A Building America Prototype Home Packed with HVAC Features

Dianne M. Griffiths
Associate Member ASHRAE

ABSTRACT

A new house plan, the Hampton, was developed for one of Michigan's largest builders and developers to bring sustainable, energy-efficient housing to the Great Lakes region. A prototype of the home, which features improvements to the thermal envelope as well as the mechanical equipment, was constructed in Fenton, Michigan. Structurally insulated panels (SIPs) were used to form the majority of the home's thermal envelope, and high-performance, low-E, argon-filled windows were used instead of the clear double-pane windows typically used by the builder. A smaller, more efficient furnace provides the home's heating, and the home is designed to use passive cooling in the summer via a centrally located stairwell with an operable skylight at the top. The home also features a unique mechanical ventilation system that can be scheduled and zoned. This paper describes the home's features, presents the results of a series of DOE-2.1E energy simulations that were performed to evaluate the impact of various aspects of the prototype home, and discusses the results of side-by-side testing of the prototype home and a conventionally built control house.

PROJECT BACKGROUND

The objective of the effort was to work with one of Michigan's largest builders and developers to bring sustainable, energy-efficient, single-family detached housing to the Great Lakes region. The builder presented the project team with one of its most popular house plans and requested recommendations for design and construction features that would enhance its attractiveness, comfort, and energy efficiency. The result was the Hampton model, and a prototype of the home was constructed to introduce the builder and the contractors to the new technologies and systems that could be employed. Another house of the same design, but constructed with the builder's conventional practices, was located three lots away and served as a control house for side-by-side field performance testing. Both new homes in Fenton, Michigan, were completed in the fall of 1999 and immediately sold, an indication that the attractiveness goal had been achieved with the design.

HOUSE PLAN AND THERMAL ENVELOPE FEATURES

The prototype design is a 1,990 square foot, two-story colonial style home intended for first-time home buyers. The first and second floor architectural plans are shown in Figure 1. The prototype, like its predecessor, features an owner's bedroom suite over a 2-car garage. The prototype home features a step-down family room on a shallow frost-protected slab foundation, and the remainder of the home is over a full pre-cast concrete basement foundation. In the control version of the house, the family room was over a vented crawl space that was connected to a conventional basement.

Structurally insulated panels (SIPs) were used to form the majority of the prototype home's thermal envelope. SIPs are constructed of an inner core of highly insulating expanded polystyrene (ESP) or polyurethane foam bonded between two sheets of oriented strandboard (OSB). The SIPs provide higher insulation and lower infiltration levels when compared to the builder's conventional construction methods. High-

Dianne Griffiths is a senior engineer at Steven Winter Associates, Inc., Norwalk, Conn.

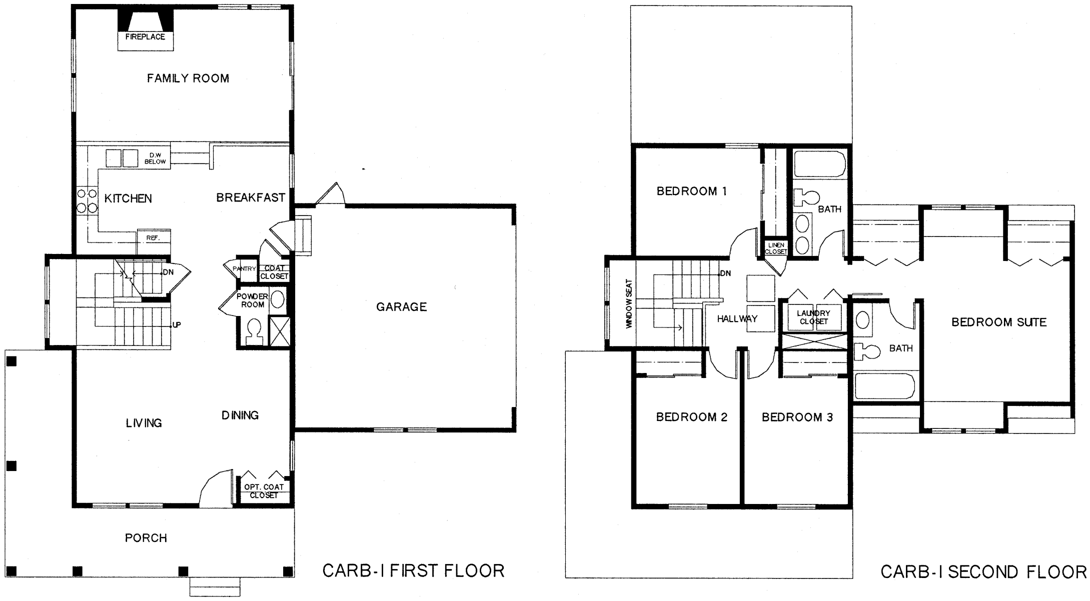

Figure 1 *Prototype home architectural plans.*

performance, low-E, argon-filled windows were used instead of the clear double-pane windows typically used by the builder.

The higher insulation levels, better windows, and reduced infiltration resulted in a significantly lower design heating load. Design load calculations, based upon the ACCA *Manual J* method, suggested a design heating load of 33 kBtuh for the prototype home. A 60 kBtuh input, 94% AFUE two-stage furnace was installed in the prototype home. This furnace is oversized for the application, but it was the smallest two-stage furnace available in the project team member's product line. The furnace should operate at its lower first-stage output of 36 kBtuh the majority of the time. The builder typically uses 80% AFUE furnaces. An 88 kBtuh input furnace was installed in the Hampton control house and a 110 kBtuh input had been typically installed in the predecessor design model.

MECHANICAL SYSTEM ISSUES

In examining the design and the installation of the mechanical system for the predecessor design, several opportunities for improvement were apparent. It was determined that the prototype system would address ventilation, comfort, and duct losses.

Ventilation

The builder currently provides a 6-inch-diameter outside air duct to the return side of the air handler as a provision for fresh air, in addition to a combustion air make-up duct to the basement where the furnace is located. The outside air duct to the return only provides fresh air to the home during furnace air handler operation. Unless the furnace was set for continuous operation, outside air would only be provided when it is cold outside and the furnace is operating. Unfortunately, this is also when infiltration alone is likely sufficient to satisfy indoor air quality requirements. Thus, outside air is introduced when it is least needed and at the greatest energy penalty because it is cold.

The improved thermal envelope characteristics of the prototype not only reduce heating loads significantly, but they should also produce a home that is too tight to ensure adequate indoor air quality. With proper home construction, a mechanical ventilation system would be warranted. At the time, there was no code in place requiring a mechanical ventilation system, but nearby Minnesota had recently adopted a new energy code with rigorous requirements for mechanical ventilation. A project objective was to demonstrate a mechanical ventilation system that would be a significant improvement over the builder's current practice, would meet the needs of a tightly constructed home, and would demonstrate a technology that could possibly become a code requirement.

Comfort

The predecessor design and the prototype both feature an isolated bedroom suite over the garage with three exterior walls. The builder had received callbacks concerning comfort in this room. The culprits were insufficient air flow and significant duct losses. The supply ducts for the room were run in the insulated floor above the garage. A quick fix would have been to calculate room-by-room loads and design the duct system for the appropriate air flows to each room. However, the project team chose to demonstrate a more energy-efficient solution—a zoned heating system that would only provide heat when appropriate to the bedroom, which is not occupied much of the time.

Duct Losses

The duct systems in the builder's homes involved numerous branch ducts and panned returns from each room. Many ducts were located in outside walls with minimal amounts of compressed insulation. Electricians crushed ducts in stud cavities to install electrical boxes. The project team saw the opportunity to demonstrate the benefits in terms of cost, comfort, and performance of a minimized duct system with central chases.

MECHANICAL SYSTEM SOLUTION

The mechanical system solution developed for the prototype home integrates several new products to provide a very efficient system that is unique and highly flexible. The system features a new furnace product, a motorized-damper zoning system, advanced thermostats, and a highly efficient and quiet bath fan designed for continuous operation. As an integrated package, this system provides zoned heating with an efficient furnace and duct distribution system and zoned balanced mechanical ventilation.

As is often the case with new products, their cost-effectiveness is not immediately apparent. Each of these products has been placed at the high-end of manufacturer product lines and therefore achieve the highest margins. No single system component is cost-effective independently; however, when integrated, the features of one component complement other components. For example, the zoning system enhances the ventilation performance as well as the heating. The efficient furnace fan motor reduces the fan energy use associated with the mechanical ventilation system. If a dollar savings can be quantified for improved comfort and indoor air quality or if a code mandates mechanical ventilation systems, this integrated package could be cost competitive. This integrated mechanical system was not intended to be a cost-effective solution in today's market, but rather a demonstration of a concept that would provide an opportunity to evaluate the additional benefits of improved comfort and indoor air quality.

Furnace

The furnace is the newest member of the manufacturer's furnace product line. It is a sealed-combustion, 94% AFUE condensing furnace with a two-stage burner and ECM (electronically commutated motor) -driven variable speed fan.

The sealed-combustion feature improves efficiency because conditioned air from the space is not used for combustion. The feature is also desirable for tight homes, which can become depressurized when clothes dryers or large kitchen exhaust fans are operating. With sealed-combustion, the potential for back-drafting or flame roll-out during depressurized house conditions is eliminated.

The two-stage burner allows the furnace to better match varying heating loads. At moderate loads, the burner will operate at the lower output for a longer period of time than a higher output single-stage system. Air is circulated throughout the home for longer periods of time, resulting in better mixing and less variation in temperatures between rooms.

The two-stage burner is also very compatible with a zoned system. When only one zone is calling for heat, the first stage should be more than adequate. Operation of the furnace at lower output for a single zone also reduces the potential for the furnace tripping out due to a high temperature limit.

The ECM-driven fan is a feature particularly important to the ventilation system. Conventional permanent split capacitor (PSC) furnace fans are very inefficient, with typical efficiencies of 50% to 60%. The use of air handler fans for ventilation requirements rather than an independent ventilation system is often discouraged because the fans are inefficient and more air than necessary, a mixture of recirculated and outside air, is handled. The ECMs are much more efficient with efficiencies above 90%. The energy penalty of using an ECM furnace fan for ventilation purposes is small and more comparable to that of an independent mechanical ventilation system.

Zoning System

The basic philosophy of all zoning systems is to save energy by only providing conditioned air to the rooms that need it rather than the entire home. In this prototype home, the central furnace located in the basement feeds two supply trunks. One trunk feeds the first floor registers and the other feeds the second floor registers. Each supply trunk has a motorized damper that is controlled by a zone thermostat.

Conventional zoned systems need to be designed with a provision for ensuring that adequate air flow is maintained across the furnace heat exchanger or air conditioner coil as static pressure in the system increases. Methods include a bypass duct with barometric damper, oversizing ducts, undersizing zone dampers, or providing a dump zone. Each of these methods defeats a portion of the efficiency gains of a zoned system.

The ECM-driven fan avoids the need for this provision because it will adjust fan speed to maintain air flow over a wide range of static pressures. This furnace fan can maintain the appropriate air flow at 1 inch static pressure. The issue now becomes one of noise if too much air is driven through supply ducts and registers. This can be resolved with proper duct design and register selection and did not appear to be a problem in this prototype home.

Mechanical Ventilation System

The mechanical ventilation system in this home is unique because it has the capability to be scheduled and zoned. Ventilation periods can be scheduled just as temperature setpoints are. And, with one control in each zone, the ventilation air is directed to a specific zone within the home. This approach works off the principle that ventilation air is necessary to control odors and is most beneficial when people are present. Just as with heating, it is only necessary to provide the ventilation air when and where it is wanted. The intent for this

TABLE 1
Thermal Envelope Characteristics Simulated

Feature	Standard Practice	Prototype
Windows U-value SHGC	Clear, double pane, vinyl 0.46 0.57	Low-E, argon-filled 0.33 0.45
Construction/Insulation Walls Roof	Wood frame R-11 R-19	SIPs R-15 R-37
Tightness/Infiltration	0.52 ACH_n	0.1 ACH_n

prototype home is to schedule ventilation for the upstairs bedrooms during sleeping hours and downstairs living areas during the occupied day and evening hours. This system may be scheduled differently for each day of the week as well.

The mechanical ventilation system is a balanced system involving a 7-inch-diameter outside air duct to the return trunk, the furnace fan, and a centrally located bath fan. The balanced approach was selected over a supply, or pressurized, method to avoid driving moisture into the walls where damaging condensation could occur in the winter. The balanced approach was preferred over the exhaust, or depressurized, method to provide a known path for the fresh air to enter the home and avoid the possibility of drawing from the attached garage. When the ventilation mode is activated at the control, the motorized outside air damper is opened, the furnace fan is brought on at its low fan-only speed, and the bath fan is turned on.

Duct Distribution System

The prototype home features a minimized duct system through open web floor joists. The design uses less ductwork and fewer registers and has minimal heat or air loss to the outside. The primary characteristics are inboard supply registers and three large returns, one centrally located on each floor and one serving the owner's bedroom suite. This is in contrast to three returns on the first floor and return grilles in each bedroom in the control house. Door undercuts provide adequate return paths in the prototype bedrooms because of the lower air flow requirements attributable to the better thermal envelope (ACCA).

Second floor supply registers were located high on internal walls in the prototype rather than floor registers located at exterior walls. For example, in the owner's bedroom of the prototype home, warm air is supplied via one register located high on the interior wall. In the control home, the room is supplied by four floor registers with ducts running in the floor above the garage.

The minimized duct system approach was also very evident in the family room which presented a bit of a challenge in the prototype because it is on a slab with only exterior SIP walls. A single supply register in the riser of the steps down into the family room was used in the prototype. A commercial-grade register was selected to provide adequate throw and spread for the room. In the control home, two floor registers were installed under the windows with ducts running through the vented crawl space.

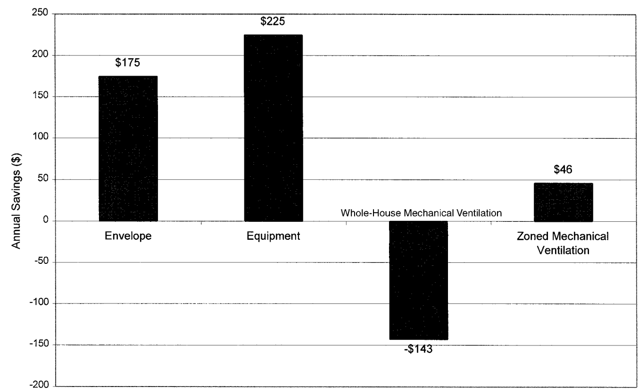

Figure 2 *DOE-2 energy savings analysis for prototype homes features.*

ENERGY SIMULATION RESULTS

A series of DOE-2.1E energy simulations were performed to evaluate the impact of various aspects of the prototype home. The simulations compare the prototype home construction to a control home of the same design but constructed with the builder's standard specifications and practices. The cumulative annual heating energy bill savings for several alternatives are shown in Figure 2. The heating season thermostat setpoints were 70°F during the day and 67°F during sleeping hours. Cooling energy use was not modeled because the prototype home is designed to use passive cooling in the summer via a centrally located stairwell with an operable skylight at the top.

The first alternative to be simulated reflected the thermal envelope improvements only. Table 1 lists the specific differences. The envelope tightness assumptions are based upon blower door testing of two of the builder's standard practice homes and an assumption for a well-constructed SIPs home. The envelope improvements alone produce a 25% reduction in seasonal heating energy requirements. At 1999 local natural gas rates of $0.40/therm, this translates into an annual heating bill savings of $175.

An improvement in the efficiency of the furnace from 80% AFUE to 90% further reduces heating energy requirements for an overall reduction in heating energy requirements of 33% or an annual savings of $225.

While these savings are attractive, they are perhaps overly optimistic because they are based upon the assumption of only 0.1 air change per hour via natural infiltration for the SIPs home. At these low levels, mechanical ventilation is necessary to ensure adequate indoor air quality.

As described earlier, a simple, low initial cost approach to mechanical ventilation is to provide outside air via a duct to the return of the central furnace. The furnace fan is used to draw the outside air in, mix it with return air, and supply the mixed air throughout the home via the heating system's supply duct system. The furnace fan runs continuously to provide 0.35 air changes per hour, which is consistent with the recommendations of ASHRAE Standard 62 (1999). To model this, the energy simulations assumed a continuous outside air requirement of 115 cfm from October 15 through May 15. Since the home is not air conditioned, it is assumed that windows will be open during the summer months for the purposes of cooling and sufficient air exchange will occur without the mechanical ventilation system. Fan energy increases significantly with this approach because the large furnace fan is used to circulate the ventilation and return air mixture throughout the home. The power draw for the fan was assumed to be 414 W or 0.4 W/cfm, which is conservatively lower than the 0.5 W/cfm found in an earlier study (Phillips 1998). The gas energy use also increases because of the need to heat this additional outside air. Thus, while good indoor air quality is maintained with this approach, a $143 increase in energy costs is incurred over the original standard practice home. The benefits of a better thermal envelope and higher efficiency equipment have been erased by the energy penalty associated with ensuring 0.35 ach ventilation with an outside air duct to the return and continuously operating the furnace fan. This finding is consistent with the results of other residential ventilation research (Wray et al. 2000; Roberson et al. 1998).

The design strategy for the prototype home utilizes the zoned heating system to reduce the total quantity of ventilation air introduced to the home. Air exchange rates of 0.35 ach are achieved, but only at appropriate times in each zone. In the simulations, it was assumed that the first floor would be ventilated during the day and the second floor (predominantly bedrooms) would be ventilated at night. The lower fan speed on an efficient ECM fan motor is assumed for energy use of 200 W. The zoned ventilation approach reduces both the fan energy and heating energy penalties. With this method, good indoor air quality is maintained in the occupied areas of the home at an increase in energy cost of $179 over the no mechanical ventilation alternate. The zoned ventilation saves $189 over the nonzoned continuous ventilation approach. Together with the better thermal envelope and high-efficiency furnace, the computer simulations predict a heating energy savings of $46 over the conventional home. This does *not* include the additional energy savings opportunities of the zoned heating system.

FIELD TEST RESULTS

Field testing was performed to validate the computer predictions and quantify the energy efficiency improvements achieved in an actual home. A side-by-side control versus prototype test protocol was employed. A house of very similar design, but with conventional construction materials and practices, was built three lots away on the same side of the street to maintain the same solar orientation.

Testing was performed in both unoccupied homes in early December to capture heating season performance characteristics. This required that homeowners leave their homes for nearly a week. Each home was monitored for seven days with four days of simultaneous testing. Tests included blower door and duct blaster measurements, natural infiltration measurements using SF_6 tracer gas methods, and short-term energy monitoring (STEM) tests to assess overall UA (Balcomb et al. 1993). The limited period of simultaneous testing and variations in weather did not allow for comparisons of heating system performance and comfort control between the two houses.

Blower Door Results

Table 2 presents the results of blower door testing for each home. A 30% reduction in the equivalent leakage area (ELA) between the control and prototype homes was measured. This improvement is most likely attributable to improved envelope tightness with SIP construction and the compact within the envelope duct design. Admittedly, the tightness of the prototype home was disappointingly high. This was the builder's first experience with SIPs and there were obvious problems with the construction.

Duct Blaster Results

Duct blaster testing was performed in both homes. Testing of the return ducts was problematic in both homes, most likely because of the outside air ducts and an inability to close them completely. Testing of the supply side ducts in each house indicated high levels of leakage. In the control house, the system could not be pressurized to 25 Pa. A supply-side

TABLE 2
Comparison of Blower Door Test Results

Parameter	Prototype House	Control House
ELA @ 4 Pa, in.^{2}	84	167
CFM50	1956	2864
ACH50	7.44	10.90
ACHn	0.36	0.53

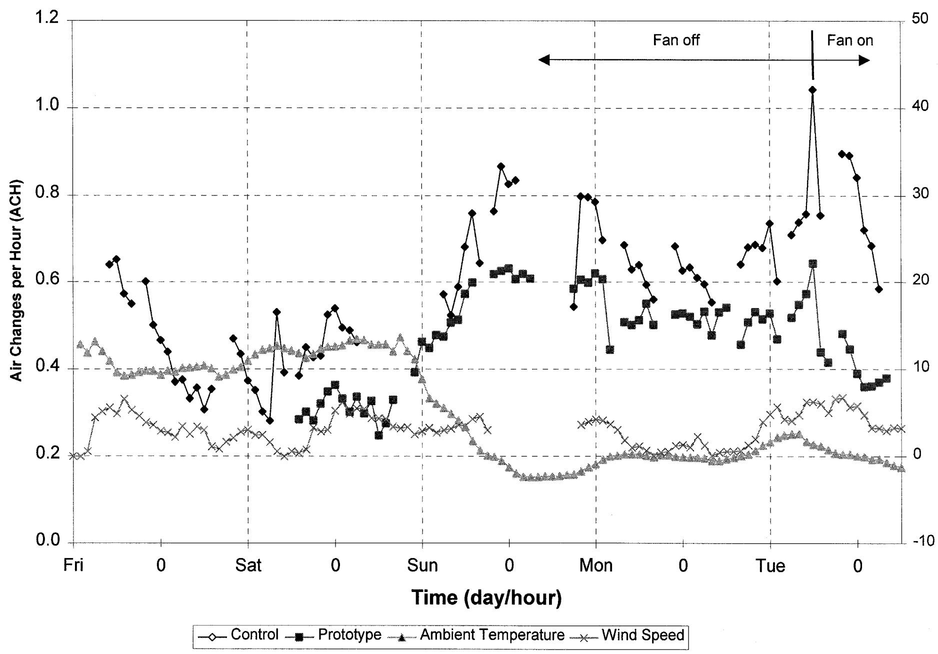

Figure 3 *Comparison of air exchange rates based upon tracer gas measurements.*

leakage of 700 cfm was indicated at 20 Pa. In the prototype house, supply-side leakage of 420 cfm was measured at 25 Pa. While the prototype system is better than the control house system, the leakage rates in both homes are excessive. One explanation for the high values is no duct sealing, not even duct tape.

Infiltration Measurements

Tracer gas measurement techniques were used to quantify the natural air exchange rates for each of the two homes. Qualitatively the results are consistent with the findings of the blower door and duct blaster results. Figure 3 presents the measured data for two different system operating modes.

The first few days represent a comparison of infiltration performance for the thermal envelope without the effect of duct leakage. Electric heaters are used to maintain a constant indoor temperature and the furnace and furnace fan are not operating. The increased stack effect with lower temperatures Sunday night and Monday is apparent along with the lower air exchange rates for the prototype home.

The second test mode, beginning Tuesday evening, is with the electric heaters and the furnace fan operating. This test mode provides an indication of the impact of duct leakage. The difference in ACH values between the control and prototype homes is greater because of the higher duct leakage of the control house. The difference between the two homes increases from approximately 0.10 ACH with just the coheaters to approximately 0.20 ACH with the furnace fan operating.

Caution is advised in comparing the actual ACH values from one mode to the next because with the operation of the air handler, the basement volume becomes involved as a result of duct leakage and the basement locations of the furnaces. ACH values can actually drop somewhat because the volume increases more than the air leakage. This is evident for the prototype.

Overall Building UA

Another performance comparison between the two homes is the total heat loss rate of each home, or UA. Figure 4 presents this comparison for the same two operating modes as the previous figure. This comparison accounts for the higher insulation values of the SIPs construction, the better windows, the lower infiltration, and the lower duct leakage of the prototype home. A 20% improvement is indicated for the envelope and a 30% improvement is shown with the duct leakage accounted for. Note, the solar heating benefit of the clear windows in the control house is evident by the drop in UA during the mid-day hours.

Ventilation System Performance

Because of changing weather conditions from one day to the next it is difficult to use tracer gas measurements to evaluate the performance of the ventilation system. Ideally, the

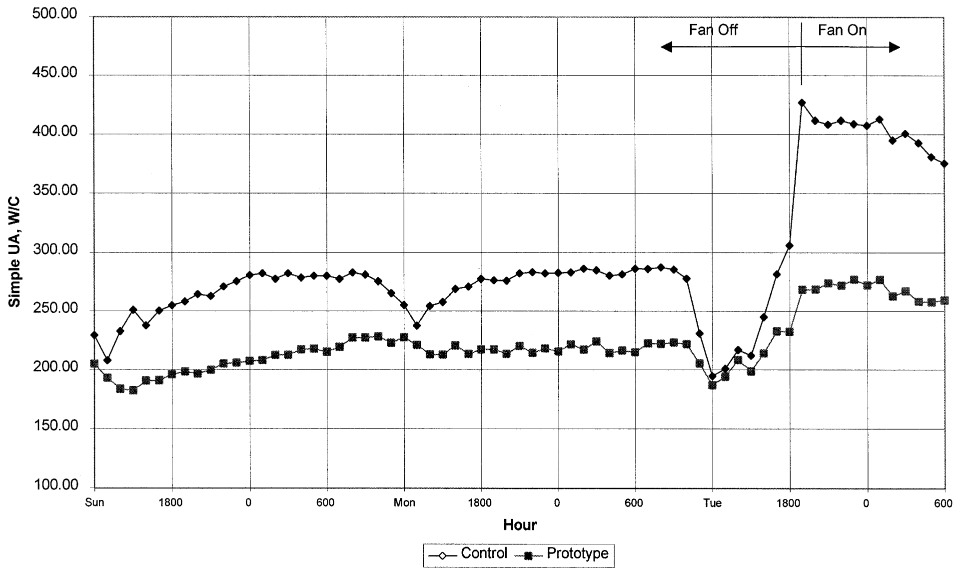

Figure 4 *Simple UA comparison.*

home was to be monitored without the ventilation system one day and with the ventilation system operating the next day. Unfortunately, the temperature and wind conditions changed as well and accurately normalizing for the different weather conditions is difficult.

The zoned ventilation system did function as intended. In response to the on/off ventilation schedule programmed at each zone controller, the outside air damper would open and the furnace fan and high-efficiency bath fan would come on. When in the ventilation-only mode, the furnace fan runs at a lower cfm fan-only setting, circulating approximately 500 cfm and drawing only 130 W.

SUMMARY

A new house plan was developed for one of Michigan's largest builders and developers to bring sustainable, energy-efficient housing to the Great Lakes region. Two versions of the new home design were constructed in Fenton, Michigan. One, the prototype, featured several improvements to the thermal envelope as well as the mechanical systems, including a mechanical ventilation system. The other, the control, was constructed using the builder’s conventional practices and systems.

DOE-2 simulation analyses demonstrated that the heating energy costs for the prototype home with a mechanical ventilation system ensuring good indoor air quality could be less than for the control home with highly variable and unreliable air exchange rates.

Side-by-side field performance testing of the two homes indicated that the thermal envelope improvements produced a 20% reduction in heat loss and the better duct system increased the reduction to 30% overall.

ACKNOWLEDGMENTS

This research was funded by the Building America Program through the Office of Building Technology, State and Community Programs at the U.S. Department of Energy. The National Renewable Energy Laboratory is acknowledged for their project monitoring role and field testing support with special thanks to Ren Anderson and Ed Hancock. All CARB members and the entire staff at Crosswinds Communities are gratefully acknowledged for their support and commitment to this project.

REFERENCES

ACCA. *Manual T Air Distribution Basics for Residential and Small Commercial Buildings.* Washington, D.C.: Air Conditioning Contractors of America.

ASHRAE. 1999. *ANSI/ASHRAE Standard 62-1999, Ventilation for acceptable indoor air quality.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Balcomb, J.D., J.D. Burch, and K. Subbarao. 1993. Short-term energy monitoring of residences. *ASHRAE Transactions* 99 (2): 935-944.

Phillips, B.G. 1998. Impact of blower performance on residential forced-air heating system performance. *ASHRAE Transactions* 104 (1B): 1817-1825.

Roberson, J.A., R.E. Brown, J.G. Koomey, J.L. Warner, and S.E. Greenberg. 1998. *Recommended ventilation strategies for energy-efficient production homes*. Lawrence Berkeley National Laboratories.

Wray, C.P., N.E. Matson, M.H. Sherman. 2000. Whole-house ventilation strategies to meet proposed Standard 62.2: Energy Cost Considerations. *ASHRAE Transactions* 106 (2).