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PRODUCTION HOMEBUILDER + PASSIVE HOUSE: LESSONS LEARNED

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ABSTRACT

The builder that IBACOS worked with is a high performance startup homebuilder, building in a new community near downtown Denver, Colorado. The builder's standard production homes are intended to achieve a Home Energy Rating System® (HERS) Index of 45 to 55 and to be ENERGY STAR® Version 3 certified. IBACOS worked with the builder to design and construct a Passive House (PH) certified model home. The architects, out of Denver, designed the new floor plan, intending it to be a standard production model with the PH standard as an upgrade option. Design began in December 2012, construction started in March 2013 and was completed and certified in August 2013.

IBACOS worked with the builder to identify a package of measures that would achieve PH certification and could be implemented in an occupied test house. The team used several modeling programs and calculation methods such as Building Energy Optimization software (BEopt), THERM, and a Passive House Planning Package (PHPP) model, as well as Air Conditioning Contractors of America (ACCA) Manual J and ACCA Manual D calculations.

Short-term performance testing in the PH house was performed. Airflow was measured from each supply register in each conditioned room. Total duct leakage was 38 CFM. Whole-building air leakage to the outside was 324.5 CFM (0.60 ACH50). Room pressures ranged from 0.2 to 0.6 Pa with the heating, ventilating, and air conditioning (HVAC) system running, and energy recovery ventilator balanced airflows measured in the laundry room were 114 CFM during the cooling season.

IBACOS is currently monitoring this house along with two other homes in the area to compare various outputs.

INTRODUCTION

The builder is a division of a parent company which is in land development. At the time, the builder was starting a production building operation in the Denver, Colorado, market, and the builder had broken ground on model homes at a new community approximately 4 miles north of downtown Denver. Although a start-up division, the builder's management team had previous experience building highly energy efficient houses in a production environment and was committed to building houses with a Home Energy Rating System® (HERS) index in the mid-50s as its standard product.

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In late 2012, the builder made the decision to build a Passive House (PH) to be certified by the Passive House Institute US (PHIUS). The builder's intent was to design and construct a PH that could be offered to potential homebuyers as an upgrade to standard production homes.

The term "Passive House" is a stringent and voluntary standard that results in ultra efficient homes that require little energy for space conditioning (i.e., heating and cooling). Passive House has been promoted by the PHIUS since the inception of the organization in 2007. PHIUS certifies consultants (Certified Passive House Consultant) and projects (PHIUS + Project Certification) in the United States, independent of the German Passivhaus Institute. PHIUS + certification is outlined on PHIUS' web site[3]. Certification is predicated on meeting the energy targets associated with energy modeling using one of two software packages—PHPP or WUFI Passive[4].

IBACOS partnered with the builder to provide design assistance and modeling for the Passive House. More specifically, IBACOS performed a number of modeling applications and mathematical calculations to optimize the specification package and design details. The key issues addressed during design included adhering to PH design standards, integrating an energy recovery ventilator (ERV) into the mechanical system, optimizing the enclosure and mechanical strategies to meet the builder's objectives, and identifying any potential thermal breaks in the design.

This project was a demonstration by the first U.S. production builder to develop a house design that could achieve PHIUS certification while fitting within a portfolio of designs for a specific community.

DESIGNING A PASSIVE HOUSE

Criteria

A primary difference between a PH and many other above-code energy efficiency programs is the stringency of the pass-fail criteria, as well as the site-specific nature of the design and modeling. Production builders generally use a worst-case approach for house design; however, for certain designs, it is easier to meet the PH targets if careful passive solar design is undertaken. The PHPP spreadsheet is a very cumbersome tool for undertaking worst-case analysis because each individual component must be entered with its specific characteristics. WUFI Passive is much more flexible in this respect, allowing the designer to easily rotate the model by orientation or to create duplicate cases to modify certain design features (e.g., window area or shading). Table 1 lists the minimum criteria as developed by Passive House:

Criteria	I.P. Units	S.I. Units
Annual Space Heat Demand	4.75 kBTU/ft^2/yr	(15 kWh/(m^{2}a))
or Peak Heat Load	3.17 BTU/ft^2/hr	(10 W/m^2)
Annual Cooling Demand	4.75 kBTU/ft^2/yr	(15 kWh/(m^{2}a))

[3] http://www.passivehouse.us/passiveHouse/PHIUSPlusChecklist/phiusprecert.shtml.
[4] http://www.wufi.de/frame_en_webshop.html.

Annual Primary (Source) Energy Demand	38 kBTU/ft^2/yr	(120 kWh/(m^{2}a))
Air Infiltration Rate	$n \leq 0.6$ ACH50*	$n \leq 0.6$ ACH50*

*Air changes per hour at 50 Pascals of pressure.

TABLE 1: Passive House Criteria

Design Specifications

The Passive House was a newly designed floor plan done by the architects from Denver, Colorado. The house is two stories and approximately 2,421 square feet. This includes 3 bedrooms and 2½ bathrooms. The front of the house faces south, and the exterior is clad in stucco and siding, which is consistent with the builder's standard construction methods. IBACOS reviewed the builder's standards and upgraded them to meet PH standards. Table 2 compares the major differences in specifications between the builder's standard product and the Passive House.

Specifications	Standard Package	PH (Test House) Package
Slab R-Value	0	R-20 under-slab/slab edge
Wall Cavity R-Value	R-27, GI	R-11 + R-30 GI
Ceiling/Attic R-Value	R-50	R-60
Heating	Natural gas furnace 96 AFUE Lennox	First Company fan coil unit with hot water coil with heat supplied from the Navien Condensing Combi unit ~0.93 AFUE
Air Conditioning	13 SEER air conditioning	21 SEER air conditioning
Ventilation	Exhaust only at laundry room (3 bedrooms @ 3200 ft^2 = 62 CFM)	Zehnder ComfoAir 350 ERV, 91% efficient
Window U-Value	0.3	0.14
Door U-Value	> 0.167	0.30 (glazed); 0.14 (solid)
Air Sealing	~2ACH50 tested	0.6 ACH50 tested
Shading	NA	Recessed windows
Lighting	100% CFL interior, exterior, and garage	100% CFL and LED interior, exterior, and garage

CFL is compact fluorescent light. GI is RESNET insulation installation Grade I. LED is light-emitting diode. NA is not applicable.

TABLE 2: Specifications for the Builder's Standard Product and the Passive House

MATHEMATICAL AND MODELING METHODS

Passive House is a pass/fail set of criteria, and modeling is done to hit a specific target. Regardless of the tool used (typically the Passive House Planning Package [PHPP] model or WUFI Passive), PH criteria reward simple, boxy, slab-on-grade designs that have a very low surface-area-to-volume ratio, with the long axis facing southward. During the design of the Passive House, IBACOS performed several modeling applications and mathematical calculations to optimize the specification package and design details. IBACOS used the following modeling programs and calculation methods to complete the final design package:

- BEopt – Optimization of thermal enclosure and mechanical system specifications; energy use and energy savings predictions (BEopt 2.1.0.1 2013)
- THERM – Specification of the amount and location of slab edge insulation (THERM 2012)
- PHPP – Passive House Planning Package model (PHPP 2012)
- ACCA Manual J and Manual D used by Four Seasons Heating[5] (the mechanical contractor) to do the HVAC system load calculation and to design the duct system, respectively (Rutkowski 2006 and 2009)

These tools use different standard operating assumptions and defaults, as well as slightly different parameters (e.g., thermostat set point, hot water draw quantity and schedule). They also use different calculation methods and simulation engines. As a result, the tools provide different outputs. IBACOS investigated WUFI Passive as a modeling tool but decided on the more familiar PHPP tool due to timeline constraints. Feedback was given to the design team regarding options and strategies to bring the house into compliance during the schematic design phase (e.g., different window sizes, different ventilation system options). Integrating the mechanical and framing trade partners into the design process early was beneficial in the long run, particularly in developing structural details for the high wind loads of the Denver region.

BEopt

IBACOS used BEopt version 2.1.0.1 was used to model the builder’s standard practice and the final PH (test house) package, as shown in Figure 1. Optimization was run, including the builder’s standard practice, additional practical energy efficiency measures, and the PH measures (test house). Figure 2 shows the optimization curve, including those features that added significant cost with little apparent cost benefit strictly from an energy perspective but were required to achieve PH certification.

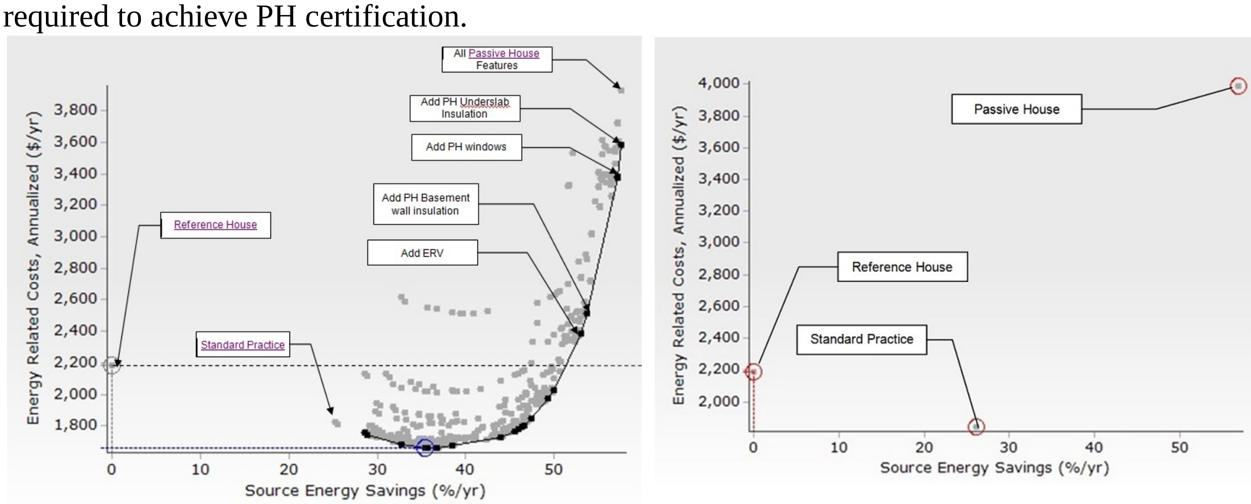

FIGURE 1: The image on the left shows BEopt optimization of the builder’s standard practice compared to various PH (test house) components and the image on the right shows BEopt optimization of the builder’s standard practice

[5] Four Seasons Heating, Denver, CO. http://www.fourseasonsheatinginc.com/.

ACCA Manual J and Manual D

Rhvac (Rhvac 2012), an ACCA-approved software program for applying ACCA Manual J and ACCA Manual D (Rutkowski 2006 and 2009), was used in the design of the HVAC system for this test house. These designs were prepared by the mechanical subcontractor. The volume of the conditioned space in the test house is 32,398 ft^3. The calculated cooling load of the test house using ACCA Manual J is approximately 14 kBtuh, and the calculated heating load is approximately 18 kBtuh.

RESEARCH/EXPERIMENTAL METHODS

To characterize the integrity of the thermal enclosure and to measure the start-up performance of the HVAC system, a number of short-term tests were completed following the finish of construction of the test house.

Room-by-Room Supply Register Airflow

The energy rater used a calibrated low-flow balometer to measure the airflow from each supply register in each room conditioned. The rater then compared these measurements to the design airflow values from the ACCA Manual J heating and cooling load calculations (Rutkowski 2006) to determine if adequate airflow was reaching each zone of the house. Table 3 compares the designed airflows and the measured post-retrofit airflows. Those measured airflows are then stated in a percentage of deviation from the design. All design and measured airflow values were measured in heating and cooling modes.

Location	Design Airflows	Measured Airflows	% Difference from Design
Bedroom 3	63	82	+26%
Bathroom 2	16	37	+79%
Bedroom 2	67	78	+15%
Hall	40	63	+45%
Master Bedroom	108	118	+9%
Master Bathroom	35	51	+37%
Kitchen	60	76	+24%
Powder Room	16	38	+81%
Great Room	87	91	+5%
Foyer	20	29	+37%
Basement	92	68	+30%

TABLE 3: Room-by-Room Supply Register Airflows

Duct Air Leakage

The duct air leakage for the units was measured using a Minneapolis Duct Blaster®[6]. Total air leakage through the duct systems was measured as well as total air leakage to the outside. The amount of air leaking through the duct system helped to characterize the performance of the air distribution system capacity for delivering the proper amount of air to the zones of the house. The total duct leakage is 38 cfm.

[6] Minneapolis Duct Blaster. Minneapolis, MN: The Energy Conservatory. http://www.energyconservatory.com/products/duct-blaster%C2%AE-systems-and-accessories.

Whole-Building Air Leakage

To evaluate the airtightness performance of the building enclosure, a test using a blower door was conducted after construction of the test house was completed. The test measures the amount of air leaking through the building enclosure under a known operating pressure differential between the house and the outside. The target test result is 0.60 ACH50, which is the maximum for PH certification. The whole-building air leakage test was performed by the builder's HERS Rater, the house size is about 3,200 square feet and the volume is 32,352. The final whole-house air leakage was 324.5 CFM50 and 0.60 ACH50.

ERV Airflow Balancing

Fresh air is supplied to the test house by a Zehnder ComfoAir 350[7] unit installed on the second floor in the laundry room. The ERV unit will run continuously and will supply the house with an amount of fresh air equivalent to 74 cfm. To verify that this ERV unit is supplying the proper amount of air to the house, airflow was measured and balanced following installation of the unit. Measurements were performed using a digital manometer.

Long-term Monitoring and Data Collection

Long-term monitoring will be performed for one year to collect data on the performance of key subsystems in this Passive House. Primary objectives of monitoring include collection of temperature and relative humidity data from individual rooms and thermal zones in the house and outside; outside incident solar radiation; interior partition door status (open or closed); and electrical consumption of the indoor air handling units and outdoor compressor units. Secondary objectives for monitoring include ERV electrical consumption and whole-house electrical measurements. A primary data logger will collect data from installed sensors and will record measurements at 1-minute, 15-minute, 1-hour, and daily intervals as needed.

DISCUSSION

Ratio of Surface Area to Volume

One area that could have had an impact on the overall thermal enclosure is the relative amount of surface area of this house compared to the enclosed volume. This constraint could not be modified, given the long and narrow nature of the lots plus the fact that this community has alley-loaded garages. Also, one design concept in this community is the flow of indoor to outdoor space on the first floor on tight lots by using a "courtyard" design, which increased the surface area of the building, likely drove up the relative R-values of the house, and increased the attention to detail necessary to air seal the house

Thermal Enclosure

Some key characteristics in the schematic design phase influenced the design included 12-inch-thick walls, passive solar design strategies, a mechanical closet located inside conditioned space, and more than 20 inches' full insulation depth in the attic. As the PHPP modeling proceeded, several key design principles became apparent that significantly influence the space layout and aesthetics of a PH project.

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[7] Zehnder ComfoAir 350. Greenland, NH: Zender America. http://www.zehnderamerica.com/products/product_list.aspx?CategoryID=1.

Basement Insulation. To achieve the PH energy use criteria, significantly more basement insulation was used, and thermal bridges were minimized. THERM version 7.1.19.0 software was used to model this and other thermal bridges, but none were found to be significant relative to achieving the PH standards.

The highly insulated basement combined with a code-minimum number of windows led to low basement heating and cooling loads compared to those of the first and second floors, as shown in Table 4.

	Peak Heating Load (Btu/hr)	**Peak Cooling Load (Btu/hr)**
Basement	2,285	1,209
First Floor	6,357	7,255
Second Floor	6,758	5,897
Total	15,400	14,361

TABLE 4: Peak Heating and Cooling Loads, by Floor

Windows

Several factors are considered in detail in the PH energy analysis: the frame versus glass area and the impact on solar gain, and the shading of each individual window. The initial design of this house also included a large number of small individual windows, or groups of small and large windows, to be consistent with the aesthetics of the other houses in the community. After an initial PHPP model was completed, it was apparent that the significant number of windows and relatively high frame area to window area would negatively impact the energy performance (i.e., more conduction through frames and less solar gain) and would increase the cost of the overall window package. Figure 3 shows the PH in the context of the other houses on the same block in the community. The PH has a larger uninterrupted glazing area, maximizing solar gain and lowering overall heat loss.

FIGURE 3: Passive House (far left) and other production houses in the community

Final Thermal Enclosure Characteristics

In the end, the final PH assemblies were as determined by PHPP modeling. The basement slab had an R-value of R-21.3, and the basement walls had an R-value of R-46.5. The above-grade walls had an R-value of 47.5, and the R-value of the attic was R-60. The floor over the garage was a value of R-52. The U-value of the windows was 0.15, with a SHGC of 0.32 (south) and 0.22 (east, west, and north). Airtightness of the enclosure was 0.6 ACH50.

Mechanical Ventilation System

Passive House analysis takes into account the surface area of the intake and exhaust ductwork to and from the ERV unit. This is generally ignored as a direct input for most modeling software. Passive House modeling requires that the specific lengths and R-values of the intake and exhaust ducts be entered. This seemingly small issue can be a factor in design because the shortest distance of duct will have the least energy impact, especially in cold climates.

One widely discussed aspect of PH construction is that the thermal enclosure is so good that the space conditioning can be achieved using the ventilation system. For a production builder, this strategy entails a high level of risk for several reasons. First, customers are unaccustomed to not having a heating and cooling system, so the sales staff must be well-equipped to overcome this concern and objection. Production builders also are very attuned to occupant comfort, and in the authors' experience, comfort complaints are common for builders, even in higher performance homes. For these reasons, the team decided to install a small, dedicated heating and cooling system as shown in Figure 4.

FIGURE 4: Mechanical closet with the air handler and water heater (left) and the ERV (right)

CONCLUSIONS

There are many different approaches to building a PH. When applying different design ideas to the PHPP model, you may get an answer that allows you to use that product. However, as the designer, you need to be sure you are using the correct details for your end goal.

The design strategy and aesthetics can significantly impact the construction costs of a PH. In this project, the team modified a standard production house to comply with PH requirements. This was necessary to keep the design and "feel" of the house the same as those of the builder's other houses in the community. The many different approaches to building a PH can change the cost dramatically. During modification, the extra costs incurred to build this house were approximately $90,000. This number is composed of many different items, as shown in Table 5.

Item	Cost
Windows	$19,000
HVAC System	$32,000
Interior Insulation	$11,000
Framing Material, Exterior Insulation, and Labor	$15,000
All Other Items Combined	$13,000

TABLE 5: Additional Costs to Create a Passive House

This Passive House did sell relatively quickly; however, the builder does not anticipate that a significant number of buyers will be interested in the PH upgrade at the current additional cost of around $90,000.Although PH is one standard that is being explored by a growing number of design professionals and builders in the United States, it currently is limited predominantly to custom homes. Passive House metrics prescribe an absolute energy use per unit floor area per year, which leads to simple, boxy designs yielding the least stringent thermal enclosure requirements due to minimizing the exposed surface area for a given floor area. The PH metrics do not easily translate to a uniform HERS Index because the HERS Index is a relative metric: the rated house is compared to the same physical layout built with a minimum set of efficiency standards. Work is needed to translate the European metrics for PH and all the associated default assumptions and use/occupancy schedules to more closely match the reality of U.S. occupancy patterns and comfort criteria that U.S. homebuilders routinely experience. Regardless, the team found that, through an integrated design and construction process, a production builder can design and build a PH on a tight timeline.

ACKNOWLEDGMENTS

This work was performed for the U.S. Department of Energy Building America program. Funding for this work was provided by the National Renewable Energy Laboratory under Subcontract No. KNDJ-0-40341-03.
The author acknowledges Brookfield Homes, KGA|studio architects, Four Seasons Heating, Inc., and EnergyLogic, Inc. for their contributions to this project.

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