Building a Simple Passive House

Keeping an eye on the thermal and air boundary during construction is key

by Terry Nordbye

In September 2009 I completed a deep energy retrofit ("A Cost-Effective Energy Retrofit," 8/10) on a small house in Point Reyes Station, Calif., some 50 miles north of San Francisco. The owners were so pleased with the results they asked if I would build a new 750-square-foot rental unit in the back of their property, designed to meet the demanding Passive House energy-use standard. (Because affordable rental housing in California is in such short supply, the state encourages the construction of such second units — though they're limited to a maximum footprint of 750 square feet.)

I began work in February 2010, using a set of plans developed by architect James Bill. It was to be the first new PH project in California. There were no textbooks, elders, or old-timers to fall back on for advice or tips. My subs had no idea what they were getting into. My workers had worked on the retrofit and had the basic concepts of air-sealing, but all in all, we felt a bit like first-time explorers going to the moon.

The Passive House Standard

The Passive House standard was developed in about 1990 by German physicist Wolfgang Feist and Swedish professor Bo Adamson. It aims to provide people with buildings that use little energy, and to achieve this through efficient air-sealing, lots of insulation, and a minimum of thermal bridging (see "Passive House Seeks Broader Appeal," *JLC Report,* 2/11).

A unique feature of the PH standard is that it imposes an absolute energy budget on a house. The building can't use more than 120 kwh per square meter per year (38,000 Btu per square foot per year), of which no more than 15 kwh per square meter per year (4,800 Btu per square foot per year) can be used directly for heating or cooling.

Hiring a consultant. Meeting that goal is made possible through the use of a sophisticated energy modeling tool available through the Passive House Institute U.S. (PHIUS). That tool, called the Passive House Planning Package, or PHPP, requires

Figure 1. An excavated bed filled with crushed stone served as a base for the stem-wall foundation, which was stepped down at its upper edge so that the exterior foam insulation wrapping the frame would cover the edge of the mudsill, eliminating a potential thermal bypass (far left). A vertical strip of polyiso board around the inside of the stem wall minimizes heat loss at the slab edge (left, top). For air-sealing the frame to the slab, the mudsills were bolted in place in a bed of roofing cement (left, bottom).

considerable training to use correctly, and with rare exceptions is accessible only to Passive House consultants who have completed an intensive nine-day training program.

When I was considering this project, I realized that I had two options: I could either take the training course myself, or hire a certified Passive House consultant to develop the plans in conjunction with the project architect.

I didn't have to think about it for long. I'm a guy who likes to build things, not crunch numbers. So we hired Lowell Moulton, a local PH consultant, to work with our architect to make sure that the house we built would meet the standard. The resulting collaboration went smoothly.

But there was still plenty for me to do. Passive House construction requires a lead person on the job every day to make sure the workers are correctly addressing critical aspects of the shell. That person has to be fully versed in air-sealing and thermal bridging. More so than with any other building I have ever done, every member of the building and design team has to understand the jobs of all the rest. If one of the team fails, the entire outcome can fail.

Foundation

The foundation we used was basically a carefully detailed, better-insulated version of the stem-wall foundations common in our area (**see Figure 1**). After pouring the concrete and stripping the forms, we leveled out and tamped the interior crushed-rock bed and covered it with a layer of 6-mil poly. On top of the poly we laid a bed of 4-inch XPS, leaving a narrow gap between adjacent sheets, which we sealed with a Pageris foam gun and Touch 'n Seal 32-ounce canisters. We added a layer of 3-inch foam over the first layer, again sealing the joints, to bring the subslab insulation to R-35. We then covered the foam with another layer of 6-mil poly (**Figure 2, page 3**).

Insulated edges. To prevent a major thermal bypass at the edges of the slab, we cut strips of 2-inch foil-faced polyiso board and applied them to the exposed portion of the stem wall, finishing flush with the top. After placing the rebar grid and pouring and finishing the slab, we bedded the mudsills in a thick layer of asphalt roofing cement. The resulting reinforced slab (which would later be stained and serve as the finish floor) was completely enclosed in foam on all five sides and air-sealed to the framing that followed.

Framing

We used OVE (optimum value engineered) framing, sometimes known as advanced framing. With this approach, studs are on 2-foot centers; you use header hangers instead of trimmers and cripples; and the headers are sized for the actual load, not for convenience, and are usually omitted on rake walls and non-load-bearing openings. Rafters are centered over the studs, eliminating the need for double top plates, and 1-bys are used in place of 2-bys for nailing corners and wherever possible.

The payoff is a strong frame — engineered to meet our local seismic codes — that contains less wood and more insulation. This minimizes thermal bridging through the framing, increasing the thermal resistance of the shell by about 8 percent. With 15 percent to 25 percent less lumber to cut and move around, OVE

Figure 2. The stone base inside the stem wall was leveled and compacted, then covered with 6-mil poly and 4-inch XPS insulation (A). A layer of 3-inch foam was laid over the first layer (B), with joints staggered and all gaps in both layers filled with spray foam (C). A second layer of poly and steel reinforcing followed (D).

framing also offers major savings in both material and labor.

Training the crew. The concept was new to most of our workers, and it took some getting use to at first. On several occasions, I had to remind the framing crew to use the 3-inch strips I'd ripped from ½-inch plywood as drywall backing at corners and top plates, rather than the 2-by material they were used to. Before long, however, they were coming up with better ways to use less wood and decrease thermal bridging.

Sealing the structural ridge. To create the open plan that would give the small house a roomier feel, the design called for a substantial glulam beam at the ridge, which would be left exposed as part of the interior finish. This was a tricky area, because it would be impossible to get a reliable air seal by simply butting the drywall against the face of the beam. Instead, we ripped some 2x6 blocking to sit flat on the top of the beam flush with the bottom edges of the rafters, making it possible to caulk the drywall to both the rafters and the blocking (**Figure 3, page 4**). We sealed the blocking to the rafters and the beam with spray foam.

The rafter tails were cut off flush with the plane of the outside walls, so both the roof and the walls could be sheathed without the usual break at the eaves — ordinarily a major source of air infiltration.

Sheathing and Air-Sealing

A Passive House can have air leakage of no more than 0.6 ACH50. For a project to hit that number, it's essential that all of the workers involved know where the air-seal boundary is, when they have punctured it, and how to reliably seal the punctures that inevitably occur from time to time.

Because the whole process was somewhat new to us and we wanted to be sure to meet or exceed the airtightness standard, we decided to double down in this area and provide an air seal at both the sheathing plane and the drywall plane, reasoning that this would also help the structure remain tight even if one layer was somehow compromised years down the road.

Taped plywood and two blower-door tests. We sheathed the structure with ½-inch FSC-certified plywood, sealing to the framing as we went with the same spray foam we'd used in the foundation (**Figure 4, page 5**). The joints between sheets were sealed with paper wallboard tape and duct mastic. That approach worked well, but was relatively slow and messy. I have since switched to a high-performance sticky tape called Wigluv 60 (siga.ch).

To ensure that the building would never become infested with powderpost beetles or termites — both of which are common out

Figure 3. Insulated headers supported by metal connectors are a hallmark of OVE framing (A). Though framed with less lumber, the shell meets West Coast seismic requirements (B). To eliminate air leakage at the ridge, the crew installed blocking between the rafters, sealing it to the framing with spray foam (C). The blocks (D) were ripped so they could be caulked into place, bearing solidly on the glulam beam and matching the angle of the rafters to provide a caulkable nailing surface for the sloped ceiling drywall.

here — I sprayed all the interior and exterior framing and plywood with a water-based borate solution called Bora-Care (800/264-0870, boracaretermitecontrol.com), using a hand-pumped garden sprayer.

I bought my own blower door a couple of years ago. It's proven to be a great investment, because it makes it easier to nail down the source of air leaks while they're easy to fix. We performed a first blower-door test before cutting the rough openings, because we wanted to be able to compare it to another one performed later, after the windows had been installed — a sequence that would make it possible to differentiate air leakage through the sheathing from leakage through or around the windows themselves. The initial test, using the E-ring on the blower door, put the air leakage of the shell at 17 cfm, or about 1.5 ACH.

Windows. The windows were Serious Energy 725 series fiberglass casements and fixed units — high-quality double-glazed windows with a suspended film that helps them approach the performance of triple glazing without the weight and bulk (800/797-8159, seriousenergy.com). Before installing them, we furred out the rough openings by an inch to allow for the layer of rigid foam that would later go on over the sheathing (**Figure 5, page 5**).

Like most window manufacturers, Serious Energy doesn't provide air-leakage figures for its products, but the second blower-door test seemed to confirm that they're extremely tight: The number we got was nearly identical to the one from the first test, and exploring the area around the windows with a smoke pencil didn't reveal any visible air movement.

Outer Roof and Exterior Foam

To reduce thermal bridging through the 2x8 rafters, the plan called for framing and insulating what amounted to a second, outer roof over the first. We started by laying 2x4 sleepers on edge over the plywood roof sheathing — staggered between the rafters below — and nailing them in place from beneath (**Figure 6, page 6**). These "outer rafters" extended beyond the wall to create a 2-foot overhang at the eaves. The spaces between the sleepers

Figure 4. To air-seal the ½-inch sheathing to the framing as it was installed, one carpenter laid beads of foam on the framing edges while another followed with a nail gun (left). The plywood seams on both the walls and the roof were further sealed with drywall tape and duct mastic (right).

were filled with 3.5 inches of polyiso board, which was allowed to overhang the wall sheathing by an inch.

Finally, the assembly was sheathed with more ½-inch plywood — which, like the sleepers and the rest of the framing and sheathing, was also treated with Bora-Care. Combined with the dense-pack cellulose that would later be blown into the framing of the lower roof, the assembly had a nominal R-value around R-49.

To create a continuous blanket of foam around the air-sealed shell, a layer of 1-inch XPS was then applied over the wall sheathing. At its upper edge, the foam on the walls was beveled to match the overhanging lip of polyiso foam exposed at the edge of the roof , and was sealed to it with more spray foam.

Plumbing and Wiring

All pipes and wires that penetrated the sheathing were carefully sealed with SIGA tape, caulk, spray foam, or some combination of the three. We also screwed flat plywood backing plates to the framing so the drywall could be caulked around them (**Figure 7, page 7**).

Electrical boxes. We used airtight electrical boxes from Airfoil

Figure 5. High-solar-gain glazing was used on the south elevation and low-gain glazing on the other sides; U-values range from 0.14 to 0.19. Inside, the units were sealed to the rough opening with spray foam (above left), then surrounded with a thermal break of rigid foam (above right). Later, the drywall was returned into the opening and finished with corner bead.

(612/280-8331, airfoilinc.com) wherever possible. Because Airfoil doesn't make a sealable three-gang box, we made our own by fastening and caulking plywood "horseshoes" in place around them, and sealing the wire penetration with nonhardening duct sealer.

Drywall and Cellulose

Our plan called for drywalling the frame first, then insulating the cavities with dense-pack cellulose. The local building department wasn't happy with that choice, because it's difficult to inspect visually. Damp-spray cellulose can be applied to open wall cavities, but this would have meant waiting for things to dry out before the drywall could go on — potentially a long time, given the cold, damp winter weather. We also wanted to avoid blowing the cellulose behind netting, because any bulging of the netting could interfere with a good seal between the drywall and framing.

Fortunately, the department agreed to meet us halfway: We

Figure 6. To provide added insulation with minimal thermal bridging, 2x4 sleepers were laid edgewise on the roof sheathing, staggered between rafters, and allowed to extend past the plane of the walls to form wide overhangs (A). Foil-faced foam cut to fit tightly between sleepers (B) slightly overhangs the sheathing and is sealed to the exterior wall insulation board with spray foam (C, D). A second layer of $^1/_2$-inch plywood was installed over the sleepers in a bead of spray foam (E).

Figure 7. To provide a caulkable surface for sealing the drywall to the framing, backing plates fashioned from scrap lumber and plywood were fastened to the edges of framing members and across rafter and stud bays (A, B). Although three-gang airtight electrical boxes were not available commercially, the crew made their own by cutting pieces of U-shaped plywood (C), caulking them to the box, and fastening the corners to the framing with finishing nails; the wires were sealed with acoustical caulk (D). The drywallers applied painter's caulk to the plates, backers, and rough openings as they hung the wallboard, using two cases of caulk for the 750-square-foot structure (E).

could do it our way, with the stipulation that we would have to hire a certified thermographer to check our work and confirm that no cavities had been missed.

Caulked drywall. Before the rockers hung each sheet of 5⁄8-inch wallboard on the outside walls, they ran a bead of Dap painter's caulk along the top and bottom plates, at corner framing, around window and door openings, and at the flanged plumbing and electrical penetrations. They applied enough caulk so that a little excess squeezed out at the edges, confirming the presence of a good air seal.

We used one tube of caulk for each 50 square feet of wallboard, or about two cases of caulk in all. This was new to the drywall crew, and they complained at first. But they quickly got the hang of it, and with a little supervision did a very good job.

Blowing the cellulose. Our insulator is very accomplished at blowing cellulose into closed cavities. He paid a preliminary visit to the site before the drywall was on and took a series of photographs of the exposed framing, allowing him to pinpoint the locations of all the cavities later. Thanks to the OVE framing, there were fewer small spaces and areas obstructed by blocking to worry about than there would have been in a conventional frame.

The rafter cavities were filled with cellulose through holes bored in the rafter blocks, to a density of 3.5 pounds per cubic foot (**Figure 8, page 8**). Because the insulation puts considerable pressure on the drywall, it's vital to check it with a moisture meter before packing the cavities — a moisture content of 20 percent or more will likely cause the drywall to bulge, or even tear away from the screws. The wall cavities were filled from inside the building, through holes bored in the drywall. The thermographer who inspected the work said it was the first job he'd seen that didn't need any additional work to deal with missed spots or problem areas.

Partitions and Interior Finish

We didn't frame any of the interior partitions until the exterior walls were fully drywalled, taped and mudded, and insulated. This approach complicated the schedule somewhat but offered two benefits: First, it eliminated difficult-to-seal inside corners

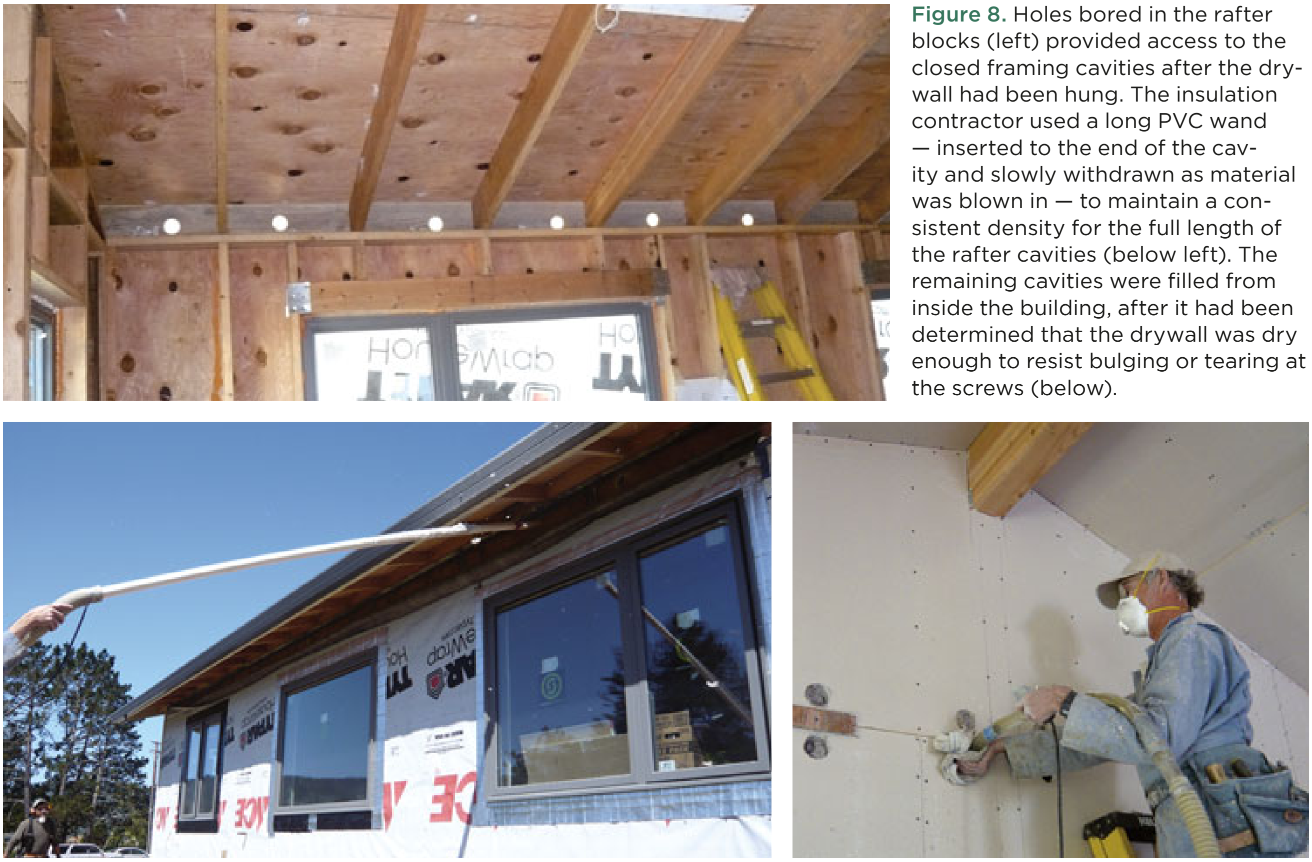

Figure 8. Holes bored in the rafter blocks (left) provided access to the closed framing cavities after the drywall had been hung. The insulation contractor used a long PVC wand — inserted to the end of the cavity and slowly withdrawn as material was blown in — to maintain a consistent density for the full length of the rafter cavities (below left). The remaining cavities were filled from inside the building, after it had been determined that the drywall was dry enough to resist bulging or tearing at the screws (below).

where the drywall on the exterior walls was interrupted at a partition. And second, partition walls can now be moved without introducing air leaks. That's not important in the short term, but when the interior is remodeled somewhere down the road, our method makes it much more likely that the air-sealed interior will maintain its integrity.

Mechanicals and final blower-door test. We built a drop ceiling over the kitchen and mechanical-room area to provide a space for the ERV and associated ductwork, and furred a 3-inch wall along most of the north side to accommodate the plumbing and electrical for the kitchen, mechanical room, laundry, and bath, and piping for the code-required sprinkler system (**Figure 9, page 9**). All this was completely within the air-sealed shell, making further sealing unnecessary. Our final blower-door test gave us a figure of 0.36 ACH — comfortably within the 0.6 ACH required by the Passive House standard.

Solar Thermal and ERV

The heating demand of a Passive House is so low that incidental heat from appliances, lights, and cooking — even body heat — can supply a large part of what's needed. The heating system for this project relies on an active solar-thermal system with an electric resistance backup, with heat distributed by the ERV.

Rooftop solar. Four rooftop-mounted solar thermal panels from Vaillant (858/205-9089, vaillantsolarsystems.com) are sized to meet about 80 percent of the home's expected demand for both space heating and domestic hot water, even during cloudy winter weather. The hot water from the panels is stored in a pair of 80-gallon superinsulated storage tanks. The plumbing was laid out as a drainback system, meaning that the water in the panels flows back to storage if there's any threat of overheating or freezing. A small 20-gallon electric water heater holds a backup supply of domestic hot water.

When the thermostat calls for added space heating, a small inline pump circulates water from the solar storage tank through an inline heat exchanger mounted in the supply duct of the RecoupAerator ERV (800/535-3448, ultimateair.com). If the storage tanks have been drained of heat by a prolonged cloudy period, an inline resistance heating coil picks up the slack.

Fresh air. To provide consistently high air quality, the ERV runs continuously, recovering up to 80 percent of the heat from the exhaust stream and transferring it to the incoming makeup air. Three ducts pull stale air from the utility room, kitchen, and bath. The normal rate is 12 cfm from the utility room, 56 cfm

Figure 9. A drop ceiling above interior partition walls (left) provided space for the ERV and associated ductwork (below left). A furred-out wall on the north side of the kitchen and utility room — completely within the air-sealed thermal envelope — made it possible to run pipes and wiring as needed without additional air-sealing or insulation (below).

from the kitchen, and 24 cfm from the bath, but both the kitchen and the bathroom have manually controlled booster switches to bump up ventilation when needed.

Balanced supply ducts are located in the bedroom and the living/dining room. A night cooling cycle controlled by a sensor in the incoming duct brings in cool air when appropriate.

Lessons Learned

There was a steep learning curve on this project, and I'd do a few things differently next time. For example, we probably spent more time than we needed to devising our own methods of sealing around pipes and wires. My next Passive House would use more out-of-the-box tapes to seal seams and penetrations.

There have also been some commissioning problems. Energy monitoring equipment installed soon after the house was completed revealed that it was using far more electricity than expected. We eventually determined that this was due to a defect that caused the solar-thermal pump to run around the clock for nearly six months. Given the small amount of heat needed, I now think the heating system is more complicated than it needs to be. Next time, I would consider using one or more wall-mounted towel warmers in place of the inline electric resistance heater in the ERV duct line.

Cost and performance. I deliberately bid a low price for this job, because I was interested in Passive Houses and saw it as a great learning opportunity. Some of the work was done by volunteers or workers who charged a reduced rate, and we had the benefit of some discounted materials from suppliers. As a result, it's impossible to give a firm cost figure for the job. Based on my experience as a builder in this area, I'd say that it cost about 10 percent more than a comparable structure built to conform with Title 24, California's current energy-conservation code. In Europe, where Passive House has a well-established track record, the PH cost premium over that of conventional construction is said to be as little as 5 percent.

The tenants now living in the house — which is owned by a local land trust — have been amazed at its ability to self-regulate and remain comfortable regardless of the weather outdoors. To me, that underscores an often-overlooked benefit of this approach to building: Because there's little need to fiddle with a thermostat or compensate for other shortcomings in the building envelope, a Passive House is both user-friendly and tolerant of occupant error.

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