can be seen in the roof section shown in Figure 13.

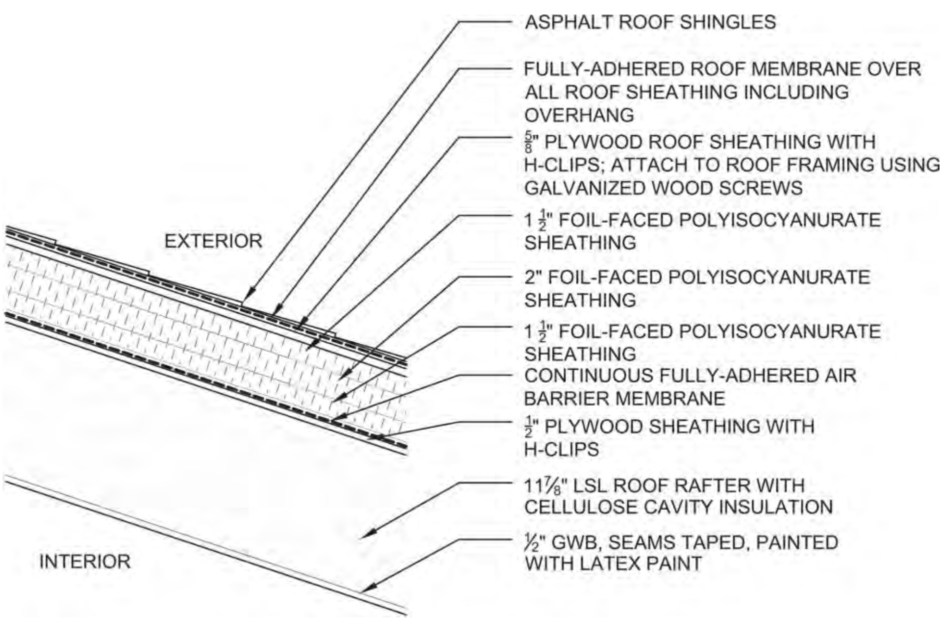


Figure 13: NZERTF Roof Section (from Construction Set)

Of particular importance for this design is the connection of the airflow control layers between the roof and the lower wall and the connection of the airflow and water control layers between the wall and lower roof. For both of these connections, the roof and wall plywood sheathing meet in an edge or corner, so the roof air barrier membrane overlaps and adheres onto the wall air barrier membrane for the former, and the wall air barrier membrane overlaps and adheres onto the roof air barrier for the latter. The water control layer at the wall to lower roof connection is designed so that the water control layer of the wall is transferred from the surface of the insulation sheathing to the step flashing which overlaps onto the lower roof membrane, which is the roof water control layer. The design of these connections is provided in details in the construction set (see Figure 14). In order to correctly implement these connections, the sequence of construction requires special planning.

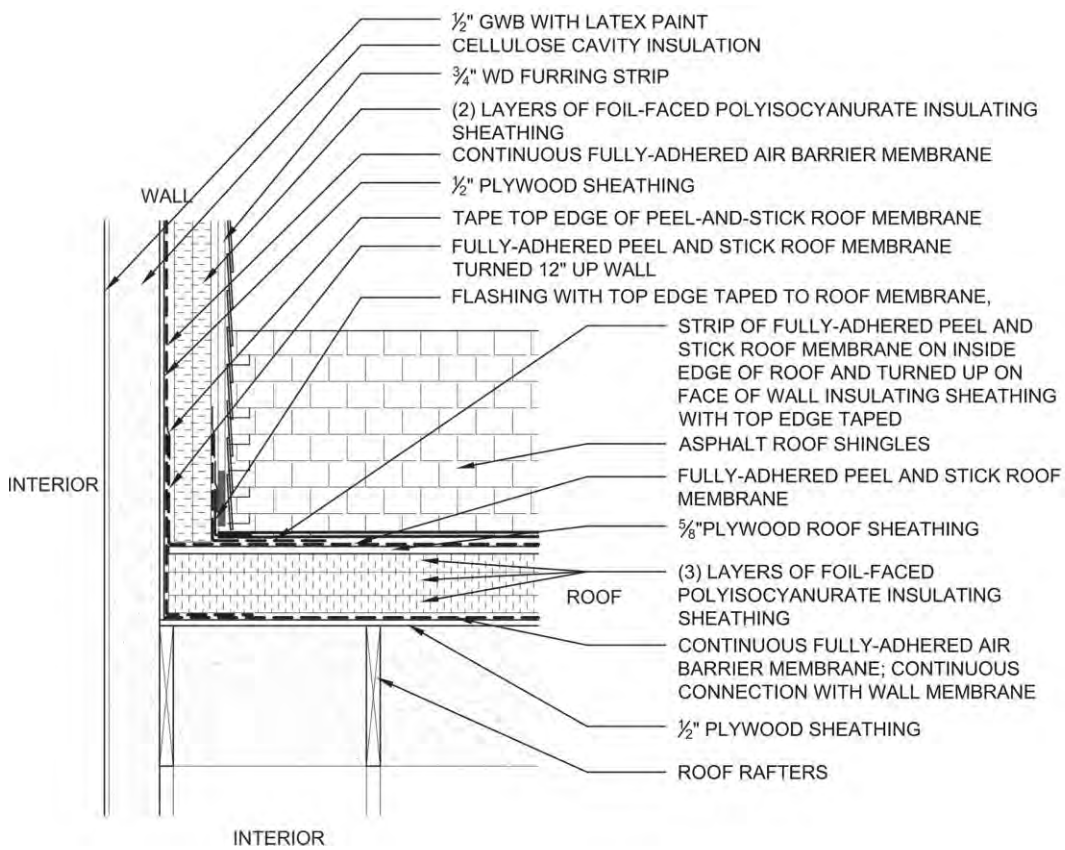


Figure 14: Wall to Lower Roof Intersection (from Construction Set)

The exterior insulating sheathing is vapor impermeable so this places the vapor control layer to the outside of the structure for both the roof and the wall. All materials located to the interior of the air barrier membrane are specified to be vapor permeable or vapor semi-permeable so that any moisture that gets into the interior part of the structure can dry to the inside.

Since most of the insulation for both the wall and the roof is applied to the exterior, the only places where thermal bridging may occur is at connections to other components. Only a single layer of plywood sheathing separates the exterior insulation where the roof and wall intersect, so the thermal bridge is effectively eliminated at that intersection (e.g., see Figure 14).

3.3.2 Foundation Enclosure Design

The foundation walls and basement slab complete the lower part of the building enclosure. As with the other parts of the building enclosure, the four control systems – water, airflow, vapor and thermal control – are required.

The material layers for the foundation wall, from exterior to interior, are as follows:

- free draining backfill (water control),
- geocomposite drainage board consisting of polypropylene and polystyrene (water control),
- polypropylene dampproofing (water control),
- concrete wall (airflow control),
- XPS insulation (thermal and vapor control),
- foil-faced polyisocyanurate insulating sheathing with seams taped (thermal, vapor and airflow control),
- gypsum wallboard.

These layers can be seen in the foundation wall section shown in Figure 15.

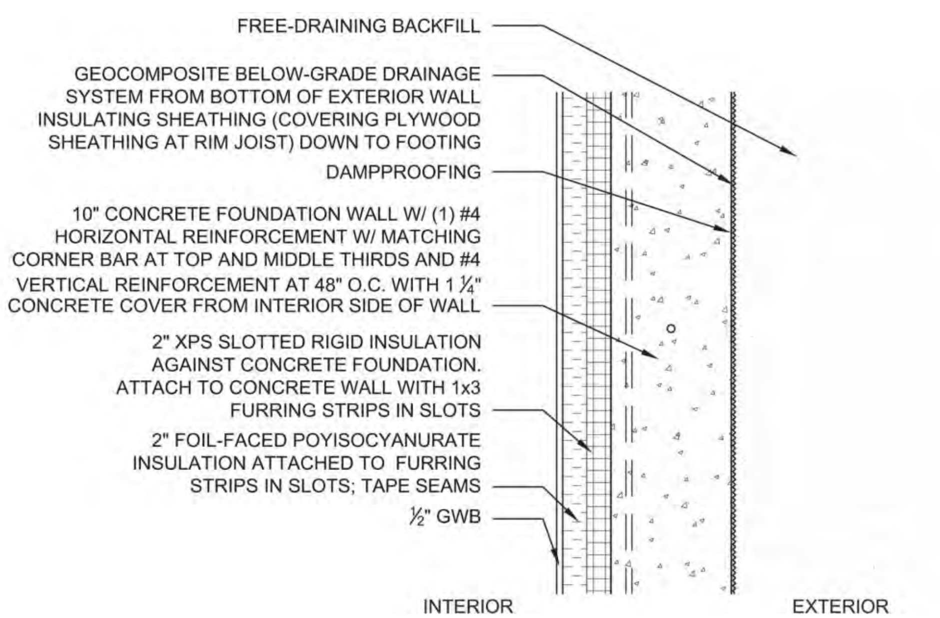


Figure 15: NZERTF Foundation Wall Section (from Construction Set)

The geocomposite drainage board, which extends from the base of the exterior wall insulating sheathing down to the footing, combines a drainage membrane, an air gap, and a filter. This board in combination with the free draining backfill prevents build-up of water against the foundation thereby eliminating hydrostatic pressure and directs ground water down to the perimeter footing drainage system. The dampproofing protects the foundation wall from absorption of groundwater via capillarity. The layer of XPS insulation applied against the interior side of the concrete wall prevents any remaining moisture in the concrete wall from moving towards the interior.

The material layers for the slab from exterior to interior are as follows:

- layer of stone (water control) over filter fabric,
- XPS insulation board (thermal control) – also along edges of slab,
- polyethylene vapor barrier membrane (vapor control), and
- concrete slab (airflow control).

These layers can be seen in the basement slab section in Figure 16.

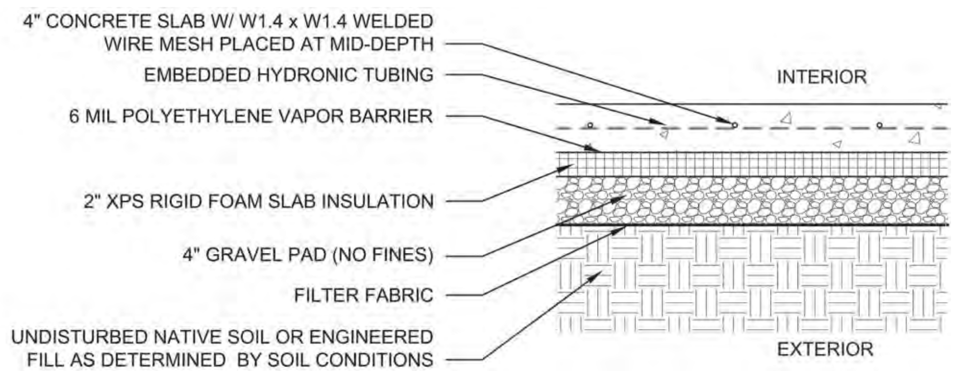


Figure 16: NZERTF Basement Slab Section (from Construction Set)

The layer of stone under the slab, which is a granular capillary break as well as drainage pad, is connected to the perimeter drainage system by pipe cast into the bottom of the footing. Thus it provides a groundwater storage buffer if needed (see Figure 17). There is a sump pit and pump in the basement that can discharge any build-up of sub-slab water to the outside. The condensate drain lines for the mechanical systems are also connected to the sump pit.

The airflow control system must be continuous throughout the basement even though it is mostly below grade; in this case, the intent of this requirement is to block the soil gas. The design detail of the airflow system connection between the basement slab and foundation wall shows how a bead of urethane sealant transfers airflow control from the slab to the XPS along the edge of the slab and then another bead transfers it from the XPS to the foundation wall (see Figure 17).

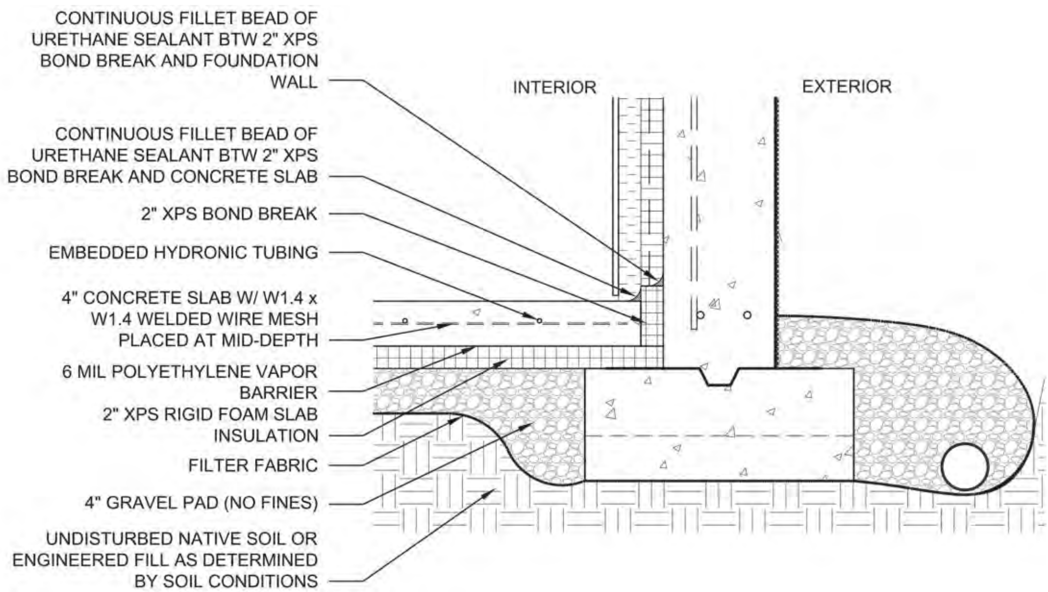


Figure 17: Detail at Basement Slab/Foundation Wall Intersection (from Construction Set)

Another aspect of airflow control in the basement is to minimize interior air from reaching the interior surface of the concrete foundation wall where it may condense. For the wall proper, the taped seams of the polyisocyanurate board suffice. For the beam pockets that are cast into the east and west foundation walls, the design calls for air sealing (using backer rod and urethane sealant) between the beam and the concrete for all edges of the beam pocket. This design detail is especially important because condensation in the beam pockets could damage the LSL beam.

3.3.3 Windows and Doors

Once the size, type and location of the windows and doors were determined based on interior and exterior design decisions, the remaining design decisions that impacted the enclosure performance were the thermal efficiency factors for products selected and the integration of the windows and doors with the control systems of the wall enclosure, especially water and airflow control.

The specification for the window product included the following:

- two layers of glass plus a suspended heat-mirror film with krypton gas-filled air space,
- insulated fiberglass frames,
- whole window R-value of 0.88 $m^2 \cdot K/W$ (5 $ft^2 \cdot h \cdot °F/Btu$) or better,
- solar heat gain coefficient (SHGC) of .25 or less.

For the entry door products, insulated fiberglass and Energy Star compliance were specified. For the patio door product, a whole door R-value of 0.53 $m^2 \cdot K/W$ (3 $ft^2 \cdot h \cdot °F/Btu$) or better was specified. These specifications represented the most energy efficient non-custom window and door products that were readily available from U.S. residential window and door manufacturers at the time.

Installation of the windows and doors differs from standard residential construction because the exterior walls of the NZERTF are much deeper than standard construction. The NZERTF walls were designed to be 254 mm (10 in.) deep measured from the interior side of the framing to the outer side of the insulating sheathing. Since windows are typically installed with the exterior face of the window aligned with the exterior face of the wall, this would place the window frame within the insulating sheathing. To provide a solid rough opening in which to install the window, the design called for a plywood box coated with vapor permeable waterproofing and extending the full depth of the wall to be inserted into the window opening. Then normal installation procedures for window installation using anchor straps along with proper flashing, drainage and airtightness detailing can be followed. For example, see Figure 18 for the window head details. A similar design approach was used for exterior door installation, except that the door is to be installed towards the interior side of the plywood box since the door needs to swing towards the interior.

The most crucial part of the installation of windows and doors is the integration of the plywood box and of the door or window frame with the control layers of the wall. The details included in the construction set show the application of sealant required to transfer airflow control from the wall to the plywood box and backer rod and sealant from the plywood box to the window frame. Flashing transfers the water control of the wall to the plywood box. Since the windows selected were flangeless, backer rod and sealant is applied around the exterior perimeter of the window frame to transfer the water control from the plywood box to the window frame. The details in Figure 18 show how the control functions are transferred at the window head. At the base of the window, weepholes are embedded in the sealant to connect the internal drainage system of the windows to the exterior.

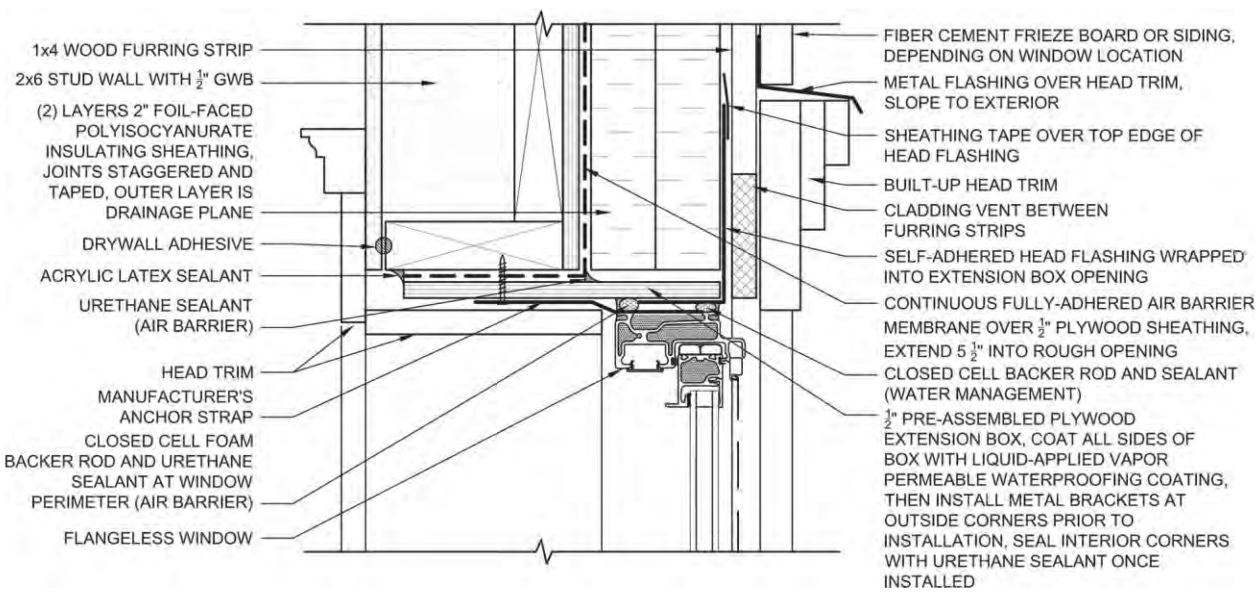


Figure 18: Window Head Detail (from Construction Set)

Window and door installation sequences were included in the construction set because the order of the installation is important for proper shingle lapping of flashing materials and for access to those parts of the assembly where sealant needs to be applied.

To ensure robust airtightness at the window/wall connection, the plywood box needs to be sized to meet the window manufacturer's rough opening requirements for the window, adjusted at the bottom as needed to establish a sloped sill under the window. In addition, the framing openings for the windows need to be sized so that the plywood box fits snuggly into the framing opening after the opening has been wrapped with the air barrier material. If the gap between the framing and the plywood box or between the plywood box and the window frame is too big, it will be difficult to provide durable air sealing; if it is too small, the box will not fit. Since the actual window and air barrier products to be used could not be selected during design of the NZERTF, these sizes required calculation during the construction phase.

3.3.4 Special Requirements for Design of the Enclosure

The acquisition and construction process for the NZERTF project was not typical for a custom residential project since the project was subject to government procurement procedures and because ARRA funding was used. In particular, products could not be single-sourced and were required to be U.S. made, correspondence with potential contractors was not permitted during bidding, correspondence with the general contractor was required to be through a third party during construction and it could not be assumed that the general contractor would be familiar with residential practices or with high performance buildings.

Because of these conditions, the construction drawings for NZERTF needed to communicate not only the design intent of the project but also to specify particular methods, materials, and conditions that were required if the high performance goals were to be met. A number of design detail and installation sequence drawings were developed and incorporated into the construction set for this purpose. Some of these are described in the following sections.

3.3.4.1 Details and Installation Sequences

Design details, some shown in three dimensions, were included in the construction set to explain those aspects of the design that are not typically used in standard residential construction. These include advanced framing techniques (e.g., see Figure 8), installation of multiple layers of exterior insulating sheathing over the wall and over the roof, establishing a drainage and venting gap behind the cladding, and some of the flashing techniques.

Section details at intersections of components (e.g., roof/wall intersection) were developed to show the materials and their relative positions needed to effectively transfer the control layers across the intersection (e.g., see Figure 14). Also details and installation sequences were included in the construction set for the different types of penetrations through the enclosure – pipes, vents, wiring, windows, and doors – to show how the air, water, and thermal control functions were to be maintained at the penetrations.

3.3.4.2 Schedule of Penetrations through the Enclosure

During the design of the NZERTF, every penetration through the building enclosure was identified and a penetration schedule was included in the construction set that lists every penetration along with a reference to the detail and installation sequence showing how that penetration is to be sealed. This schedule includes not only windows and doors, but also conduits, wire penetrations and vents.

Using this schedule, the construction could be planned so that all penetrations are made while the appropriate enclosure elements are still fully accessible. For example, penetrations through the foundation wall will be more airtight if they are cast in the concrete rather than bored through the wall after the fact. Similarly a penetration through the air barrier membrane needs to be sealed at the air barrier before subsequent layers of construction are applied, and then again at each layer; if the penetration is made after all layers have been installed, it cannot be adequately air and water sealed.

3.3.4.3 Construction Sequence

Although the section and detail drawings specify all of the components required to create continuous control systems they do not convey how these systems are to be made continuous. In some cases, if standard construction sequencing is used, it may not be possible to make the systems continuous because the components that need to be connected are not accessible at the same time. For example, both the sheathing over the rafters and the wall sheathing must be installed and exposed at the same time to apply the air barrier membrane correctly. Furthermore, once the air barrier membrane has been installed, there should be no further penetrations made through the wall other than what is required to complete the wall (e.g., screws to attach the furring strips) so that the air barrier is not compromised.

During the design, a specific construction sequence was developed and included in the construction set that showed the order of construction required so that the control systems could be made continuous. The construction sequence was initially developed to ensure the correct implementation of the airflow and water control systems but because of inter-dependencies among the components, it was necessary to include the structural and thermal components in the sequencing as well. One benefit of this sequence of drawings was that it helped explain the issues to the contractor so that as the project progressed, the contractor was able to suggest acceptable alternatives that would not compromise the continuity of the control systems. The construction sequence is shown in Figure 19, Figure 20 and Figure 21. (Note: architectural plans are available at http://www.nist.gov/el/nzertf/).

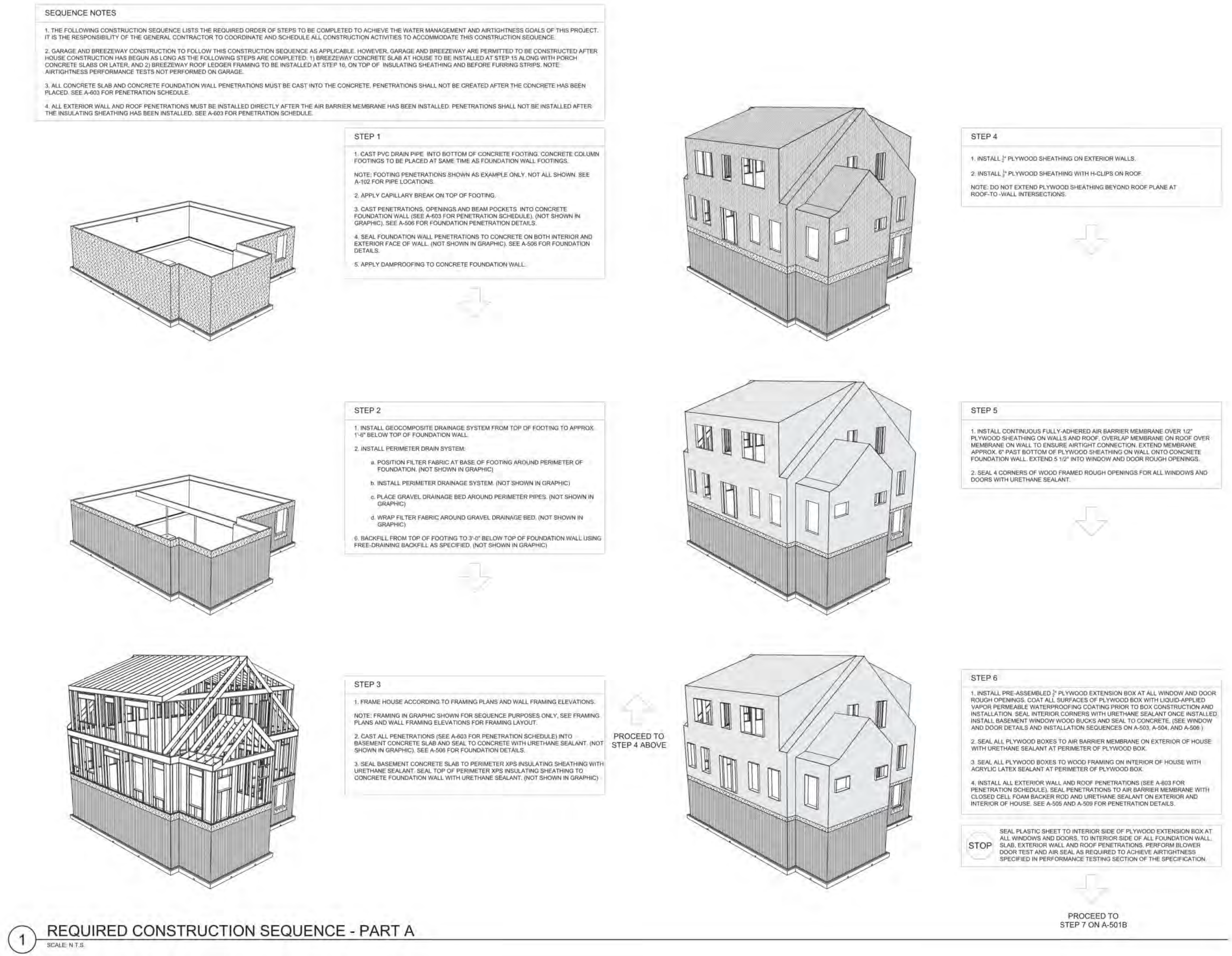


Figure 19: NZERTF Construction Sequence (Part A)

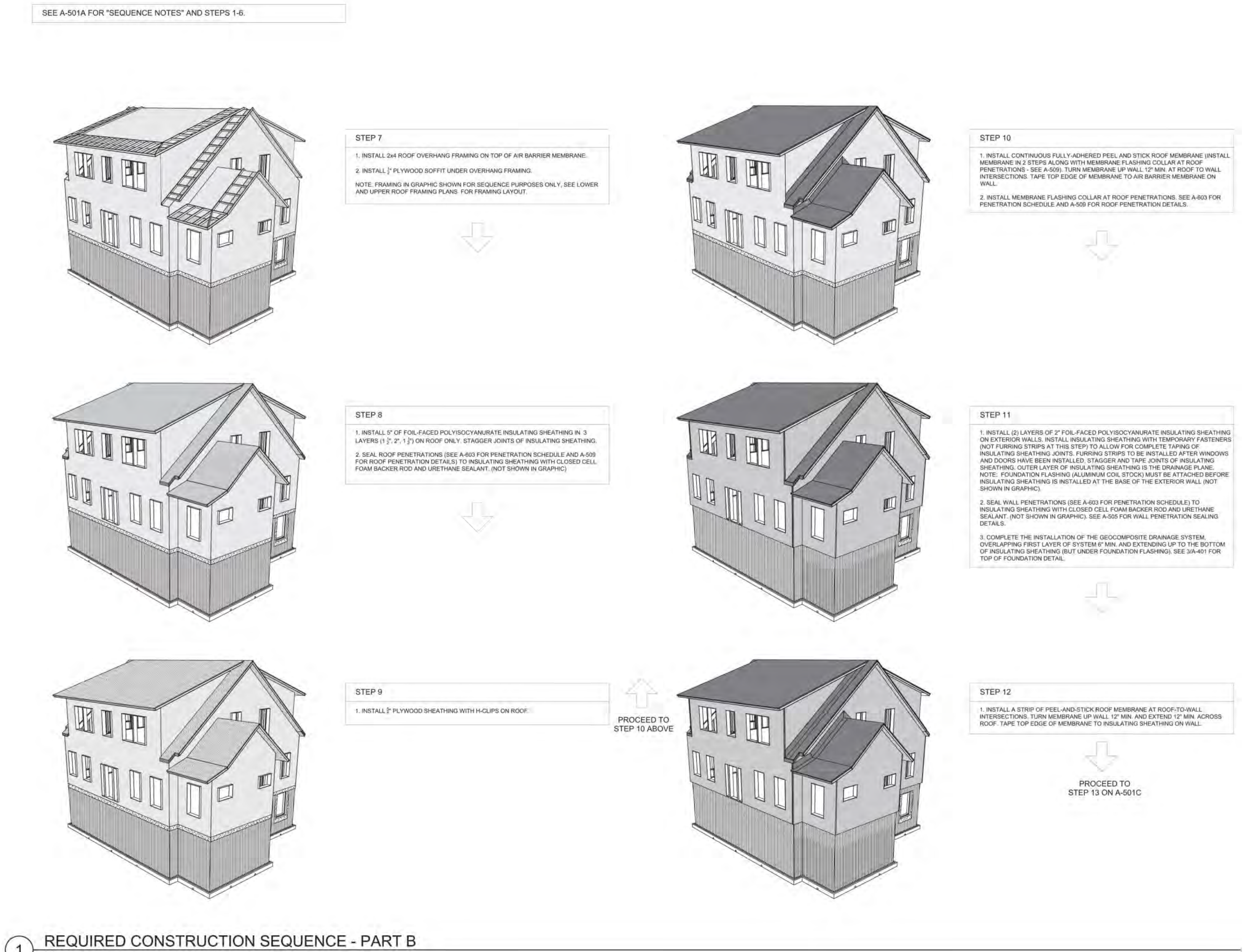
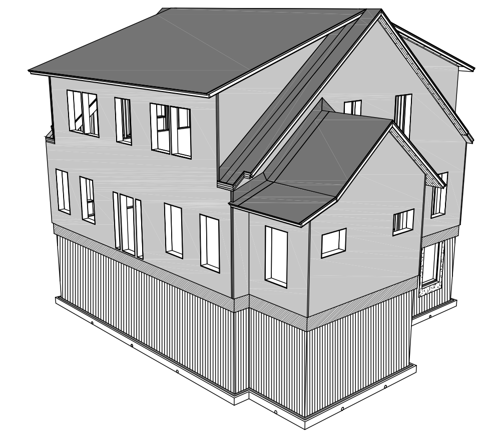


Figure 20: NZERTF Construction Sequence (Part B)

SEE A-501A FOR "SEQUENCE NOTES" AND STEPS 1-6, AND
A-501B FOR STEPS 7-12.

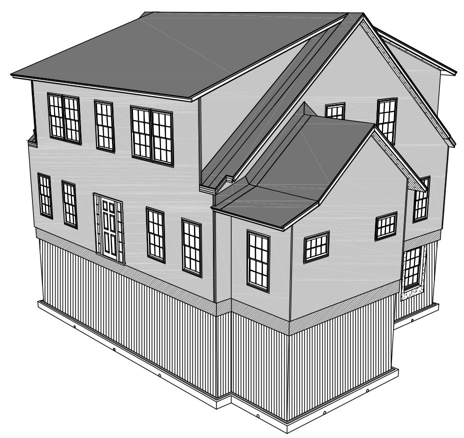


STEP 13

1. INSTALL MINERAL WOOL INSULATION COVERED WITH CEMENTITIOUS BOARD AROUND HOUSE PERIMETER AT TOP OF FOUNDATION WALL - FROM INSULATING SHEATHING DOWN 2'-0". NOTE: DOOR SILL FLASHING AND THRESHOLD BLOCKING NEED TO BE INSTALLED BEFORE THIS STEP (SEE A-504 FOR DOOR INSTALLATION SEQUENCE.)

2. INSTALL WINDOW WELL AT BASEMENT WINDOW. (NOT SHOWN IN GRAPHIC). SEE A-506 FOR WINDOW WELL DETAIL.

3. INSTALL REMAINING BACKFILL. (NOT SHOWN IN GRAPHIC)



STEP 14

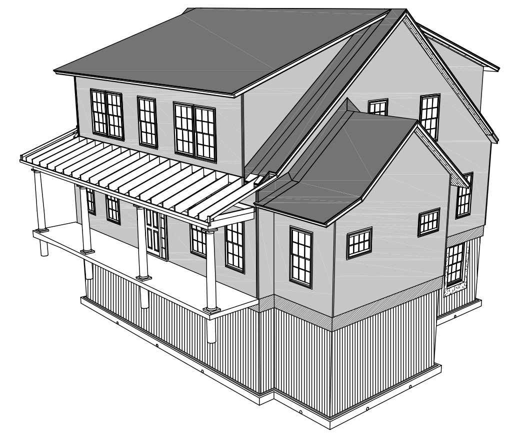
1. INSTALL ALL WINDOWS AND DOORS. SEE A-503 AND A-504 FOR WINDOW AND DOOR OPENING WATERPROOFING DETAILS AND INSTALLATION SEQUENCES.

STEP 15

1. INSTALL FOUNDATION SYSTEMS FOR FRONT PORCH AND SCREEN PORCH. (SCREEN PORCH NOT SHOWN IN GRAPHIC)

2. INSTALL CONCRETE SLAB FOR FRONT PORCH AND SCREEN PORCH OVER COMPACTED SUBGRADE AND STONE. (SCREEN PORCH NOT SHOWN IN GRAPHIC)

PROCEED TO
STEP 16 ABOVE

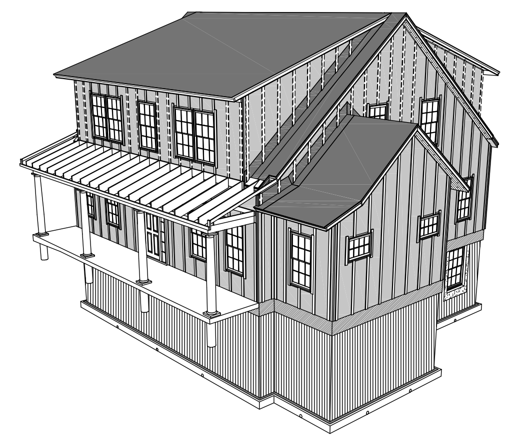


STEP 16

1. INSTALL BOTH FRONT PORCH AND REAR SCREEN PORCH FRAMING. (REAR SCREEN PORCH NOT SHOWN IN GRAPHIC)

2. INTEGRATE PORCH ROOF AND WALL FULLY-ADHERED MEMBRANE WITH HOUSE ROOF AND WALL FULLY-ADHERED MEMBRANE. PORCH ROOF SHEATHING, WALL SHEATHING AND FULLY-ADHERED MEMBRANES NOT SHOWN IN GRAPHIC.

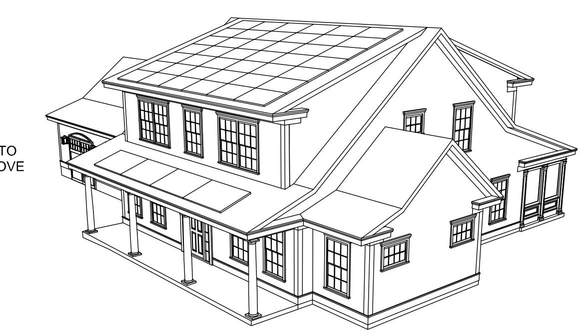
NOTE: FRAMING IN GRAPHIC SHOWN FOR SEQUENCE PURPOSES ONLY, SEE PORCH FRAMING PLANS FOR FRAMING LAYOUT.



STEP 17

1. REMOVE TEMPORARY INSULATING SHEATHING FASTENERS AND INSTALL 1X4 WOOD FURRING STRIPS. SEE A-503 AND A-504 FOR FURRING STRIP INSTALLATION AROUND WINDOWS AND DOORS.

NOTE: DO NOT INSTALL FURRING STRIPS AT ROOF-TO-WALL INTERSECTIONS (SHOWN AS DASHED LINES) UNTIL FLASHING, TAPE AND SHINGLES HAVE BEEN INSTALLED AT ROOF-TO-WALL LOCATIONS. SEE 4/A-508 AND 4/A-509 FOR DETAILS.



STEP 18

1. INSTALL FIBER CEMENT SIDING, TRIM AND ROOFING. SEE A-505 AND A-509 FOR PENETRATION DETAILS.

NOTE: FINAL IMAGE SHOWN WITH GARAGE STRUCTURE, REAR SCREEN PORCH AND SOLAR THERMAL AND PV PANELS.

1 REQUIRED CONSTRUCTION SEQUENCE - PART C
SCALE: N.T.S.

Figure 21: NZERTF Construction Sequence (Part C)

3.3.4.4 Testing for Airtightness

Included within the specified construction sequence was the requirement to test for airtightness of the building enclosure just after the airflow control system for the walls, roof, and foundation had been completed and the plywood boxes for the windows and exterior doors had been installed. The test was performed at this point in the construction phase to measure the effectiveness of the airflow control system and to locate any air leakage while it still could be corrected. Testing was performed by BSC using a blower door according to ASTM Test Method E779 (ASTM, 2010). For testing, the exterior openings of the door and window plywood boxes and of all above grade penetrations were sealed from the outside; the openings of all below grade penetrations were sealed on the inside. The blower door fan was used to depressurize the house to a 50 Pa difference relative to the outside and to measure the airflow in cubic feet per minute required to maintain that pressure differential. The result of the first airtightness test was quite remarkable, 117 m^3/h (69 cfm) at 50 Pa. Using 1270 m^3 (44 864 ft^3) as the volume of the house,[19] this corresponds to 0.09 air changes per hour at 50 Pa.

BSC performed a second airtightness test during construction after the windows and all exterior insulation had been installed but exterior doors, cladding, interior-side insulation and interior wall board had not yet been installed. Another airtightness test was performed by the LEED for Homes provider after substantial completion of the project. Upon completion of the NZERTF, NIST researchers performed two additional blower door tests. In the first, the HRV input and output, make-up air, dryer, and kitchen vents were sealed. In the second, only the HRV input and output vents were sealed. All test results were well below the 1.0 h^{-1} at 50 Pa requirement given in the NZERTF specifications. The test results for all five airtightness tests are shown in Table 3. The uncertainty in the flow rates reported by the instrument manufacturer is ±4 %.

[19] 44 864 ft^3 is the volume that was calculated by the LEED for Homes provider.

Status of Building when tested	Organization	Airflow measured in m^3/h for 50 Pa differential	Air changes per hour for 50 Pa differential
August 2011: Air barrier system complete; window and door openings and penetrations sealed	BSC	117 (69 cfm)	0.09
December 2011: Windows, exterior insulation, and roofing membrane installed; door openings and penetrations sealed	BSC	573 (337 cfm)	0.45
July 2012: Construction substantially completed; HRV input and output sealed	LEED for Homes provider	775 (456 cfm)[20]	0.61
March 2013: Construction completed; HRV input and output, make-up air, kitchen and dryer vents sealed	NIST	700 (410 cfm)	0.55
March 2013: Construction completed; HRV input and output, make-up air sealed; kitchen and dryer vents open	NIST	802 (470 cfm)	0.63

Table 3: Airtightness Test Results

As expected, the blower door test results were progressively higher as additional work was performed, but the increase between the first and second tests was quite large. Much of this increase was probably due to air leakage through the installed windows. Another possible source of increased air leakage is where sealant may have pulled away from surfaces while curing. This condition was observed between some of the plywood window boxes and the framing shortly after the first airtightness test; where observed, sealant was re-applied to correct the situation. It also is possible that some penetrations through the enclosure were added or adjusted during the period between the first two tests.

3.4 Space Conditioning System Design

The purpose of space conditioning is to provide a comfortable and healthy indoor environment by maintaining the temperature, the humidity, and the air quality within acceptable ranges. The functions to be provided include adding or removing heat, adding or removing humidity, providing outdoor air, and distributing the conditioned air throughout the space. The basic strategy used in the design of the system for the NZERTF was first to make the work to be done by the system as easy as possible and then to select individual HVAC components that were simple to control and optimized for the particular function to be provided. This is the principle for creating "perfect HVAC" systems for reliability, comfort and energy efficiency.[21]

[20] EveryDay Green (2012).
[21] Straube, J. (2009).

There are several factors involved to make the work required of the system as easy as possible. These include keeping heating and cooling loads low, controlling unintended air leakage through the enclosure, and minimizing the distance and complexity of the delivery path for distributing the air. If there is less work to do, there will be less energy needed to do it.

The main components of the conditioning system are the heating/cooling system and the ventilation system, each with its own distribution and filtering system. Since the house was to be all-electric for the demonstration phase, a central air heat pump split-system with integrated dehumidification was specified for heating/cooling and dehumidification and a heat recovery ventilation system was specified for ventilation. By keeping ventilation and heating/cooling equipment completely separate, the controls of the systems are simplified and efficiencies for each system can be introduced that are consistent with the primary function of the equipment.

3.4.1 Heating/Cooling Loads

Once the building form, orientation, room layout and enclosure components of the house were determined, heating and cooling design loads were computing per Manual J using the software program Rhvac (Residential HVAC) from EliteSoft. This program provides a room-by-room calculation using the room layout and enclosure information and user-specified parameters for infiltration, ventilation, and heat gain from appliances and people. The parameters were specified in accordance with BSC's "Design Process for Sizing."[22] The default parameters and the calculated loads for the house are shown in the following tables.

[22] Rudd, A. (2006).

Parameter	Value used during Design	Comments
Infiltration	0.1 h^{-1}	Design is for an airtight enclosure; basement not included in this calculation
Ventilation	ASHRAE 62.2-2010 equation	Basement not included in this calculation
Appliance heat gain	1 appliance in laundry; 2 appliances in kitchen	Use 600 Btu/h per appliance
People heat gain	2 people in master bedroom; 1 person in each secondary bedroom; 2 people in living room	Per person: 230 Btu/h sensible, 200 Btu/h latent

Table 4: Default Parameters used for Manual J Calculation

The following table gives the design peak heating and peak cooling loads for the whole house and for the individual rooms using ASHRAE Fundamentals 2009 1 % and 99 % design conditions for Washington/Dulles in Virginia.

	Sensible Gain (Btu/h)	Latent Gain (Btu/h)	Net Gain (Btu/h)	Sensible Loss (Btu/h)
Full house	**11,358**	**4,756**	**16,114**	**19,336**
1-Basement	326	78	404	4,090
2-Living	2,045	621	2,666	2,072
3-Dining	933	152	1,085	1,531
4-Kitchen	2,039	69	2,108	622
5-1st Floor Bath	221	89	310	583
6-Mudroom	235	45	280	541
7-Office	889	338	1,227	1,219
8-Entry	271	40	311	610
9-East Bedroom	895	366	1,261	1,513
10-Master Bedroom	1,183	550	1,733	1,425
11-Master Bath	314	95	409	819
12-2nd Floor Bath	218	33	251	345
13-West Bedroom	1,015	359	1,374	1,548
14-2nd floor Hall	255	41	296	628
15-Master Closet	60	25	85	156

Table 5: Manual J Design Loads for NZERTF (calculated using Rhvac)

3.4.2 Central Air System

3.4.2.1 Split System

The design for the all-electric central air system called for a split air-source heat pump system with the following performance characteristics for the indoor air handler and matching outdoor unit:

- SEER of 14.8 or better and HSPF of 8.5 or better,
- ECM fan for variable supply air speed,
- indoor coil for use with refrigerant R-410A,
- supplemental electric resistance heat of 7.5 kW,
- modulating hot-gas condenser reheat for integrated supplemental dehumidification,
- digital scroll compressor (for variable refrigerant flow).

A modulating hot-gas condenser reheat mechanism provides supplemental dehumidification when cooling is not needed by operating the compressor and directing a controlled amount of the hot discharge gas to an indoor heating coil to reheat the cooled and dehumidified air to the room neutral air temperature.[23] This method of supplemental dehumidification retains the efficiency of the refrigeration cycle, avoids overcooling, and makes use of the waste heat that is generated.

The heat pump capacity required for the central air system is based on the total cooling system size requirement. For NZERTF, this requirement was calculated to be 4.7 kW (16 114 Btu/h) so the system size needed to be the smallest available that is at least 5.4 kW (18 000 Btu/h = 1.5 tons) and that meets the specified performance requirements. At the time of design, the only residential unit meeting all of the requirements was a 10.8 kW (36 000 Btu/h = 3 ton) system with a rated SEER of 15.25 and HSPF of 9.6. Since the digital scroll compressor of that system allows it to operate down to 40 % capacity or 4.2 kW (1.2 tons), this system can operate efficiently for this application even though it would be oversized if operating at full capacity.

At the time of installation, the manufacturer of the heat pump had brought to market a new 7.0 kW (24 000 Btu/h = 2 ton), two-speed system that would more closely match the cooling and heating loads of the house. Also, the part load performance of the smaller, two-speed system was better than the larger system due to inefficiencies in the digital scroll compressor at part load; therefore, the 7.0 kW (2 ton), two-speed system was selected as a replacement. The two-speed heat pump operates down to 75 % capacity at low-speed, or 5.3 kW (1.2 tons), and has a rated SEER of 15.80 and HSPF of 9.05.

To meet the air quality requirements, the manufacturer-supplied air filter at the air handler was replaced with a MERV 13 rated filter.

3.4.2.2 Air Distribution

The duct sizes and duct layout were designed for the central air system. The air handling unit, located in the southeast quadrant of the basement, has T-shaped supply and return trunks – the

[23] AAON.

north-south trunks connect to the air handler with the stem trunks running to the west. All ductwork was specified to be sheet metal and the supply trunk was to be insulated.

During the demonstration phase, the conditioned air is to be supplied by high wall or ceiling diffusers. Run-outs, without branching, are routed from the supply trunk to each of the rooms in as direct a path as possible passing through walls, chases and the open-web floor trusses. An air return is provided on the east and on the west ends of each of the habitable floors. Transfer grilles over the bedroom and office doors and between the basement and first floor are also part of the return air system.

	System Heating Supply Airflow m^3/h (Rhvac)	**System Cooling Supply Airflow m^3/h (Rhvac)**	**Final Design: Supply Airflow m^3/h for Room**	**Final Design: # and Size of Supply Air Run-outs for Room**
Full House	**2039 (1,200 cfm)**	**2039 (1200 cfm)**	**2268 (1335 cfm)**	
1-Basement	471 (277 cfm)	61 (36 cfm)	306 (180 cfm)	3-127 mm (5 in.)
2-Living	239 (140 cfm)	382 (225 cfm)	374 (220 cfm)	2-152.4 mm (6 in.)
3-Dining	177 (104 cfm)	175 (103 cfm)	178 (105 cfm)	1-177.8 mm (7 in.)
4-Kitchen	71 (42 cfm)	381 (224 cfm)	289 (170 cfm)	1-177.8 mm (7 in.), 1-127 mm (5 in.)
5-1st Floor Bath	68 (40 cfm)	44 (26 cfm)	41 (24 cfm)	1-101.6 mm (4 in.)
6-Mudroom	63 (37 cfm)	44 (26 cfm)	42 (25 cfm)	1-101.6 mm (4 in.)
7-Office	141 (83 cfm)	167 (98 cfm)	170 (100 cfm)	2-127 mm (5 in.)
8-Entry	70 (41 cfm)	51 (30 cfm)	51 (30 cfm)	1-101.6 mm (4 in.)
9-East Bedroom	175 (103 cfm)	168 (99 cfm)	221 (130 cfm)	2-127 mm (5 in.)
10-Master Bedroom	165 (97 cfm)	221 (130 cfm)	204 (120 cfm)	2-127 mm (5 in.)
11-Master Bath	95 (56 cfm)	59 (35 cfm)	59 (35 cfm)	1-127 mm (5 in.)
12-2nd Floor Bath	39 (23 cfm)	41 (24 cfm)	42 (25 cfm)	1-127 mm (5 in.)
13-West Bedroom	73 (105 cfm)	190 (112 cfm)	255 (150 cfm)	2-152.4 mm (6 in.)
14- Hall	178 (43 cfm)	48 (28 cfm)		
15- Master Closet	19 (11 cfm)	12 (7 cfm)	34 (20 cfm)	2-101.6mm (4 in.)

Table 6: Design of Duct Airflow and Sizing for Supply Air Run-outs[24]

The design airflow for the 3 ton system is 2039 m^3/h (1200 cfm). With this system size as input, the Rhvac software computed the airflow distribution required to be supplied to the individual rooms based on the calculated heating and cooling loads. BSC used this airflow distribution as

[24] From *NIST NZERTF Duct Sizing with HRV.xls*; this was submitted during construction in response to RFI0028 – Manual J&D Design Criteria for HVAC

the basis for the design of the ductwork. All of the supply air ductwork, except for the basement, was sized based on the airflow for cooling. To ensure that sufficient heating would be provided in the basement, the basement airflow was adjusted to be consistent with the heating to cooling airflow ratio for the other spaces. The supply air ducts were sized to keep the run-out velocity below 2.54 m/s (500 ft/min). The following table shows the heating and cooling airflows computed by Rhvac and the final design for the supply airflow as well as the number and size of ducts for each room.

The following table shows the final design duct airflow and size for the return air run-outs.

	Final Design: Return Airflow in m^3/h	**Final Design: Return Duct Size**
Full House	**2039 (1200 cfm)**	
Mudroom	680 (400 cfm)	1-356x381 mm (14 in.x15 in.)
Dining Area	612 (360 cfm)	1-254x254 mm (10 in.x10 in.)
Master Bedroom	289 (170 cfm)	1-356x89 mm (14 in.x3½ in.) -> 203x152 mm (8 in.x6 in.)
West end of 2nd Floor Hall	459 (270 cfm)	1-483x140 mm (19 in.x5½ in.)

Table 7: Design of Duct Airflow and Sizing for Return Air Run-outs[25]

Duct pressure drops were calculated according to Manual D for several of the longest and most complex duct runs. The runs with the highest computed pressure drops were the main supply trunk to the west bedroom on the 2nd floor and the return from the master bedroom to the main return trunk. The sum of the pressure drop for these two runs and the filter was 88 Pa (0.353 in. w.g.) which is well within an acceptable range for the air handler.[26]

A duplicate system of supply run-outs from the supply air trunk was designed using floor diffusers rather than wall/ceiling diffusers; for the kitchen, the diffuser for this duplicate system is in the ceiling rather than in the floor since floor diffusers are not practical in a kitchen. This second system of run-outs is for use during the research phase.

Both a manually operated damper and a motorized isolation damper were called for at the base of each supply run-out. The manual damper is to be used for balancing the air distribution system. The isolation damper is used to close the run-outs that are not to be included in the current air distribution system. For the demonstration phase, all isolation dampers at the run-outs to the floor diffuser distribution system are to be closed. In the future, the motorized isolation dampers will be used to switch between the high wall and the floor air distribution systems or to implement zoning.

The NZERTF specifications called for duct leakage testing of the air distribution ductwork. Since all ductwork is in conditioned space, duct leakage to the exterior is not a concern. However, airtight ductwork is needed so that the conditioned air is distributed as designed. BSC

[25] From *NIST NZERTF Duct Sizing with HRV.xls*; this was submitted during construction in response to RFI0028 – Manual J&D Design Criteria for HVAC

[26] Max total static is 560 Pa (2.25 wg) according to AAON F1 Series Air Handling Units, Installation, Operation and Maintenance

performed the duct leakage testing on the central air supply and return systems just after duct rough-in so that the ductwork would still be accessible if leakages were found. At that time, the ducts were remarkably tight – so much so that some of the testing had to be run at a pressure difference of +50 Pa rather than the standard +25 Pa in order to register a result. The approximate total duct leakage at 25 Pa for the central air distribution system was 251 m^3/h (148 cfm).[27] This is "approximate" since some of the results were derived from +50 Pa testing. Final ductwork leakage testing was performed by the LEED for Homes provider at substantial completion with a reported result of 535 m^3/h (315 cfm).[28]

3.4.3 Support for Alternate Conditioning Systems

Support for a standalone dehumidifier to be integrated into the central air distribution system in the future was included in the design. As designed, this could be used with a cooling/heating system that did not provide supplemental dehumidification, or it could be used in conjunction with a heating/cooling with dehumidification system for specific conditions. The ductwork for the standalone dehumidifier was designed to take input air from the living room at 255 m^3/h (150 cfm) and deliver the dehumidified air into the main supply trunk to be distributed to the living areas using the central air supply distribution system.

In the future, NIST plans to install a ducted 2-to-1 mini-split system as an alternate heating/cooling system to use for research. BSC designed the ductwork for that system with the 2nd floor air handler and ductwork in the attic and the 1st floor air handler to be concealed in the 1st floor laundry closet with ductwork in the space between the first and second floors. In addition, future testing is planned for a small duct, high velocity (SDHV) heat pump system; NIST provided the ductwork design for ductwork for this future system.

The final architectural and mechanical drawings specified the layout and size of the ducts for four distinct heating/cooling systems—central air with high wall distribution, central air with floor distribution, 2-1 ducted mini-split, and SDHV heat pump — and described how the ducts were to be routed up through the walls and chases and how they were to pass through the open-web floor joists.

3.4.4 Mechanical Ventilation System

The basic requirements for the design of the ventilation system were that it be an independently ducted, energy efficient, balanced residential ventilation system capable of meeting the ASHRAE 62.2-2010 ventilation rate capacity required for the house. To address the energy efficiency requirement, heat recovery between the exhaust and the supply air streams was specified. Also the design incorporated the bathroom exhaust into the whole house ventilation system thereby reducing the number of penetrations through the enclosure and the number of fans required. The decision to incorporate the bathroom exhaust into the heat recovery ventilation system is not consistent with the principle of the perfect HVAC since this is a combination of the ventilation function and the spot exhaust function. This tradeoff was made primarily for the airtightness benefit.

An HRV system rather than an ERV system was specified. Since an ERV system exchanges both heat and moisture between the exhaust and supply air streams, it is not appropriate for use when

---

[27] Building Science Corporation (2011).
[28] EveryDay Green (2012).

the exhaust air for the system is taken from the bathrooms where the moisture level is elevated. In general, BSC does not recommend using an ERV in a humid climate.

The ASHRAE 62.2-2010 ventilation requirements for the house are as follows:

- Bathroom ventilation: for each bathroom, 85 m^3/h (50 cfm) for intermittent use or 34 m^3/h (20 cfm) for continuous ventilation
- For whole house ventilation: 137 m^3/h (80 cfm)

The whole house ventilation was calculated using the equation:

$$Q = (N_{br} + 1) \times 7.5 + 0.01 \times FA$$

where Q is the continuous ventilation rate in cfm, N_{br} is the number of bedrooms, and FA is the conditioned floor area in square feet. For NZERTF, N_{br} is 4 and FA is 4200 ft^2 or 390 m^2.

The specific requirements specified for the HRV included the following:

- ECM motor(s),
- an operational capacity of the system of at least 255 m^3/h (150 cfm) with 100 Pa (0.4 in.w.g.) static pressure,
- support for multiple speeds;
- remote “boost” control mechanism for use in the bathrooms.

A search for residential ventilation products found that no U.S.-made HRV met these requirements.[29] Therefore a Canadian made HRV system was installed. The HRV was the only product installed in the NZERTF project for which an acceptable U.S.-made product could not be found.

The HRV unit is located on the north side of the basement with outside supply air taken from the west side of the house and exhaust air discharged to the north side of the house. The ducts between the HRV unit and the exterior are insulated.

The air distribution for the ventilation system takes exhaust air from each of the three bathrooms and provides supply air to each of the second floor bedrooms and to the dining area. The HRV ductwork design for the exhaust to the HRV called for individual ducts from the bathrooms joining a common trunk in the basement running to the HRV. The supply distribution HRV ductwork design consisted of a common supply trunk that branched in the basement between the dining area and a common riser for the second floor bedrooms; the common bedroom duct branched into run-outs at the 2nd floor level.

---

[29] *Report: MEP Buy American Supplier Scouting – U.S. Domestic Manufacturing Capacity for Select Energy Efficiency Products*, An Analysis Performed by the Manufacturing Extension Partnership for the National Institute of Standards and Technology Office of Facilities and Property Management, Draft of Findings, July 2011.

The pressure drop for each supply and exhaust path was calculated during design to verify that it would be low enough to achieve the 255 m^3/h (150 cfm) capacity of the HRV at high speed based on the fan curves.

The following chart summarizes the HRV ductwork design and calculated pressure drop.

Supply Location	Design flow rate	Design Path and Duct size	Calculated Pressure Drop: Path	Calculated Pressure Drop: Full Supply Direction
Dining room	68 m^3/h (40 cfm)	HRV->178 mm (7 in) common supply-> 102 mm (4 in.) run-out	40 Pa (0.161 in.w.g.)	95 Pa (0.381 in.w.g.)
Master Bedroom	68 m^3/h (40 cfm)	HRV->178 mm (7 in.) common supply -> 178 mm (7 in.) 2nd floor riser -> 127 mm (5 in.) run-out	33 Pa (0.132 in.w.g.)	88 Pa (0.352 in.w.g.)
West Bedroom	59 m^3/h (35 cfm)	HRV->178 mm (7 in.) common supply -> 178 mm (7 in.) 2nd floor riser-> 127 mm (5 in.) run-out	10.5 Pa (0.042 in.w.g.)	84 Pa (0.338 in.w.g.)
East Bedroom	59 m^3/h (35 cfm)	HRV->178 mm (7 in.) common supply ->178 mm (7 in.) 2nd floor riser -> 127 mm (5 in.) run-out	12 Pa (0.048 in.w.g.)	87 Pa (0.351 in.w.g.)

Table 8: Design of HRV Duct Airflow and Size for Supply Air[30]

Exhaust Location	Design flow rate	Design Path and Duct size	Calculated Pressure Drop: Path	Calculated Pressure Drop: Full Exhaust Direction
First Floor Bath	85 m^3/h (50 cfm)	127 mm (5 in.) run-out -> 178 mm (7 in.) common exhaust -> HRV	42 Pa (0.168 in.w.g.)	81 Pa (0.327 in.w.g.)
Second Floor Bath	85 m^3/h (50 cfm)	127 mm (5 in.) run-out -> 178 mm (7") common exhaust -> HRV	51 Pa (0.206 in.w.g.)	91 Pa (0.365 in.w.g.)
Master Bath	85 m^3/h (50 cfm)	127 mm (5 in.) run-out -> 178 mm (7 in.) common exhaust -> HRV	52 Pa (0.209 in.w.g.)	92 Pa (0.368 in.w.g.)

Table 9: Design of HRV Duct Airflow and Size for Exhaust Air[31]

[30] From *NIST NZERTF Duct Sizing with HRV.xls*; this was submitted during construction in response to RFI0028 – Manual J&D Design Criteria for HVAC

[31] From *NIST NZERTF Duct Sizing with HRV.xls*; this was submitted during construction in response to RFI0028 – Manual J&D Design Criteria for HVAC

The operation of the installed HRV during final testing differed from the design flows in that the system delivered only 180 m^3/h (106 cfm)[32] at high speed rather than 255 m^3/h (150 cfm) as was projected. The uncertainty in these measurements is estimated to be 10 %. This suggests that the actual pressure drop is higher than what was calculated during design. There are several possible explanations for this:

- some of the ducts that were designed to be 178 mm (7 in.) were inadvertently changed to 152 mm (6 in.) during the preparation of the mechanical drawings;
- the pressure calculation during design did not account for the difference in pressure drop between round and oval ducts;
- due to the extent of ductwork in the house, some compromises during installation were made such as using oval ducts where a round duct was indicated or using unusually compact elbows.

While the capacity of the installed ventilation system is lower than expected, it still complies with the ventilation capacity requirements of ASHRAE 62.2-2010.

3.4.5 Other Ventilation Systems

This section describes additional mechanical ventilation systems that were installed.

3.4.5.1 Kitchen Exhaust

Spot kitchen exhaust for removal of cooking-related moisture, contaminants and pollutants is provided by a range hood that exhausts to the exterior. The range hood is located over a 762 mm (30 in.) induction cooktop. The Home Ventilating Institute (HVI) recommends 170 m^3/h (100 cfm) of ventilation per lineal foot of cooktop for wall-mounted hoods, so 425 m^3/h (250 cfm) kitchen exhaust would meet the HVI recommendations.[33] The cooktop and range hood products selected for the NZERTF were from the same manufacturer. The smallest internal, in-line blower available for the range hood, a 510 m^3/h (300 cfm) fan, was installed with the air exhausted to the exterior on the north side of the house.

3.4.5.2 Make-up Air System

Based on the extraordinarily airtight results of the first blower door test, BSC recommended that a make-up air system be installed to prevent depressurization of the house when the kitchen exhaust and/or the clothes dryer is operating. The principle of the makeup air system is that it be closed when no exhaust device (kitchen exhaust or clothes dryer) is operating, but open when an exhaust device is operating and the pressure differential between the interior and exterior is greater than 10 Pa.

The design of the system consists of a 203 mm (8 in.) round duct penetration through the attic wall on the west side of the house with a normally-closed, spring-return motorized damper that opens when the kitchen exhaust and/or the clothes dryer is operating. To the interior side of the motorized damper, a barometric damper is installed which begins to open when there is a pressure differential of 10 Pa. The air that enters the attic through the 203 mm (8 in.) make-up air

---

[32] Installed HRV measurements from LEED for Homes inspection of NZERTF performed July 2, 2012; reported via 2012-07-06 email from EveryDay Green.
[33] http://www.hvi.org/publications/HowMuchVent.cfm

duct will be tempered as it moves through the attic space and down into the living area (see Figure 22).

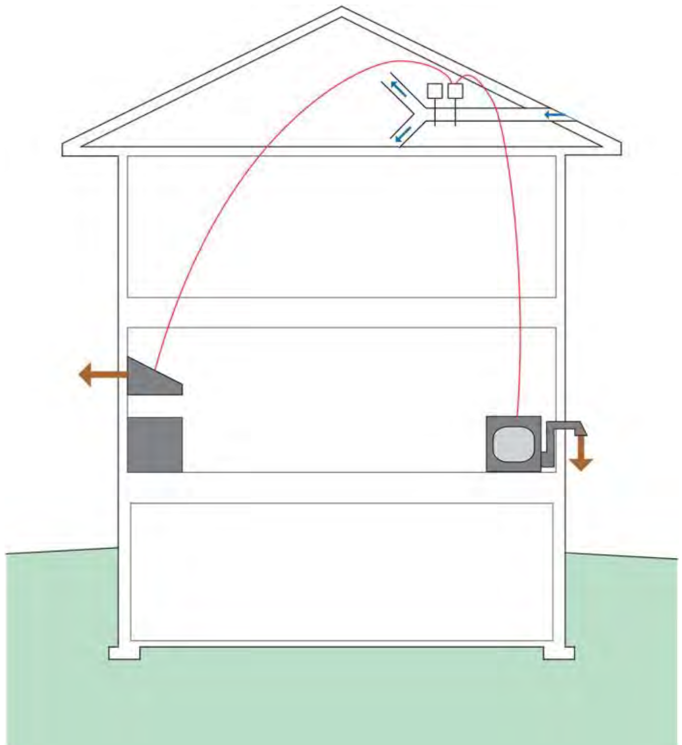


Figure 22: Schematic of Make-up Air System

3.4.5.3 Passive Radon Mitigation System

Radon and other soil gases filter through cracks and other holes in the below grade portion of buildings due to pressure difference. The airflow control system in the below grade portion of the basement provides some protection from infiltration. For additional protection, a passive radon mitigation system was installed that depressurizes and vents the sub-slab space created by the stone layer below the slab where soil gas can collect.

The system consists of a 102 mm (4 in.) vent stack installed through the basement slab, through the conditioned basement, within the partition walls in the first and second floor bathrooms, through the conditioned attic and then out through the roof. The base of the vent stack has a T-connection with a 102 mm (4 in.) perforated pipe embedded in the layer of stone under the slab. The collection space under the slab is passively depressurized by the stack effect of the vent stack so that the air beneath the slab is vented up and out through the roof. With the vent stack located in conditioned space, the stack effect is primarily induced by the temperature difference between the cool below-grade collection space and the warmer vent stack.

The radon level in the house will be monitored. If this passive approach to radon mitigation does not keep the radon level low enough, a fan can be incorporated into the vent stack at the attic level to convert the passive system to a mechanical radon mitigation system. An electrical outlet was included near the stack in the attic for this purpose.

3.5 Domestic Water System Design

This section describes efficiency measures included in the design of the domestic water system.

3.5.1 Hot Water System Design

With net-zero energy use as the goal and with collected solar energy as the only on-site energy source, the domestic hot water was designed to be provided by a solar hot water heating system. In the initial design, the solar collectors were to be mounted on the south-facing shed dormer roof along with the photovoltaic array so that the supply lines from the solar collectors could be routed directly into the conditioned attic space. For the final design, the solar collectors were relocated to the (uninsulated) front porch roof to accommodate a larger photovoltaic array on the shed dormer roof. This location creates some limited exposure of the supply lines to unconditioned air, but it also shortens the distance between the collectors and the storage tank (in the basement).

A hot water system that relies on solar heating requires a backup system so that acceptable hot water temperature is available at all times. Since the demonstration phase was to be all-electric, the design called for an air-to-water heat pump system as the backup to be integrated downstream from the solar hot water heating system. The mean temperature to be maintained by the full system was to be 49 ^{o}C (120 ^{o}F).

The components of the solar hot water heating system design include the following:

- two flat plate solar collectors (approximately 4.6 m^2 or 50 ft^2 total surface area) with a solar energy factor of 2.0 or greater and a solar fraction of 0.6 or greater;
- active, indirect forced circulation with a propylene glycol mixture heat-transfer fluid;
- heat exchanger;
- insulated supply line (from collector to heat exchanger);
- 303 L (80 gallon) insulated pre-heat storage tank in the basement.

The requirements specified for the backup heat pump water heater included the following:

- Energy Star qualified,
- 189 L (50 gallon) storage tank,
- Energy factor of 2.0 or greater,
- Electric element backup with maximum input power of 4.5 kW.

In this design, the heat pump water heater only operates if the water fed to it from the solar pre-heat storage tank requires additional heating.

Although only two solar collectors were needed to meet the needs of the house, two additional solar collectors were mounted on the porch roof for future use. These panels were integrated into a separate solar water heating system with a 454 L (120 gallon) pre-heat storage tank; this second system is to be used for research following the demonstration phase. Also for future use, a conduit was installed through the enclosure to support installation of a natural gas hot water heater as an alternate and more efficient backup system.

3.5.2 Plumbing Fixture Design Specifications

To support efficient distribution of the hot water, the design specified a central PEX manifold system with insulated home run 9.5 mm (3/8 in.) supply lines to the fixtures. With all fixtures located in the same quadrant of the house as the manifold, supply runs were of minimal length. With the exception of the hose bibs, no plumbing lines were to be located in the exterior walls.

Low flow and WaterSense fixtures were specified as follows:

- all lavatory faucets to be WaterSense certified and flow rate of 5.7 L/m (1.5 gpm) or less;
- kitchen faucet to have flow rate of 8.3 L/m (2.2 gpm) or less;
- all shower fixtures to have flow rate of 6.6 L/m (1.75 gpm) or less;
- all toilets to have a water usage of 3.8 L per flush, (1.1 gallons per flush) or less.

3.6 Electrical Design

The electrical requirements for the NZERTF were significantly more complex than what would be required for a typical net-zero energy house because of the need to support simulations, monitoring and instrumentation and test equipment used by the NIST researchers. The electrical design, which was developed by NIST in conjunction with BSC's FMEP consultant, EBL Engineers LLC, separated the house loads (mechanical equipment, lighting, appliances, and plug loads) from the other loads through the use of independent breaker panels. A description of this part of the design is beyond the scope of this report.

The approach for the lighting and appliance design of the NZERTF was to follow typical residential design trends with respect to number and location of lights and types of appliances but to select fixtures and appliances that are designed to have low energy use.

3.6.1 Lighting Design

The lighting plan for the NZERTF provides an overhead light and switched outlets for plug-in lamps for each room except for the kitchen and the living room. Halls, closets, and basement have overhead lighting only. Bathrooms use special task lighting. The living room has dimmable downlights for overhead lighting and some accent lighting as well as switched outlets for plug-in lamps. The kitchen has more built-in lighting – both overhead light and task lighting – than the other parts of the house.

While the design of the lighting layout is intended to be typical, the design goal was to be energy efficient through the use of Energy Star fixtures using only LED or pin-based CFL lamps. The initial design for fixtures and lamps used the following criteria:

- downlights: LED with minimum 500 lumens for 102 mm (4 in.) apertures and 650 lumens for 152 mm (6 in.) apertures, maximum 11 W;
- under cabinet lights: LED with minimum 180 lumens, maximum 6 W;
- compact fluorescent lights: at least 60 lumens/W;
- lighting quality: color rendering index (CRI) minimum 90, correlated color temperature (CCT) 2700 K to 3000 K.

Since the kitchen has the most lighting, some reduced lighting strategies were incorporated into the kitchen lighting design. All of the kitchen fixtures were specified to use LED lamps. The kitchen ambient lighting consisted of only three downlights that are located over the counters (457 mm or 18 in. from the wall). A photo sensor controlled by the daylight level and a manually controlled dimmer were provided for the ambient lighting. Separate switches were provided for each of the following:

- single down light over kitchen sink,
- under cabinet lights on west wall,
- under cabinet lights on north wall,
- downlights over kitchen peninsula.

The switches located at the entrances to the kitchen are for ambient lighting only so that the remaining kitchen lighting will only be turned on as needed for specific tasks. The lighting in the living room uses separate switching as well – one for the ambient down lights and one for the accent lights – with a dimmer for the ambient lighting.

For maintenance, it would be preferable to use only two or three different lamp types throughout the house, but with the then-current state of CFL and LED lighting, this was not practical to specify during the design phase. With the final fixture selection, however, it was often the case that fixtures from the same manufacturer did use the same lamp types which will simplify maintenance.

Initially there was a requirement for ceiling fans in the bedrooms and living room for use in future IAQ research. The performance specifications for energy consumption and air moving performance of the ceiling fans were as follows:[34]

- low: 12.5 W for 4120 m^3/h (2425 cfm) or 330 m^3/h per W (194 cfm/W);
- medium: 25.6 W for 6485 m^3/h or 253 m^3/h per W (149 cfm/W);
- high: 53.3 W for 10 367 m^3/h or 194 m^3/h per W (114 cfm/W).

No U.S.-made ceiling fan product could be found so these were removed from the design but wiring for future installation of ceiling fans was retained.

3.6.2 Appliance Specifications

The types of appliances included in the design were those that are typical for a new house of this size. The size and features specified for the appliances were a combination of what is typically expected for a family of four and what was of particular interest to the NIST researchers. The specifications for each type of appliance were based on the most efficient Energy Star qualified appliances that were available at the time with the desired size and features.[35]

The appliance design specifications were as follows:

- Refrigerator

[34] Based on efficiency of Energy Star ceiling fans available at gossamerwind.com
[35] Building Science Corporation (2010b).

- top mounted freezer with 0.14 m^3 (5.0 ft^3) capacity;
- 0.4 m^3 (13.9 ft^3) refrigerator capacity;
- energy consumption of 343 kWh/year or less.

- Dishwasher
  - at least 12 place settings and soil sensing technology;
  - 180 kWh/year or less, 6 L/cycle (1.56 gal/cycle) or less, 0.46 energy factor (EF) or higher.
- Cooking appliances – no energy use ratings are provided for cooking appliances:
  - 762 mm (30 in.) electric induction cooktop with range hood ventilation to exterior;
  - Built-in 762 mm (30 in.) electric wall convection oven with 0.13 m^3 (4.7 ft^3) capacity;
  - Built-in 762 mm (30 in.) convection microwave oven with 0.04 m^3 (1.5 ft^3) capacity.
- Stackable Clothes Washer
  - front loading;
  - CEE Tier III;
  - 0.12m^3 (4.4 ft^3) capacity;
  - Energy consumption of 130 kWh/year or lower, 2.55 modified energy factor (MEF) or higher, 3.5 water factor (WF) or lower.
- Stackable Electric Clothes Dryer
  - vented to exterior;
  - 0.19 m^3 (6.7 ft^3) capacity.

Some of the products on which these specifications were based were either no longer available or not U.S. made but acceptable products with comparable characteristics and ratings, or products specifically requested by the NIST researchers, were provided.

3.7 Renewable Energy Production System Design

For a net-zero site energy capable house, the renewable energy system needs to be designed so that it produces at least as much energy on a yearly basis as is consumed on site. For a new house, the predicted energy consumption is determined by developing an energy model for the house.

3.7.1 Initial Energy Model and Solar Panel Design

Shortly after the design of plans and elevations for the NZERTF started, approximately one month into the design phase, the EnergyGauge USA (EgUSA) software was used to develop an initial energy model for a quick check to verify that net-zero energy use was achievable based on the early design decisions about the enclosure and type of mechanical equipment that had been made. The annual consumption (site energy) projected by this early model was 9739 kWh/year. The initial PV panel layout design was based on residential panels rated at 230 W with a conversion efficiency of 18.5 and inverter of 96.6 % peak efficiency. To meet the projected consumption, the design called for 34 panels mounted at an 18.4 degree tilt (roof slope of 4:12) for a 7.8 kW system with a predicted output of 10 100 kWh/year.[36] The PV panels were to be

[36] Ueno, K. (2009).

mounted on both the front shed dormer roof (along with the solar thermal panels) and on the front porch roof.

3.7.2 Final Energy Model and Solar Panel Layout

As design proceeded, the EgUSA energy model continued to be updated. At design completion, the updated energy model projected energy consumption of 12 405 kWh/year distributed as follows:

- Heating: 3305 kWh/year or 26.6 % of total
- Cooling: 519 kWh/year or 4.2 % of total
- Water Heating: 1028 kWh/year or 8 % of total
- Lights: 1274 kWh/year or 10.3 % of total
- Appliances: 2440 kWh/year or 19.7 % of total
- Plug Loads: 3839 kWh/year or 30.1 % of total

The layout of the PV array was changed between the initial design and the final design to accommodate more PV panels. The solar thermal panels were moved to the front porch roof so that the full area of the front shed dormer roof was available for PV panels. With this change, there was enough space for a 7 row x 6 column array of 230 W panels for a 9.66 kW system with a predicted output of 13 950 kWh/year.[37]

There was yet another change made to the PV array design during construction when it is was learned that the 230 W panels were not U.S.-made. The 230 W panels were replaced with 320 W panels with 19.5 % efficiency from the same manufacturer. Using the 320 W panels, there was enough space on the roof to mount a 4 row x 8 column array for a 10.24 kW array. The predicted annual output of the installed PV array is 14 800 kWh/year.[38]

3.8 Beyond Net Zero

As has been mentioned in the previous sections, there were some non-energy-related requirements that had a significant impact on either the design or the final construction of the NZERTF. These included accessibility (current and adaptable for future), the "Buy American" mandate, and the research-specific requirements.

There were some additional requirements that did not necessarily contribute to the energy use of the house itself, but fall into the broader category of sustainable design. Most of these were introduced by two sets of requirements: LEED for Homes certification and the NIST-provided Indoor Air Quality specifications. In this section, the impact that these two sets of requirements had on the design is described.

3.8.1 LEED for Homes Certification

The approach taken to the LEED for Homes certification was to first determine which credits would be automatically earned just by using BSC's standard approach to low energy use

---

[37] Projection based on REMRate model for NZERTF as developed by LEED for Homes provider (EveryDay Green).

[38] Projection based on REMRate model for NZERTF as developed by LEED for Homes provider (EveryDay Green).

residential design. Additional credits would then be selected that were consistent with the design approach and would benefit NIST or would reduce the ecological impact of the new building.

The LEED for Homes 2008 credits relevant to the design and construction of the NZERTF fell into the categories of Sustainable Sites, Water Efficiencies (for indoor water only), Energy & Atmosphere, Materials and Resources and Indoor Air Quality. Of these, the only areas for which there were applicable requirements not already met were in the Sustainable Sites and the Materials and Resources sections.

Two credits from the Sustainable Sites section were selected that required additional design for the project. These were a basic landscaping credit -- the goal of which is to limit the amount of turf used and to make extensive use of plantings – and the credit for use of light-colored materials for the areas of hardscape around the house to reduce local heat island effects. The credits that called for erosion control during construction (a prerequisite), non-invasive species (a prerequisite), drought tolerant turf and plants, and a primarily vegetated site (versus impermeable surface) were standards required by NIST facilities department and thus already part of the project.

In the Materials and Resources section, the framing credits were all achievable using the construction documents and advancing framing design that were already planned for the project. However, the selection of the materials to use was adjusted to in order to earn LEED points as follows:

- Use of FSC certified wood for all wall framing, wall and roof sheathing, cabinets, interior doors, and flooring
- Use of local products for flooring, foundation aggregate and cement,
- Use of recycled glass product for countertops.

To support indoor air quality, low VOC paints, coatings and adhesives were already planned for the NZERTF, a step made even more important because of the low infiltration rates necessary to achieve a thermally efficient envelope.

Due to a delay before the start of construction, Energy Star version 3 went into effect between the completion of the design documents and the LEED for Homes registration. Since the paths chosen in LEED for Homes during the design phase included the Energy Star path for the energy performance credits and Energy Star with Indoor airPlus path for the Indoor Air Quality credits, this change was applicable to the NZERTF project. However, the only impact to the NZERTF design of this change was the requirement for some additional documentation.

Although the LEED for Homes certification had minimal impact on the design of the NZERTF, the certification process added work during the construction phase which might not otherwise have been needed, primarily supporting documentation and arranging for 3rd party verification of the Durability and Energy Star checklists and of certain other credits.

3.8.2 NIST-Provided IAQ Specifications

The intent of the NIST-provided IAQ specifications was to select products and materials that have low emissions of volatile organic compounds (VOCs) with particular emphasis on emissions of VOCs that are toxic, cause sensory irritation and/or have low odor thresholds. The pollutants and chemicals targeted by these specifications include sources of aldehydes (with particular attention to formaldehyde), VOCs emitted from wet-applied materials, and acetic acid, which is found in numerous interior products.

The definition of "interior" product to which this specification was applied includes every material and product used to the inside of the airflow control layer (or air barrier membrane). The wall and roof sheathing and framing were interior products for NZERTF and thus subject to the limits of the IAQ specifications. All engineered or composite wood products contain adhesives, including plywood, OSB, and LSLs, and thus there is concern about off-gassing from these products. Furthermore, products that are intended to be used as exterior products, such as OSB and exterior plywood, are not usually subject to the same emission restrictions as interior products. To partially address these concerns, it was determined that no OSB would be used inside the air barrier membrane for NZERTF. It should be noted that this restriction also prevents use of most TJIs (Truss Joist I Beams) since OSB is often used for the web of a TJI. Use of OSB sheathing and TJIs are typical in home construction and are less expensive than other wood products. For the NZERTF, plywood was used for all sheathing and LSLs were used for the roof framing.

Composite wood products that are typically used in the residential interiors include particleboard, MDF, and hardwood plywood (HWPW). To reduce formaldehyde sources in the interior, the specifications prohibited the use of particleboard and MDF. In general, interior woodwork and cabinetry was to use HWPW with no-added formaldehyde (NAF) veneer core and containing no urea formaldehyde (UF) resins or to use solid wood. This restriction on cabinetry eliminated many of the less expensive residential cabinetry products.

The specifications included the emissions restrictions from the LEED for Homes 2008 Materials and Resources credit for adhesives and sealants, for paints and coatings, and for cavity insulation but also added more restrictions. In general, product suppliers and manufacturers were unable to verify that the requirements of the IAQ specification were met except for those that are part of the LEED for Homes 2008 specification. It was sometimes necessary to submit the full technical product information to NIST for verification by specialists that the product was acceptable, including those products that were substituted for previously approved products.

4. Conclusion

This report presents BSC's ten principles for net-zero energy residential design and describes the architectural and MEP design for NZERTF that was consistent with these principles. This design approach emphasizes the role of a high performance, high-R, and durable building enclosure for reaching the net-zero energy capable goal.

The effectiveness of the building enclosure to provide the water, airflow, vapor and thermal control functions is the most important contribution to a low energy use building. Therefore a design that specifies how the building enclosure provides these control functions as complete, continuous and durable systems along with high R-values is the baseline requirement for an effective net-zero energy capable house. Communicating this information and the reasons for it to the general contractor are fundamental for actually achieving the performance results anticipated by the design. The NZERTF design and resulting construction set demonstrate an effective method of providing this information, especially in cases where the general contractor could not be assumed to have any previous experience with construction of high performance homes. Even for an experienced contractor, the detailed information presented in the design reminds the builder of why these details are important and how important the quality of the construction is to make these functions effective. Based on the airtightness measured at the completion of construction and the level of insulation provided, the building enclosure for the NZERTF should provide the high performance quality required for a net-zero capable house.

With the reduction in heating and cooling loads resulting from the high performance enclosure, the significance of the energy efficiency of mechanical equipment, lighting fixtures, and appliances becomes more important. Therefore the goal for the NZERTF design was to specify the most efficient equipment currently available. The requirement that all products be U.S.-made made achieving that goal more challenging since some of the most efficient residential products are currently manufactured, or made of components manufactured, outside of the U.S. In the NZERTF project, this was found to be the case for the HRV, the backup electric water heater, some LED lighting fixtures, and some of the appliances. Except in the case of the HRV, acceptable U.S.-made products were located and are not expected to significantly increase the annual energy consumption.

As demonstrated in the NZERTF project, specification of products that meet stringent IAQ requirements remains something of a challenge. The information needed to determine if a product meets the requirements is not always made available by the manufacturer, though this situation should improve as more “transparency” is demanded. But perhaps just as important is the question of understanding the product content information and the actual impact that its use will have on interior air quality.

5 References

AAON, "Modulating Hot Gas Reheat: the Split System Humidity Solution," http://www.aaon.com/Documents/Technical/ModReheat_Split_071012.pdf, accessed April 1, 2014.

AAON F1 Series, "AAON F1 Series Air Handling Units, Installation, Operation and Maintenance," https://www.aaon.com/Documents/Manuals/F1_IOM_120509.pdf, accessed April 1, 2014.

ASHRAE Fundamentals. 2009.

ASHRAE Standard 62.2. 2010. "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings."

ASTM International. 2010. ASTM E779-10: Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. ASTM International, West Conshohocken, PA.

Brown, G.Z. and DeKay, Mark (2001). Sun, Wind & Light: Architectural Design Strategies, Second Edition, John Wiley & Sons, Inc., 2001.

Brown, Richard; Rittelmann, William; Parker, Danny and Homan, Gregory (2006). "Appliances, Lighting, Electronics, and Miscellaneous Equipment Electricity Use in New Homes," Florida Solar Energy Center FSEC-CR-1675-06. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1675-06.pdf.

Building Science Corporation (2009a). "Air Barriers: Airtight Drywall Approach," 2009, http://www.buildingscience.com/index_html.

Building Science Corporation (2009b). "High R-Value Wall Assembly 01: Standard Wall Construction," BSC: Enclosures That Work, 2009, http://www.buildingscience.com/index_html.

Building Science Corporation (2009c). "Supplemental Humidity Control," BSC: Info-620, 2009. http://www.buildingscience.com/index_html.

Building Science Corporation (2010a). "Cold Climate: Concord Cape Prototype," BSC: Designs That Work, 2010, http://www.buildingscience.com/index_html.

Building Science Corporation (2010b). Net Zero Residential Test Facility Specifications, March 30, 2010.

Building Science Corporation (2011). Memo: NIST NZERTF Airtightness , 15 December 2011

Building Science Corporation (2013). "Balanced Ventilation Systems (HRVs and ERVs)," BSC: Info-611, 2013, http://www.buildingscience.com/index_html.

Code of Federal Regulations (1997). Uniform Federal Accessibility Standards. Appendix A to Subpart 101-19.6. 41 CFR Ch. 101, July 1, 1997.

EveryDay Green (2012). "NZERTF Infiltration and Duct Tightness Testing Results, 7/10/12"

International Code Council (2012). 2012 International Energy Conservation Code.

Lstiburek, J. (2008a). Builders Guide to Cold Climates, Building Science Press, 2008.

Lstiburek, J. (2008b). "The Perfect Wall," BSC: BSI-001, 2008, http://www.buildingscience.com/index_html.

Lstiburek, J. (2010). "Advanced Framing," BSC: BSI-030, 2010, http://www.buildingscience.com/index_html.

Lukachko, A. (2011). "Strategy Guideline: Advanced Construction Documentation," U.S. Department of Energy: Building Technologies Program, 2011, http://www.nrel.gov/docs/fy12osti/53459.pdf.

Rudd, A. (2006). "Design Process for Sizing: Heating and Cooling Capacity, Room Airflows, Trunk and Runout Ducts, and Transfer Air Ducts," BSC: Guides and Manuals, 2006, http://www.buildingscience.com/index_html.

Straube, J. (2008). "Airflow Control in Buildings," BSC: BSD-014, 2008, http://www.buildingscience.com/index_html.

Straube, J. (2009). "The Perfect HVAC," BSC: BSI-022, 2009, http://www.buildingscience.com/index_html.

Torcellini, P.; Pless, S.; Deru, M. and Crawley, D. (2006). "Zero Energy Buildings: A Critical Look at the Definition," National Renewable Energy Laboratory, NREL/CP-550-39833, June 2006, http://www.nrel.gov/docs/fy06osti/39833.pdf.

Ueno, K. (2009). Memo: NIST NZERTF Zero Energy Performance, October 28, 2009

Ueno, K. and Straube, J. (2010). "Understanding Primary/Source and Site Energy," BSC: BSD-151, 2010, http://www.buildingscience.com/index_html.

Ueno, K.; Wytrykowska, H. and Bergey,D. (2013)."Transformations, Inc.: Partnering to Build Net-Zero Energy Houses in Massachusetts," BSC: BA-1303, 2013, http://www.buildingscience.com/index_html.

U.S. Department of Energy, "Installing and Maintaining a Home Solar Electric System" http://energy.gov/energysaver/articles/installing-and-maintaining-home-solar-electric-system, Last accessed August 26, 2014.

About the Authors

Betsy Pettit, FAIA, is the president of Building Science Corporation and is a registered architect with over 30 years of professional experience. She is currently the project manager for Building Science Corporation's Building America project that has provided whole system designs for over 3,000 high performance houses nationwide.

Hunter Fanney, Ph.D. and **William M. Healy, Ph.D.,** are with the U.S. Department of Commerce Energy and Environmental Division, Engineering Laboratory.

Direct all correspondence to: Building Science Corporation, 3 Lan Drive Suite 102, Westford, MA 01886.