Moving Ducts Inside: Big Builders, Scientists Find Common Ground

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ABSTRACT

Many national building science experts recommend the best way to increase HVAC system efficiency is by moving the air handler and ductwork from unconditioned space to inside the home (ASHRAE 2004). Techniques for moving the HVAC system within the conditioned space are well known, and the costs for making this transition are generally less significant than other residential energy conservation measures. However, in practice this approach is rarely used by production builders.

In working with production builders in the Pacific Northwest, the WSU's Building America research team has found it possible to move the HVAC system inside (within the thermal and pressure boundary of the home), with minimal cost increases, inconsequential loss of indoor space, and significant energy savings.

Using field test data as inputs, energy simulation software models were used to evaluate energy use in four high performance Energy Star test homes. Moving the HVAC system inside offered the highest incremental energy savings compared to all other above code energy features. Computer simulations predicted annual savings of about $100 in Portland, OR, and $200 in Spokane, WA (Lubliner et al. 2007).

This paper will focus on making the case that this technique saves energy, is practical for production builders (when accompanied by careful pre-planning), and creates significant and marketable energy savings for homebuyers. The paper will discuss design charrettes with production builders, best practices from building scientists and builders, and provide examples of how other builders can apply this approach.

Background

In the Pacific Northwest, standard practice is to locate the furnace in the garage, supply ducts in the crawl space, and return ducts in the attic. As typically installed, this "default" design is assumed in codes to reduce system efficiency by about 20 percent. A well installed system, with good insulation and exceptional air sealing is assumed to result in 88% distribution system efficiency and 96% when located in the conditioned space of the home (ICC 2006).

Other references emphasizing the value installing HVAC systems inside conditioned space include:

- In 1995, the report "Costs of New Residential Conservation Measures in the Pacific Northwest" used phone surveys of builders and HVAC contractors, as well as R.S. Means Residential Construction Cost Data to estimate the incremental cost of moving ducts into the conditioned space – $31 less for a 1344 square foot prototype and $71 more for a 2200 square foot prototype. These costs include added $277-$488 for additional framing and drywall for duct chases and savings of $308 - $417 related to elimination of code required R8 duct insulation, shorter duct runs and reduced labor costs. This report also found that over two thirds of builders build without basements and 61% install HVAC systems and ducts in garages, attics and crawlspaces (Lubliner et al. 1995).

- The NAHB research center's "Builder's Guide to Placement of Ducts and HVAC Equipment in Conditioned Spaces" gives practical guidance to builders and HVAC contractors in the design and installation of HVAC systems placed entirely within the conditioned space. The guide has chapters on design and layout planning with technical approaches to fit variations in house style, building code implications, and effective marketing of this approach. (NAHB 2000)
- The California Energy Commission has also produced a Guide entitled Home Builders Guide to Ducts in Conditioned Space. Diagrams from this guide were used in the ASHRAE Systems Handbook (see #4, below) (CEC 2003).
- The ASHRAE Systems and Equipment Handbook, Chapter 9, "Design of small forced air heating and cooling systems" reads "[Residential duct system] losses can be almost entirely eliminated by simply locating ducts in the conditioned space…which is a cost-effective way to increase heating and cooling equipment efficiency and lower utility bills. Benefits include improved comfort, improved indoor air quality, and lower utility bills and equipment cost. Any losses (air or conductive) from ducts in conditioned space still provide space conditioning." (ASHRAE 2004).
- Pacific Northwest residential new construction market transformation programs assume savings of 795-1902 kWh per year in the Portland and Seattle climates for moving ducts inside (see figure 1) (RTF 2006). These deemed savings are shown for both a typical new Washington state energy code and Energy Star home, cases without basement. Both cases assume an 8.5 HSPF heat pump; the Energy Star case assumes commissioning for charge, flow and controls. Assumed cost for moving ducts inside is $650.

Table 1. Deemed Savings for Moving Ducts Inside

Climate	Energy Star with HP (kWh/year)	WA state code with HP (kWh/year)
Portland	795	1,874
Seattle	811	1,902
Boise	1,918	4,399
Spokane	2,058	4,785
Missoula	3,239	7,091

Source: Regional Technical Forum (RTF)

Utility incentives tied to these deemed savings, along with state and federal tax credits help to encourage builders to consider moving ducts inside in the Pacific Northwest conservation programs.

- A code revision proposal, sponsored by USDOE, was made at the February 2008 International Code Council Meeting; the proposal language would require ductwork to be tested, and allows for an exception if the HVAC system is located within the conditioned space (full proposal text can be found at http://www.energycodes.gov/codedevelop/pdfs/ICC_duct_sealing_new.pdf) (ICC 2008a). The proposal was approved by the International Energy Conservation Code committee, but rejected by International

Residential Code committee; the IRC committee action statement indicates the proposal was rejected because “it is unclear what is required by the testing procedure. Verification of duct sealing can be achieved with a visual inspection.” (ICC 2008b). Final action on this proposal will be taken by the ICC in September 2008, following public comment.

- ASHRAE guideline 24 notes the IAQ impact of duct leakage for systems located outside of conditioned space: “Return leaks depressurize the zone in which the ducts are located, entraining air from this space to be distributed throughout the home…supply leaks pressurize the space in which they are located. This can prevent pollutants from entering these spaces from outside the space, but it forces pollutants that were already in the space into the home at a greater rate. For example, a supply duct leak in a crawl space may reduce the rate of radon migration, whereas a supply duct leak in an attached garage can increase the rate at which car exhaust enters the home” (ASHRAE 2008).

Building America Case Studies

The U.S. Department of Energy’s Building America Program supports research and development efforts by WSU building science specialists, including technical assistance at design, construction, commissioning and post occupancy phases of new single family residential homes and communities. One significant area of focus has been the moving of ducts within the conditioned space, as discussed in this paper. Another approach not discussed in this paper is moving the envelope around the ducts by using a conditioned attic and/or crawlspace (Lstiburek 2005).

Single Home Case Study - Habitat for Humanity

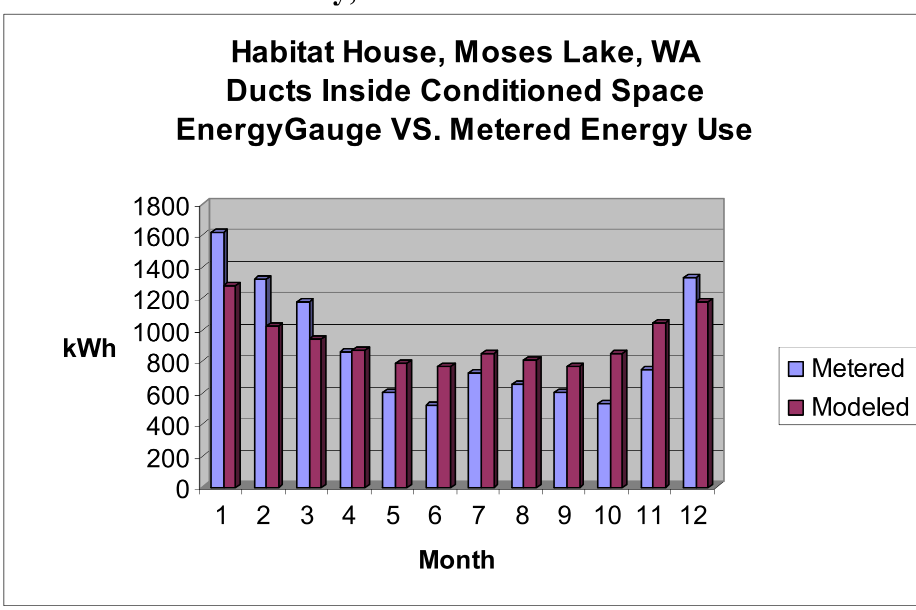
In 2004, Building America efforts with Habitat for Humanity in Moses Lake, WA showed that moving ducts and air handler into the conditioned space was less than $500 in materials and additional design revision (specifically, a dropped ceiling serving as a duct chase) for a typical 1000 ft2 single-story three bedroom rambler. This Northwest Energy Star home has a commissioned HSPF 8.25, SEER=13.6 air source heat pump, 95% Energy Star lighting and appliances (NEEA 2007). The home was blower door tested at 4 ACH50, with U= 0.32 windows, R21 walls, R30 floors over a vented crawlspace, and R49 ceilings. Figure 1 shows the main duct chase down the central hallway pre and post drywall. The chase was framed and ducts installed after the hallway ceiling dry wall was installed.

Figure 1. Habitat for Humanity, Moses Lake - Duct Chase Pre- and Post-Drywall

Source: David Hales, WSU

This effort was implemented by Habitat volunteer workers, with assistance from WSU staff, local HVAC contractor and utility. The 2006 monitored energy use was very low, as shown in Figure 2. The total actual 2006 energy use of 10,687 kWh/year compared to an Energy Gauge USA® simulation estimate of 11,167 kWh/year. It appears that metered use was higher in winter during heating and lower in summer during cooling when compared to the modeled usage. EnergyGUSA® modeled 31% cooling and 39% heating savings from just moving the ducts into conditioned space compared to a typical code home (BAIHP 2008).

Figure 2. Habitat for Humanity, Moses Lake – Modeled vs. Metered Energy Use



Total Energy Use: Metered = 10687 kWh Modeled = 11167 kWh

Source: Building America Industrialized Housing Program

Community Case Studies

While the benefits of moving HVAC systems to conditioned space are significant, it is hardly mainstream practice for production builders. Building America team members have been working with two major Northwest production builders, New Tradition Homes and Quadrant Homes, to move their homes' ducts into conditioned space. The techniques adopted by these builders are remarkably simple and affordable, both in terms of first costs and long-term system operation. The critical component in making this transition is to have the HVAC contractor engage in duct design discussions with the builder, and architect to make changes to a given plan.

New Tradition Homes. New Tradition Homes, headquartered in Vancouver, Washington, serves new homebuyers in both the southwest and central regions of the state. New Tradition has been a Building America partner for several years, and utilizes an internal building science team, whose members represent a cross section of the company's operations. This structure, which promotes buyoff from many departments within the company, is essential to effective implementation of energy efficient building design changes. New Tradition works with WSU and BIRA to continually identify, test, and implement new designs and technologies. New Tradition built over 400 homes in 2005, but has decreased construction with standing inventory and the tightening of the local home market.

WSU staff worked with New Traditions on a four-home Energy Star demonstration project to evaluate energy efficient construction methods for achieving compliance with the 2005 Energy Policy Act (EPACT) tax credit for new homes (IRS 2005). For two of the homes, New Tradition worked with WSU and their subcontractor, Area Heating, to bring the HVAC system inside the envelope (ducts from the crawlspace and attic, air handler from the garage). This transition increased the sales price of the home by $675. This price increase reflects the addition of dropped soffits to accommodate the ductwork – the drywall contractors were required to come out a second time. Modeling indicates savings from the transition at $110/year. Duct leakage to the exterior for the two homes with HVAC inside was 20 and 29 CFM25, compared to 83 and 61 CFM25 for the homes with ducts outside conditioned space (Lubliner et al. 2007). The minimal amount of leakage to the exterior can be explained by either small series leakage paths through the floor cavity to the rim joist, potentially exacerbated by differing pressures between the conditioned space and the floor cavity, which can exaggerate the leakage number.

With pre-planning between builder, architect and subcontractors, the process of moving the HVAC inside conditioned space was relatively painless for New Traditions and Area Heating, and cost increases were minimal. With future redesigns, New Traditions hopes to further reduce first costs, and assess new challenges associated with new floor plans (Tapio 2007). Due to the re-design, there is more usable space on the 1st floor (ceiling registers free up floor space); this is offset by a reduction, on the 2nd floor (floor registers, which need to be taken into account when furniture is placed).

As shown in Figure 3, New Traditions ran a supply duct beneath and perpendicular to the 1st floor trusses, supplying the 1st floor through ceiling registers and the 2nd floor with floor registers. New Tradition typically uses a closed web truss, which makes it challenging to incorporate large ducts between floor cavities and within the conditioned space.

New Traditions places special emphasis on proper sealing of ducts and rim joists as essential to bringing the ductwork within the conditioned space. Here again, testing the ducts for leakage (before dry wall, while remedial actions can be taken) and the envelope for air tightness are very important. With this approach care must also be taken to ensure that electrical and plumbing chases be properly sealed and pressure isolated from the HVAC chase. With all of this attention to reducing duct and rim leakage, an air barrier is not required.

Figure 3. New Tradition Homes – Ducts Between Floors, Pre- and Post-Drywall

Source: David Hales, WSU

The use of a trunk duct did require coordination between the HVAC and framing subcontractors – the ducts are installed after framing is complete, requiring a repeat visit to frame the ceiling chase. While a significant scheduling and coordination issue, it is somewhat mitigated with a production builder such as New Traditions, as trades are typically working on other homes in the same or a nearby community, and return visits are more easily coordinated by the builder.

The air handler was included in the envelope by either extending the conditioned space into the garage or locating equipment under an interior stairwell (see Figure 5). Both approaches had the benefit of not reducing usable internal space.

Figure 5. New Tradition Homes – Air Handler in Conditioned Space, under Stairwell

Source: David Hales, WSU

The only difficulty that arose in the process was that New Traditions was so taken with the benefits of the redesigned HVAC that they wanted to integrate improvements into homes already under construction, and were unable to do so. This further emphasizes the need to address HVAC improvements in the design phase.

The keys to New Tradition's successful transition include:

- New Tradition's integrated building science team helped insure a smoother transition to new improvements in building design and construction. This team had the experience and knowledge to bring the HVAC system inside, and was able to identify how design changes affected other aspects of construction (for example, the additional framing needs for the duct chase.)
- New Traditions was already building quality homes to Northwest Energy Star specifications for air sealing and insulation (NEEA 2008), helping ensure a well insulated and sealed area between floors that is actually within conditioned space
- Area Heating is committed to innovative, energy-efficient duct design and installation. Indeed, Area Heating has integrated energy efficient design and testing into their overall business plan, and is a significant performance testing and verification contractor for the Energy Star new homes program in southwest Washington.
- The intensive, hands-on approach used by WSU staff with New Traditions led to great success. Largely as a result of interactions with project staff, New Traditions committed to becoming a 100% Northwest Energy Star builder, was recognized by both the Northwest Energy Star program and the local building association, received significant media coverage, and was designated by WSU health sciences as the namesake for a scholarship for sustainability and design.
- Homes are 2 story with 9 foot ceilings (the 1 foot duct chase is not a significant intrusion on interior space).

To obtain the 50 percent reduction in home heating efficiency required to meet the tax credit requirements, a number of additional measures beyond the Washington State Energy Code were required. This includes upgrading the furnace to 0.94 AFUE, and improving window performance (maximum average 0.30 U-factor, minimum average 0.28 SHGC). Air leakage needs to be verified using a blower door (specific leakage area less than .00028 $in^2/ft.^2$, or about 3.7 ACH50 – a metric New Traditions meets in most of its homes).

Moving forward, New Traditions is examining all of their designs, with an eye to bringing all HVAC to interior space. As part of their systems approach, New Traditions is determining how duct chases, dropped ceilings and other approaches to including ducts inside can be used to improve architectural elements within the home.

In 2008, New Traditions is building a community of homes to tax credit compliance levels. As new home designs are developed with ducts inside, New Traditions is prepared for new challenges with the HVAC, drywall and framing subcontractors; this is particularly true with single-story homes, as locating duct runs between floors is not an option.

Quadrant Homes. Quadrant Homes, a subsidiary of Weyerhaeuser Corporation, began building in the Seattle area in the 1960s, with sales of over 8,000 mainly entry level new homes since 1996. Quadrant is generally acknowledged as the largest builder in the Northwest, and annually boasts industry-leading profit margins. Quadrant's predicted 2007 sales of 1,500 homes represent approximately 4% of all single family starts in Washington State (Peng 2008).

Quadrant Homes has obtained notable market results, using an even-flow, predictable scheduling scheme in which it begins six homes per day and finishes each house in precisely 54 days. Quadrant follows recognized lean principles (as used by companies like Toyota), including designing its value stream toward customer needs, balancing work so all stages flow evenly, operating on the basis of customer pull, and continuously improving internal processes.

Quadrant has achieved admirable results in both envelope and duct tightness testing as performed by Washington State University (WSU) in both Energy Star and non-Energy Star homes. Quality assurance testing indicates consistently low envelope leakage numbers – below 5ACH50, with some homes testing as low as 2.5 ACH50. Duct leakage numbers are similarly impressive – averaging 2.11% of conditioned floor area at 25 Pa – some are as low as .6%. Random sampling of non-Energy Star homes shows performance numbers consistent with these results, emphasizing the quality of Quadrant's air sealing and duct installations. This attention to detail also extends to other energy-related areas such as framing detail and insulation quality.

In 2006, WSU Energy Program facilitated a design charrette that included Quadrant' home design manager, staff from Quadrant's HVAC contractor, Bob's New Construction, and builder outreach staff from the Energy Star Homes Northwest Program. The target was to develop a new home design that achieved the EPACT tax credit. While there were still a number of efficiency improvement goals still needing to be met (upgrading the furnace to either 0.915 or 0.94 AFUE [size dependant], improving window performance to average maximum 0.30 U-factor /minimum 0.28 SHGC, envelope leakage to 3.4 ACH50), the measure that required the most significant changes in design and installation in approach was moving the HVAC system inside (air handler and return ducts from the attic, supply ducts from crawlspace).

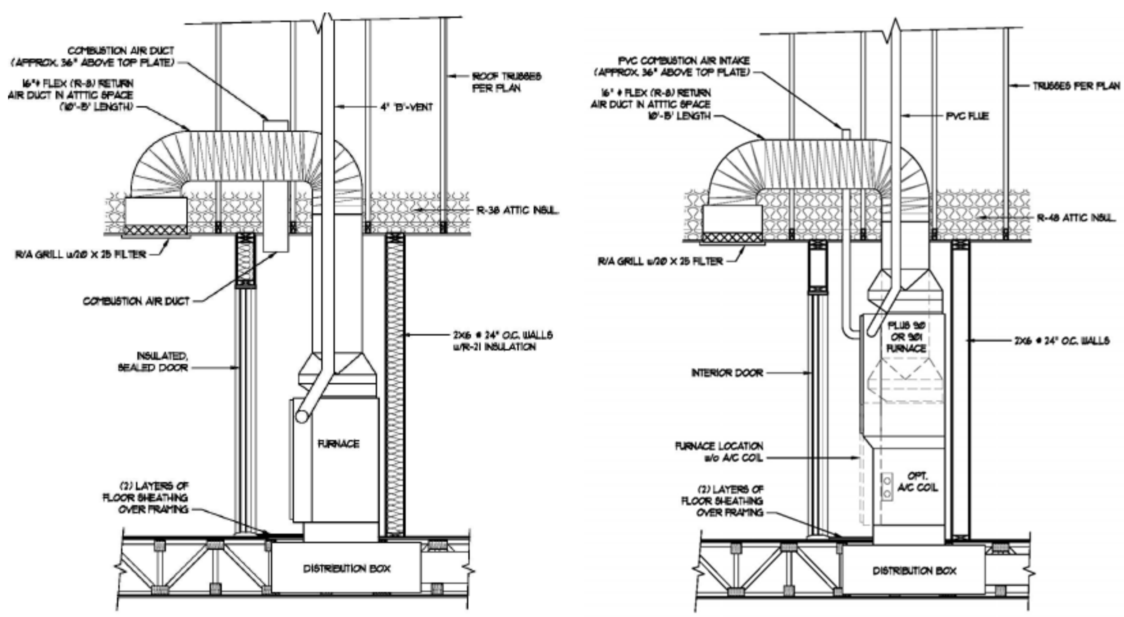
All of the supply ducts are located in an open web floor joist supporting the second floor. The furnace is located in a utility closet centrally located on the second floor of the home. A short return duct is installed in the attic – not an ideal location, but easily verified and controlled, due to the limited run and simple design.

In 2007, Quadrant modified all of their two-story home designs to accommodate most of the heating system inside the conditioned space of the space of the home. In addition, Quadrant plans to build at least 30 homes to EPACT tax credit level in 2008 as a voluntary "Sound Energy" package. An uncertain energy market, accompanied by outreach from Energy Star program staff, may have an impact on the marketability of this package; in February of 2008, Quadrant reported sales of over 20 Sound Energy homes (Peng 2008).

The most important element of the new design is that the supply ducts are all located between the 1st and 2nd floor, running through the open-web trusses. The open-web trusses allow Quadrant the flexibility to run plumbing, electrical, and ductwork through the open webbing. As with New Traditions, bringing the ducts between floors necessitates strict attention to reducing air leakage pathways in the under floor area, especially at the rim joist. The additional costs for the new truss design were offset by cost savings in the HVAC system equipment and installation. These cost savings were made possible through shorter, un-insulated duct runs and the purchase of smaller, less expensive furnaces (sizing reduction made possible by moving the HVAC system inside). The 18" open-web trusses also streamline construction and accommodate floor plans with longer 2nd floor truss spans. Such changes do not require additional bearing walls, a necessity when using I-joint trusses.

The modified design includes an insulated mechanical closet built to outside space code requirements (insulated walls, exterior door, venting) to accommodate a non direct vented 0.80 AFUE furnace. Energy Star homes, with a 0.90+ AFUE furnace, do not require the exterior closet, but do require a condensate drain, as well as combustion air and a flue gas vent. Figure 6 shows the design detail of both the code and tax credit compliant mechanical closets.

Figure 6. Quadrant Homes – 2nd Floor Mechanical Room, Code (Left), Energy Star/Tax Credit (Right)



Source: Quadrant Homes

For Quadrant, there is little to no cost for moving the HVAC system into conditioned space. The only associated costs are loss of usable space, and the materials cost for the insulated closet in the 0.80 AFUE case (Peng 2008). In Seattle, the tax credit home is estimated to save $204/year over Quadrant's code home (which, with supply ducts inside, performs better than a standard code home – savings over a standard, ducts outside conditioned space, code home is $264/year.)

Conversations with builder and subs suggested that the additional costs for open-web trusses (including materials associated with additional home height - usually at least 4 inches taller to accommodate room for ducts and structural requirements) will be offset by reductions in callbacks, labor and materials savings for trades taking advantage of the flexibility of the open web trusses, and materials savings for the builder resulting from the longer floor spans made possible through stronger web trusses.

There is a limited 16"x 8' run of return flex ductwork still in the attic. The duct is insulated to R-8 per Washington code and surrounded by additional insulation in some areas. According to REM/Rate, the most commonly used tax credit compliance software in Washington, the attic return has a minimal contribution to overall operating costs ($24 per year), but had a negative impact of 4% on the tax credit compliance score (AEC 2007).

Wade Craig of Bob's Heating, says "It is easier for installers to do a quality job in the home when they are not lying in mud deep in a corner of the crawlspace where they know an inspector will not crawl around to inspect their sealing around boots and the like". Additionally, when ducts are installed between floors it is clearly visible to the general contractor and inspector, thus better installations follow. Another major concern is "trade damage" and "trade fighting" when electrical or plumbing subs compromise ducts to squeeze their wires and pipes in place. With open-web trusses there is enough room for all trades making each subs work easier. Craig says his firm can lower its bid when the HVAC system is moved inside. Additionally, Craig points out that moving the furnace from the attic to a mechanical closet on the 2nd floor facilitates easier equipment servicing, and reduces worker safety for installation and retrofit, due to the weight of lifting the air handler into the attic during construction and out of the attic when replacement is required (Craig 2008).

Quadrant is aware of the potential for air leakage pathways between floors, and the need to reduce those pathways via proper insulation and sealing of the rim joists. Even with the ducts located inside, all ducts in Quadrant homes are well sealed with mastic, and tested with a Duct Blaster™.

Conclusions

Habitat for Humanity, New Tradition Homes and Quadrant Homes are changing one of the most important details of home construction by addressing the location of HVAC systems. The techniques adopted by these builders offer great promise for builders across the country. These techniques are cost-effective and offer benefits beyond energy savings, including reduced installation and maintenance costs, and improved indoor air quality.

Implementing HVAC designs that locate ducts and equipment in conditioned space takes strong commitments from builders and subcontractors, as well as critical planning at the design stage, and quality control processes both during and post-construction. These two production builders have demonstrated that costs associated with making this transition are offset by estimated space heating energy savings, making it a cost effective homeowner investment even without energy tax credits or utility incentives.

Future Efforts

As these production builders continue the implementation of the changes their HVAC designs, WSU and ConSol will work with them to evaluate the impact of these changes. This work will include:

- Evaluations of temperature distribution and stratification issues in unoccupied test homes,
- Occupant surveys related to comfort, register locations, and aesthetics,
- Development-level utility billing analysis, and
- Evaluation of challenges, solutions and costs for new floor plans and house types.

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References

[AEC] Architectural Energy Corporation. *REM/Rate, Version 12.42*. Boulder, Colo.: AEC, 2007

[ASHRAE] American Society of Heating and Refrigeration. "Chapter 9." *2004 ASHRAE Handbook - HVAC Systems and Equipment*. Atlanta: ASHRAE, 2004.

[ASHRAE] American Society of Heating and Refrigeration. *ANSI/ASHRAE Guideline 24P – Ventilation and Indoor Air Quality in Low-rise Residential Buildings*. Atlanta: ASHRAE,. 2008.

[BAIHP] Building America Industrialized Housing Project. *BAIHP Annual Report – 2007*. Cocoa Beach, Fla.: Florida Solar Energy Center, 2008.

[BIRA] Building Industry Research Alliance. *Contract with WSU Energy Program for USDOE Building America*. Stockton, Calif.: BIRA, 2007.

[CEC] California Energy Commission. *Home Builders Guide to Ducts in Conditioned Space*. Sacramento: CEC, 2003.

Craig, Wade (Bob's Heating). Personal communication. Seattle, 2008

[ICC] International Code Council. "Table 4.4.5.2(.2) – Default distribution system efficiencies for the proposed design." *2006 International Energy Conservation Code*. ICC: Washington, 2006.

[ICC] International Code Council. *Proposals to the 2009 International Energy Conservation Code – submitted by USDOE.* ICC: Washington, 2008.

[ICC] International Code Council. *International Energy Conservation Code Committee Hearing Results.* ICC: Washington, 2008.

[IRS] Internal Revenue Service. *Notice 2006-27. Certification of Energy Efficient Home Credit. Part III -Administrative, Procedural, and Miscellaneous*. IRS: Washington, 2006.

Lstiburek, Joseph L. *Builder's Guide to Mixed-Humid Climates*. Westford, Mass.: Building Science Press, 2005.

Lubliner, Micheal R., et al. *Costs of New Residential Conservation Measures in the Pacific Northwest; Results of Construction Costs and Practices Study from the Regional Cost Research Advisory Group*. Portland, Ore.: Bonneville Power Administration, 1995.

Lubliner, Micheal R., et al. "Crawlspace Design in Marine and Cold Climates".: *Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings X Conference*. Atlanta: American Society of Heating and Refrigeration Engineers, 2007.

[NAHB] National Association of Homebuilders. *Builder's Guide to Placement of Ducts in Conditioned Space*. Washington, D.C.: NAHB, 2000.

[NEEA] Northwest Energy Efficiency Alliance. "Single Family Standards." *Northwest Energy Star Program*. http://www.northwestenergystar.com/index.php?cID=119 (17 June 2007).

Tapio, Steve (New Traditions Homes), and Mike DeLoria (Area Heating). Personal Interview. 2007.

Peng, Tien (Quadrant Homes). Personal Interview. 2008.

[RTF] Regional Technical Forum. *Deemed Savings for New Construction Homes*. Portland, Ore.: 2006.

[SBCC] Washington State Building Code Council. *Washington State Energy Code, 2004 Second Edition*. Olympia, Wash.: SBCC, 2005.

Bibliography

[FSEC] Florida Solar Energy Center. *Energy Gauge USA, Version 2.6*. Cocoa Beach, Fla.: FSEC, 2006.

[FSEC] Florida Solar Energy Center. *USDOE Building America Industrialized Housing Partnership Annual Report - 2006*. Cocoa, Fla.: FSEC, 2007.

Hales, David. "Duct Leakage in Washington State Residences: Findings and Conclusions." *ASHRAE Transactions* 109, no. 2 (2003): 393-402

Ecotope, Inc. *SEEM (Proprietary Software).* Seattle: Ecotope, Inc., 1997.