Final Report for Field Evaluation of Path Technologies

Habitat for Humanity Home Schenectady, New York

AUGUST 2003

field evaluation

U.S. Department of Housing and Urban Development
Office of Policy Development and Research

NAHB RESEARCH CENTER

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Final Report for

Field Evaluation of

PATH Technologies

Habitat for Humanity Home

Schenectady, New York

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EXECUTIVE SUMMARY

The Partnership for Advancing Technology in Housing (PATH) field evaluation at the Schenectady, New York, Habitat for Humanity site examined two heating technologies--a hydronic radiant subfloor heating system and Air Admittance Valves (AAVs). The two-story, 1,344 square-foot home was built to New York Energy Star® guidelines and construction was completed in November 2001.

Hydronic radiant heating system

The radiant floor heating system used a sealed combustion, natural gas–fired boiler as its heat source. The two-zone radiant distribution system consisted of flexible plastic (PEX) tubing installed beneath a wood subfloor. All areas except the kitchen used aluminum plates to improve heat transfer.

The evaluation compared the radiant system to a conventional central forced-air system. A natural gas–fired furnace and hard-ducted supply and return plenums and trunklines with insulated flex duct branching to individual rooms characterized the single-zone forced-air system. Both heating units were located in the semiconditioned basement. All ductwork was located within the insulated building envelope.

NAHB Research Center staff developed the monitoring plan and installed an extensive Data Acquisition System (DAS) to measure the performance of the two heating systems. In addition to measuring the energy use of each system on an hourly basis, the evaluation plan documented the occupants' perceived comfort, design and installation issues, and installed costs for each system. The systems operated in alternating two-week periods during the winter of 2002.

The Radiant Technology Institute (RTI) provided materials and consulting services for the radiant system. Slant/Fin, Inc., provided the boiler. Design of the radiant system involved a collaborative effort between the NAHB Research Center, RTI, and Slant/Fin, Inc. The design of the forced-air system was based on ACCA Manual J and Manual D sizing methods. The Carrier Corporation donated the forced-air furnace for the project.

Significant findings:

1. It was extremely difficult to find small, high-efficiency, moderately priced boilers or furnaces for well-insulated homes with tight building envelopes and small heat loads.[1]

2. A cast-iron boiler in combination with a "dry" hydronic radiant floor distribution system is more "sensitive" to over-sizing than a furnace in a ducted forced-air system.

3. All things equal, energy use in the radiant and forced-air systems showed no significant differences.

[1] Both the boiler and the furnace were over-sized for the home – the boiler heat output was 12% higher than the calculated heat load, the furnace heat output was 27% higher.

4. Temperatures throughout the home were more uniform under radiant system operation than under the forced-air system.

5. Room air temperature stratification measured in two locations was less under radiant system operation than under the forced air system. However, the average temperature difference between high and low sensors under the forced-air system did not exceed three degrees F.

6. The occupants expressed greater comfort during operation of the radiant system.

7. The installed cost of the radiant system was almost twice as high as that of the forced-air system. Although the cost gap could have been reduced given different radiant system components, a hydronic radiant floor system is generally more expensive than a forced-air system.

Air Admittance Valves (AAVs)

Air Admittance Valves are plumbing vent components that allow air intake into the drain-waste-vent system but prevent sewer gases from entering the living space. AAVs can reduce the need for the long runs of vent pipe that are traditionally used to vent residential drain lines. Further, by eliminating multiple penetrations through the roof, they can offer cost savings and durability benefits.

Significant Findings:

1. Although most of the country's building codes permit the use of Air Admittance Valves, some code officials and plumbing contractors remain skeptical about their reliability.

2. For this project, the cost savings resulting from the use of AAVs versus conventional venting methods totaled $293.

3. The use of AAVs is particularly advantageous in remodeling projects and in larger new homes where plumbing may involve long runs.

4. No significant construction issues were noted with respect to the use of AAVs.

5. No operational issues have arisen regarding the AAVs since project completion.

1.0 INTRODUCTION

In November 2001, the Schenectady, New York, Chapter of Habitat for Humanity (HFH) completed a two-story, 1,344 square-foot house. Figures 1 and 2 show the floor plan. Under the U.S. Department of Housing and Urban Development's PATH Program, the NAHB Research Center evaluated two residential heating technologies: an in-floor radiant heating system and Air Admittance Valves (AAVs).

The radiant floor heating system used a sealed combustion, natural gas–fired boiler to as its heat source. The two-zone radiant system consisted of flexible plastic (PEX) tubing installed beneath a wood subfloor on the first and second stories of the house. Most of the tubing was installed in aluminum track to improve heat transfer. A single-zone forced-air heating system was used as the base case for comparing the radiant system's cost and performance. The forced-air system used a natural gas furnace and central ductwork for air distribution throughout the house. Individual thermostats were installed for each system to ensure that the settings remained constant throughout the test period. The systems operated for alternating two-week periods throughout the winter of 2001–2002.

The evaluation plan for both the radiant floor heating and forced-air systems called for extensive performance monitoring throughout the winter of 2001–2002. A Data Acquisition System (DAS) to measure the performance of both systems was installed during construction of the house. Operating parameters monitored during the test period included indoor and outdoor temperature and relative humidity, gas and electrical consumption by both systems, and room air temperature stratification.

The evaluation results for the heating systems focus on the following:

- Design considerations
- Construction and installation issues
- Installed costs
- Operating energy use per heating degree day (HDD)
- Indoor temperature stratification
- Occupant observations and perceived comfort.

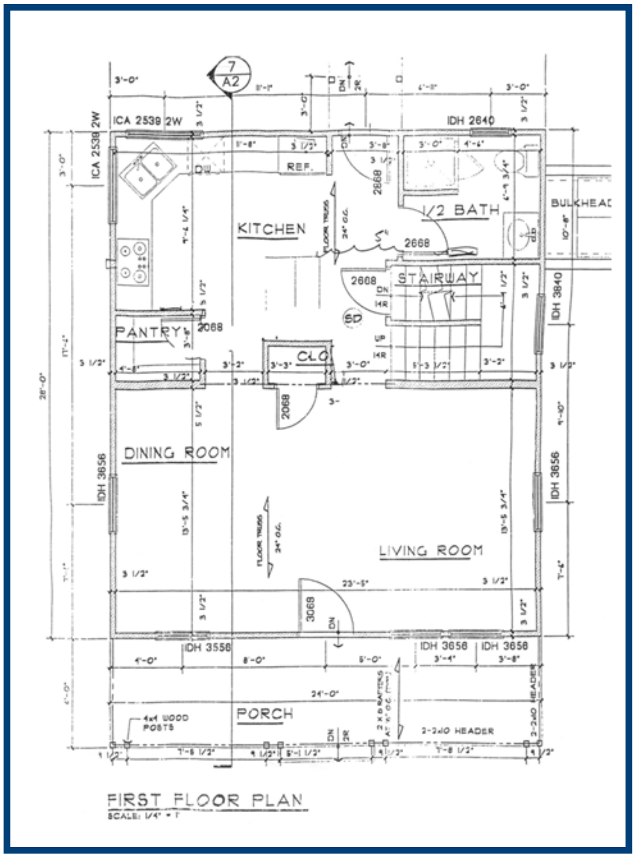

Figure 1 First floor plan

Air Admittance Valves (AAVs) are an innovative component that allow air intake into the drain-waste-vent system but prevent sewer gases from entering the living space. The technology can reduce the need for long runs of vent pipe and often eliminate the multiple roof penetrations. The benefits of AAVs include reduction in labor and material costs as well as enhanced durability as a consequence of fewer roof penetrations.

The evaluation plan for the AAVs called for tracking and addressing building code issues, obtaining feedback from contractors and code officials, and assessing the installation of the valves to capture impacts on labor, materials, and other trades. NAHB Research Center staff also assisted with the permitting procedures and local code approval associated with the use of the AAVs.

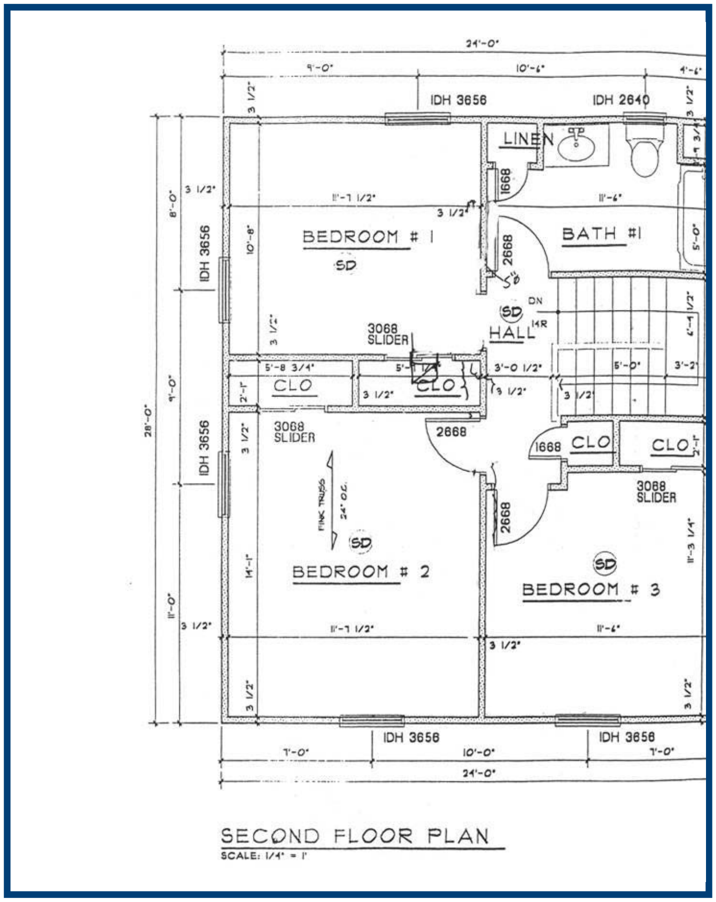

Figure 2 Second floor plan

2.0 COMPARISON OF HYDRONIC IN-FLOOR RADIANT HEATING AND FORCED-AIR SYSTEMS

2.1 Project Overview

The comparison portion of the project involved a side-by-side evaluation of two different types of heating systems installed in the same home. One heating system used a sealed combustion boiler and a radiant design with PEX tubing installed in aluminum track beneath a wood subfloor. A glycol solution was pumped through this two-zone system in order to eliminate any concerns regarding freezing. The other system was a forced-air ducted design with a condensing, sealed combustion furnace as the heat source. All ductwork was located within conditioned space or within the semiconditioned basement. Both systems used natural gas as their fuel source. Heating equipment for both systems was located in the semiconditioned basement. The use of a natural gas–fired furnace for comparison purposes is appropriate given that 70 percent of new, single-family detached homes in 2001 used such a heating system.[2]

[2] NAHB Research Center Annual Builder Practices Survey, 2001.

The equipment manufacturers and material suppliers as well as contractors experienced in the design and installation of radiant floor and forced-air systems provided engineering and design support. The Radiant Technology Institute, Slant/Fin, Inc., and the Carrier Corporation assisted with system sizing, design, and layout and equipment selection.

2.2 Preconstruction Phase

2.2.1 Radiant Systems-Background

Hydronic radiant floor heating systems permit the use of a wide variety of connection methods, materials, equipment, and components. Some common system types include the following:

- *Plastic tubing set in a concrete slab*. The tubing is attached to wire mesh to hold it in place until the concrete floor is poured.

- Tubing set in Thinset concrete. The tubing is fastened to the top of a wood subfloor. Lightweight concrete or Gypcrete is then poured on top of the subfloor, typically in a 1½ -inch thickness. Finish flooring is installed over the Gypcrete.

- Tubing set within aluminum track. The track can be set either below or on top of the subfloor. If placed on top, wood or plastic spacers are used to attach the finished flooring. Channels in the track accept tubing, and the aluminum surface helps to distribute heat uniformly to the finished floor above the plates.

- Tubing set within subfloor boards. This approach is similar to routing tubing within subfloor plates, except that premanufactured boards with an aluminum facing are installed on top of the subfloor deck.

- Tubing installed beneath the subfloor without aluminum track. The tubing is held by plastic connectors that are then screwed to the subfloor or joist system.

- Tubing hung in the joist area beneath the subfloor. The tubing is suspended several inches beneath the subfloor in the joist space. This approach requires a higher loop temperature than methods that directly transfer heat to the subfloor or finished floor via conduction (e.g., heat transfer between surfaces in contact with each other).

In all cases, insulation should be installed beneath the tubing, concrete, or Gypcrete to ensure that heat is more readily supplied to the intended zone or living space.

Each approach gives rise to different installation materials and costs, system operating temperatures, finished floor installation procedures, and performance, along with different implications for the design and construction of the home itself. For instance, a slab on grade concrete–embedded radiant system requires full insulation beneath the slab. A radiant system placed on top of the subfloor and embedded in a layer of lightweight concrete requires alteration in wall heights, door rough openings, and the height of the electrical and plumbing rough-in layout.

In addition to the several ways in which tubing can be installed for radiant floor heating systems, the technology demands the consideration of several operational issues. For example, radiant systems have been claimed to:

- Eliminate drafts sometimes experienced in forced-air heating systems as radiant systems heat without the use of fans or ductwork.[3]
- Eliminate the noise sometimes associated with forced-air heating systems as radiant systems do not rely on fans and airflow to heat a home.[4]
- Allow occupants to feel comfortable at a lower thermostat setpoint temperature.[5]
- This claim is based on occupants feeling more comfortable at lower temperatures as a consequence of warmer floors and surrounding surfaces. However, some research has indicated that thermostat setpoints are not necessarily correlated with the type of heating system but rather depend on varied individual occupant preferences.[6]
- Reduce or eliminate vertical temperature stratification by heating surfaces through radiant heat transfer rather than by blowing warm air into rooms.[7]
- Perform more efficiently than other heating technologies, with some claims as high as a 20 to 40 percent reduction in monthly energy bills.[8]

The NAHB Research Center staff conducted an extensive literature search before designing the field evaluation and found no field or controlled laboratory tests to support the above claims. Claims of increased comfort appeared to be based on interviews and surveys of occupants. Claims regarding reduced energy use were typically based on an assumed two-– to three-degree F lower

[3] John Siegenthaler, P.E., *Radiant Basics – A Course in Hydronic and Electric Radiant Panel Heating Components, Installation Specifying and Sequencing*, (Radiant Panel Association, 2002).
[4] John Siegenthaler, "Why Use Hydronic Heating?", *PM Plumbing & Mechanica - Hydronics Toolbox, Business News Pub., 1999*. Alex Wilson, "Radiant Floor Heating: When It Does – and Doesn't – Make Sense", *Energy Design Update*, (Vol. 11, Number 1 – January 2002).
[5] Siegenthaler, *Radiant Basics.*
[6] Canada Mortgage and Housing Corporation. *Thermostat Settings in Houses with In-Floor Heating*, 2001.
[7] Siegenthaler, *Radiant Basics.*
[8] Building Systems Magazine, "Factory Installed Radiant Heat", July/August 2001. Building Design and Construction, "Heat Rises", Hugh Cook, January 1999.

thermostat setting during the operation of a radiant system versus a conventional forced-air system.

The design of the evaluation plan for the current PATH technology took into consideration the various performance claims. While the first two claims proved difficult to measure objectively and quantify, the field evaluation plan directly addressed the latter three operating claims. The evaluation plan called for assessment of the following:

- Energy consumption and operational cost through one heating season,
- Installation practices and average cost of each system, and
- Feedback from contractors as well as from the homeowners.

2.2.2 System Design and Equipment Selection

The process of designing a fair and meaningful comparison of two different heating systems required the balancing of several considerations in much the same way that a contractor or homeowner might move through the range of choices regarding types of heating system. The process figured more so in the case of the radiant system more than in the case of the forced-air system; the latter is more straightforward as a technology and certainly more common. In addition to researching the variety of options for radiant system design, NAHB Research Center staff relied on the equipment and material manufacturers/suppliers (Radiant Technology Institute, Slant/Fin, Inc.) to provide design guidance.

Equipment. In accordance with the PATH goals, NAHB Research Center staff identified the following criteria for selecting equipment for the forced-air as well as for the radiant heat system:

Given the tightness of the building envelope under the Energy Star® label,[9] the heating equipment should be sealed combustion. Benefits derived from sealed combustion equipment include:

- Elimination of the potential for backdrafting or spillage of combustion byproducts and
- Reduced infiltration since combustion air is taken from the outdoors rather than from indoor air.
- The Btu output of the equipment should match the heat load of the house as closely as possible.
- The equipment and components of each system should be moderately

[9] Blower door test results indicated envelope air leakage at 2.23 ACH_{50}. Using the LBL method, the natural air exchange rate was calculated to be .28 ACH_{nat}.

priced.

- The cost of the heating equipment for each system should be as similar as possible.

- The equipment and components should be readily available in the local market and relatively simple to operate without complicated controls.

- The rated efficiencies of the equipment for both systems should be similar.

The NAHB Research Center staff found it difficult to meet all of the criteria for both the radiant and forced-air systems. High-efficiency, sealed combustion, moderately priced space heating equipment with a low Btu output (approximately 26,800 Btu/hour) proved particularly difficult to find.[10]

<u>Radiant System</u>

For the radiant system, the NAHB Research Center staff selected a Slant/Fin (Model CB-45) sealed combustion boiler with an adjustable Btu output and an 85.6 percent AFUE rating. At its lowest setting, the 30,000 Btuh output came close to the design heat load of the house (26,800 Btuh). The heating capacity of the boiler was about 12 percent higher than the calculated heat load.[11] The 85.6 AFUE rating was also close to that of the furnace at 90 percent AFUE. Table X presents the boiler specifications

Table 1. Slant/Fin Boiler Input and Output Rate Specifications

Concept 21 Model No. CB-45			
Input Settings	**Input (Btuh)**	**Capacity (Btuh)**	**AFUE%**
Minimum	34,000	30,000	
Nominal	45,000	39,000	85.6
Maximum	52,000	44,000	

Because the Slant/Fin boiler had a cast-iron heat exchanger, the manufacturer recommended a minimum high-temperature-limit setting of 180 degrees F and a primary loop off the boiler to ensure return water temperatures of 130 degrees F, thereby preventing the possibility of flue gas condensation on the heat exchanger.

[10]A modulating boiler that adjusts the burn rate according to the return water temperature helps to prevent short-cycling during warmer outdoor winter conditions. However, this type of heating equipment has significantly higher initial costs. A Munchkin modulating boiler is about twice as expensive as the Slant/Fin. High-efficiency sealed combustion water heaters are typically intended for combined space and water heating. They have high heating capacities and also high price tags. A tankless water heater would not have been sealed combustion and does not have a rated efficiency, but would have matched the load and been more moderately priced.

[11]Manual J was used to calculate the heat load of the house. The Radiant Panel Association recommends that the heating equipment be within 100-120% of the calculated building heat load.

"Wet" versus "dry" system. The primary rationale for selecting a "dry" system, or one in which the tubing is installed with a wood subfloor rather than embedded in a concrete slab, was the Schenectady HFH chapter's desire for a basement in the home. As most homes in the region have basements, HFH believed that a basement help ensure the dwelling's future marketability. Furthermore, the narrow lot was better suited to a two-story design. The NAHB Research Center staff approved a house design developed by Betsy Petit, Architect (Westford, Massachusetts), and used by the Denver Habitat for Humanity Chapter.

"Below floor" versus "above floor." The following two factors drove the decision to install the tubing beneath rather than on top of the subfloor:

1. The difficulty in finding a Gypcrete or lightweight concrete supplier who would deliver a relatively small load at a reasonable price in the Schenectady area.

2. The desire to specify relatively familiar and conventional framing and construction methods in that volunteers would be performing much of the work and project oversight.

Aluminum plates versus "staple-up" tubing. At the Schenectady site, aluminum plates were attached to the underside of the subfloor, with cross-linked polyethylene (PEX) tubing clamped onto that. Tubing was spaced eight inches apart in each joist space (see Figure 3). Although the aluminum plates increase the cost of the radiant system, they improve heat transfer and reduce the possibility of temperature "striping" or large temperature variation across the floor. Eliminating the aluminum plates also would have necessitated higher water temperatures, which can pose problems for a wood floor. Wood laminate flooring was used throughout the entire first floor in the Schenectady home.

Figure 3 Supply and return manifolds for the second floor (zone valves located on the upper manifolds)

Number of zones. The radiant system was designed as a two-zone system per RTI's recommendations. The first and second floors were separate zones with their own circulating pump and mercury-bulb thermostat. Each zone was divided into individual loops that supplied heat to each room. The individual loops within each zone had brass ball valves that allowed a greater degree of control in adjusting and balancing the system (see Figure 4).

Outdoor temperature reset. The NAHB Research Center staff considered the use of an outdoor temperature reset. The reset control senses the outdoor temperature and shuts off the burner sooner under moderate outdoor temperature conditions, thereby reducing the likelihood of overheating. Such a control would have added approximately $700 to the system. Based on cost considerations and recommendations by the Radiant Technology Institute, the NAHB Research Center staff decided against the reset control.

Figure 4 Radiant tubing and aluminum installation.

Forced-Air System

For the forced-air system, NAHB Research Center staff selected a Carrier Model 58MCA040-08 sealed combustion condensing furnace as the heat source. The manufacturer's rated AFUE for the furnace was 90 percent. The furnace also has the lowest output within its product line (37,000 Btuh) and was the closest match to the design load without moving to a significantly more expensive variable-speed unit. However, as with the boiler, it was still oversized for the home by approximately 27 percent.

Table 2: Furnace Input and Output Rate Specifications

Carrier Model 58MCA040-08		
Input (Btuh)	**Output (Btuh)**	**AFUE %**
40,000	37,200	90

Delivery system. The forced-air system was a conventional ducted system with the ductwork located entirely within the conditioned space (e.g., all ducts were located inside the home's insulation boundary). Manual D was used to size and lay out the duct system. Both the supply and return trunk lines were made of sheet metal. The branch lines from the trunk to each supply register were insulated flex duct. Floor-mounted supply registers were used throughout the home, and two return air grilles were centrally located on the first and second floors.

Controls: The forced-air system was a single-zone system with one thermostat located on the first floor. Installation of a separate mercury-bulb thermostat ensured constant temperature settings throughout the test period as each system operated for alternate two-week periods throughout the heating season. Separate thermostats eliminated the necessity of resetting a thermostat at the beginning of each two-week period.

2.2.3 Product and Material Availability

The primary difficulty encountered in the project was the lack of small furnaces or the lack of moderately priced boilers with a high AFUE rating. Most high-efficiency, sealed combustion space heating equipment features Btu outputs starting at about 50,000 Btuh or approximately twice the heat load of the project house. Even high-efficiency, sealed combustion water heaters have high heat outputs; they are usually intended to provide both space heating and domestic water heating.

They also carry a significant cost premium. Natural draft, power-vented, or electric water heaters offer more moderately priced options. Nonetheless, the more moderately priced options offer neither the benefits of sealed combustion equipment that are preferable in a tight home nor the greater efficiency and lower operating costs associated with gas versus electricity.

The project did not use a thin-slab design with the tubing embedded in lightweight concrete. However, when the option was under consideration, NAHB Research Center staff checked for product availability with several local concrete suppliers. Interestingly, most of them did not stock gypsum-based or lightweight concrete. In less active markets such as upstate New York, a full range of materials is often not available due to lower demand.

Design Phase: Lessons Learned

- In the case of radiant floor heating systems, the process of selecting distribution systems and properly matching distribution systems, type of delivery, and specifications for other features in the home, such as floor finishing, require considerable engineering and design support.

- Communication and coordination between and among manufacturers and designers of radiant system materials, heating equipment manufacturers, material suppliers, and radiant system installers is necessary to ensure a sound match between radiant system design, heating equipment, and installation procedures in the field

- The use of a cast-iron boiler in a radiant system demands special attention to the boiler manufacturer's recommendations for setpoints for high-temperature limits and return water temperature. These settings must be matched with the required supply temperatures and flow rates of the radiant delivery system. To ensure the appropriate setpoints, boilers with cast-iron heat exchangers usually require a primary loop design that returns water to the boiler at a sufficiently high temperature to prevent condensation that could damage its heat exchanger.

Small, high-efficiency, moderately priced space heating equipment is not readily available. It is difficult to find such equipment that meets the needs of small, well-insulated, and tightly sealed homes.

- Incorporating a thin-slab floor design necessitates a plan review before construction begins. Changes in framing may be necessary to accommodate proper window, cabinet, and ceiling heights. Rough-in for plumbing and electrical trades may also be affected.

Gypsum-based or lightweight concrete used for thin-slab radiant floor systems may not be readily available in all regions. In addition, concrete distributors outside the local area may not find it cost-effective to deliver small quantities of material.

In comparison to the ductwork for a forced-air system, the piping for a radiant system requires less interstitial space and is typically easier to route. For instance, in Schenectady's Habitat home, half of the first-floor coat closet and half of a second-floor bedroom closet were needed for the return trunkline for the forced-air system.

2.3 Construction Phase

2.3.1 Construction Cost Estimates

As a Habitat for Humanity project, the Schenectady house received many donated or discounted materials. For example, Carrier donated the furnace and RTI discounted the tubing and track. Volunteers installed the radiant track but not the tubing, and they insulated the basement and first-floor ceilings. Therefore, in some cases, the reported costs were estimates rather than contractor prices. The prices for the boiler and furnace represent Manufacturer's Suggested Retail Price (MSRP), not necessarily the price that an HVAC contractor would charge for providing labor and materials and labor for a job.

Table 3: Heating System Cost Comparison

Component	Forced-Air Heating System Costs ($)	Radiant Floor Heating System Costs ($)
Heating Equipment (MSRP)	830	1,600
Radiant plates, tubing, circulators, valves, relays, pipe supports		1,579
Labor, including ductwork, piping, flue piping, thermostats, expansion tank, tubing and track installed	3,400	4,400
Electrical Labor (estimated)	50	50
Ceiling Insulation (R-11)	0	350
Insulation Labor (estimated)	0	300
Total	**$4,280**	**$8,279**

The cost of the radiant system could have been reduced if the aluminum track had not been used and a less expensive boiler or water heater had been selected. The price of the aluminum track was $575; labor for installation of the track totaled approximately $400. The list price for a natural draft 83 percent AFUE boiler is about $1,300 and that of a tankless water heater approximately $1,000. Therefore, the cost of the radiant system could have been reduced to about $7,000.

2.3.2 Project Schedule

The Schenectady Habitat for Humanity chapter typically selects forced-air heating systems for its homes and usually contracts with an HVAC professional for installation. Therefore, the forced-air system in the project can be viewed as the “standard” or conventional system. The design and installation of the system did not require any special efforts and did not affect the project schedule.

The radiant system on the other hand, required additional coordination during the design phase. As mentioned, RTI, the system manufacturer, designed the radiant system and provided specifications for tubing location and layout, identification of zones, and a piping diagram showing locations of valves, manifolds, pressure relief, and so forth. Although the specifics of the radiant system design were not required for building department approval, they would be needed at the proposal stage in typical contract work so that an accurate bid could be developed for the customer.

The time required for rough-in of the radiant system was longer than that required for the forced-air system. Installation of the ductwork for the forced-air system took approximately 16 person-hours while installation of the radiant track and tubing took approximately 30 person-hours. About two-thirds of the time involved installation of the track. A less time-consuming and fairly common alternative approach is to attach tubing directly to the underside of the subfloor, although the metal track improves heat transfer.

Owing to the need to insulate both the basement and first-floor ceilings, the radiant system had another impact on schedule (and cost). It took approximately eight person-hours and $350 in materials to insulate both floors. The insulation ensures that the large share of the heat from the system’s tubing is transferred upward to the intended zone. In the absence of radiant heat, the floor system between the first and second floors would rarely be insulated. Similarly, insulation of the basement ceiling is generally rare; instead, basements are often insulated at the foundation walls.

2.3.3 System Integration

The radiant system required additional coordination with trade contractors during both the design and construction phases. In addition to the need for an experienced professional to design the overall system, the system designer had to determine maximum recommended temperatures with respect to different finish flooring materials. Flooring suppliers recommended a maximum temperature of 80 degrees F for vinyl and wood laminate flooring, with no maximum recommended temperature for carpeted areas. These temperature considerations factored into the specification of tube sizing, mixing valves, and loop layout and length in order to maintain the required room temperature. For example, a tubing loop to heat a large room with wood laminate flooring would have to use mixing valves to moderate the tube temperature. The use of several loops is also often necessary to maintain even temperatures across the entire floor area. A room with carpeting would present the opposite challenge; higher loop temperatures would be needed to transfer heat through the subfloor, the carpet pad, and the carpet.

Trades working in the house following the radiant system installation had to exercise caution in preserving the system’s integrity. Given that the track and tubing must be installed before insulation and drywall work can begin, the trades must take care during later phases of construction to ensure that nails or screws are not driven into tubing. For instance, when installing underlayment or toilet flanges, the trade contractor must use shorter fasteners or mark out tubing locations to avoid punctures.

The Schenectady radiant system used separate equipment for space and domestic water heating, permitting a more direct determination of energy consumption under forced-air and radiant heating system operation. However, a boiler or conventional water heater often supplies both the domestic hot water and the space heating for a home. In this case, coordination between the HVAC and plumbing contractor would be essential.

2.3.4 Complexity of Installation

Radiant system designs can range from a simple one- or two-zone system to more complex multiple-zone systems with sophisticated controls. Schenectady's Habitat home was designed as a two-zone system. The first and second floors were independent zones with separate circulation pumps and thermostats.

The system was designed such that the two zones would not heat concurrently. The first-floor thermostat took priority, and the second-floor pump did not turn on unless the first-floor zone was satisfied and the second-floor still called for heat. This feature was intended to reduce the potential for overheating, which could occur if both systems ran simultaneously and heated the thermal mass within the house to a point where temperatures would continue to rise even after the radiant system cycled off. Monitoring results indicate that the second-floor pump rarely ran because the first-floor loop usually provided sufficient heat for both floors.

As noted, the installation of the aluminum track for the radiant system was labor-intensive and time-consuming. Installation of the track and tubing took almost twice as long as the installation of the ductwork for the forced-air system. It is imperative that the designer of the radiant system provide clear drawings and instructions describing the exact location and number of tracks to be installed in each bay as well as the number and length of loops in each area. Such factors not only affect the ability of the system to heat the living space adequately but also prevent "hot spots" on the floor surface. The track and tubing layout are also based on the design supply and return water temperatures.

Several tips regarding the installation of the track and tubing follow:

- A slight gap should be left between adjacent sections of aluminum track to prevent noise resulting from expansion and contraction.
- All bends and turns in the tubing must be gradual to prevent crimping and thus restrict flow.
- If tubing is minimally damaged or crimped, it can be repaired by applying heat. The damaged section will return to its original shape.

- Radiant tubing should be kept at least six inches from toilet flanges in order not to risk melting the wax gasket.

Construction Phase: Lessons Learned

- Clear and specific design and installation specifications must be communicated when installing a new or unfamiliar system.
- The method of tubing installation (e.g., wet versus dry, plates versus hung) affects the speed and ease of installation and as well as the performance of work by the other trades.
- Before the system is concealed, code requires the pressure testing of the distribution system to identify any leaks.
- The trade contractor's decision to give the first-floor circulating pump priority may have contributed to the short-cycling of the boiler.[12] All such decisions made in the field should be verified with the radiant system designer.

2.4 Monitoring and Evaluation

2.4.1 Monitoring

The evaluation of the forced-air furnace system and radiant floor heating system compared energy consumption, evenness of temperatures throughout the home, temperature stratification in several locations, and occupant observations regarding comfort. NAHB Research Center engineers installed a comprehensive Data Acquisition System (DAS) that used a datalogger and sensor network to monitor and record the performance of the two heating systems. Performance monitoring included measurement of the following parameters:

- Gas consumption for the furnace (forced-air) and boiler (radiant).[13]
- Electrical consumption for the furnace blower and radiant system pumps.[14]
- Supply and return temperatures of the fluid within the radiant loops.

[12] By allowing only one zone to operate at any one time, the boiler's heat distribution area was essentially halved. The smaller the heat distribution area, the higher the radiant system's return water temperature. When return water temperatures reach a preset limit, the boiler shuts down to avoid boiling the glycol solution. If the return water temperature reaches this preset limit too quickly, short-cycling of the boiler results.

[13] In order to obtain the amount of gas consumed under the operation of each heating system, the gas valve relay was calibrated using the utility gas meter. With all other gas equipment in the home turned off, the furnace and the boiler were each operated independently. Using the utility gas meter with a reported accuracy of +/- 2%, the length of time for the consumption of 2 cubic feet of gas was recorded under the operation of each unit. The amount of gas consumed per minute could then be calculated. With this information, the total gas consumed was calculated on the basis of the length of time the gas valve was open during furnace or boiler operation.

[14] On-site power measurements were taken for each piece of equipment using a Fluke multi-meter. These measurements were used to verify the watt-hour meters used to monitor the runtime of the blower and circulating pumps during system operation. For instance, the Fluke measurement of the power consumed by the furnace blower was compared to that measured by the watt-hour meter and subsequently recorded by the Campbell datalogger. Each pulse at the datalogger reflected 10 watt-hours. By recording the number of pulses per minute and calculating watts/hour, the watt-hour meter measurements could be compared to the reference measurement of the Fluke meter. Such calibration improved the accuracy and reliability of the recorded data by referencing it to a backup measurement.

- Supply and return temperatures in the forced-air system plenums.
- Subfloor temperatures in the family room, kitchen, first-floor bath, and bedroom #1.
- Room air temperatures at heights of one, four, and seven feet to assess temperature stratification.
- Indoor (basement, first floor, second floor) and outdoor temperature and relative humidity.
- Primary and secondary loop flow rates for the radiant system.

Indoor temperature and relative humidity were monitored at two locations in the home. Sensors were located in vented plastic boxes mounted on interior walls near the first and second floor thermostats. Basement temperature was recorded with a thermistor suspended from the basement ceiling. In addition, six temperature sensors were used to identify differences in temperature stratification under operation of the two heating systems. Three sensors were configured to protrude approximately 3” from an exterior wall of the living room at heights of 1’, 4’, and 7’. On the second floor, the sensors were positioned to extend 4” from an interior bedroom wall at the same heights.

Using supply and return temperature sensors as well as flow meters, the DAS calculated radiant system efficiency as:

$$\frac{\text{Heat Supplied by Boiler}}{\text{Heating Value of Natural Gas Consumed by the Boiler}}$$

Heat Supplied by Boiler = $\rho C p \Delta T V$

P = density of water

Cp = specific heat of water[15]

ΔT = difference between supply and return water temperature

V = volume of water flowing across heat exchanger

Operating efficiency of the furnace was not calculated because accurate flow rates could not be measured. A built-in bookcase prevented sealing off a bedroom supply register, and a reliable duct-blaster measurement could not be obtained.

The DAS was designed to enable and disable each heating system for alternating two-week periods. In other words, the radiant system was in use for a two-week period, followed by two weeks of forced-air system operation. The same sequence continued throughout the 2001–2002 heating season.

[15] The actual specific heat of the water-glycol solution is estimated as the specific heat of water.

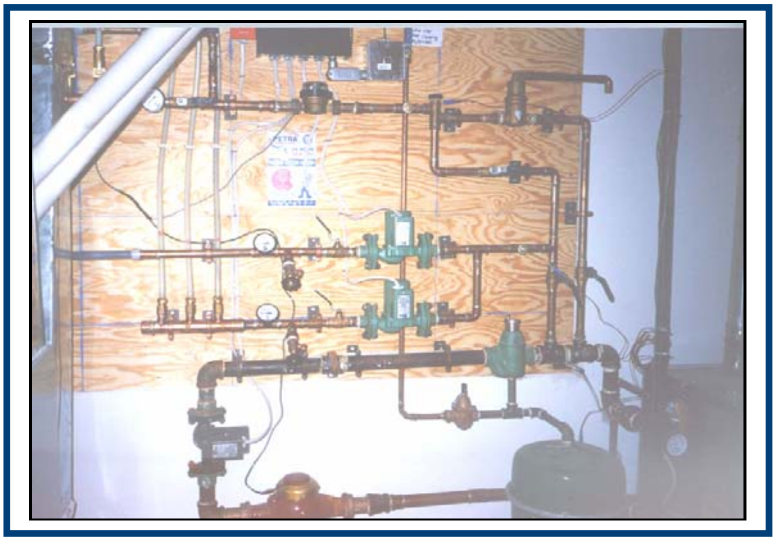

Figure 3 Radiant system piping layout in semi-conditioned basement

2.4.2 Field Results and Data Analysis

To facilitate the comparison between the two systems, the evaluation plan identified specific issues for examination, including the following:

1. How do the two systems compare in terms of natural gas and electrical energy consumption on a normalized basis, e.g., kBtu/DDh?[16]
2. Was there a significant difference in thermostat setpoints between the forced-air and radiant floor heating systems?
3. Was there a significant difference in room air temperature stratification between the forced-air and radiant floor heating systems?
4. Were there noteworthy operational issues with either system (e.g., short/long cycles, overheating, inability to meet load)?

In the data analysis regarding the amount of natural gas and electrical energy consumed during the operation of each system, we discarded the first day of data after switch-over of the systems, thereby eliminating any potential benefit accruing to the forced-air system from either the residual heat of the water in the radiant tubing or the warmer temperatures of interior surfaces. Elimination of the first day's data also allowed the radiant system time to achieve steady-state operating conditions.[17] Using the heat content of natural gas (1,030 Btu/cubic foot) obtained from Niagara Mohawk (the local utility), we normalized the heat used under operation of each system to Btu/DDh.

[16]A heating degree-day is a unit that represents a 1° F deviation from a fixed reference point (here 65° F) in the daily outdoor temperature (calculated as the average of the daily minimum and daily maximum). For instance, a day in which the daily high was 50° F and the daily low was 30° F would represent 25 DD_h (65°F – [(50° F + 30° F)/2]. Heating degree-days are often used as an indicator of the heating load on a house.

[17]To insure that a 24-hour period was sufficient to eliminate residual effects, the data was also analyzed by discarding the first three days of operation of each system. The difference in normalized system energy use between the two methods of analysis was less than or equal to 1% for each system. Therefore, the decision was made to only reject the first day of data in order to work with a larger, more robust data set.

1. How did the two systems compare in terms of natural gas and electrical energy consumption on a normalized basis, e.g., kBtu/DDh?

For the five-month period from January 2002 through May 2002, the average electrical consumption of the radiant system and the furnace system was the same at 0.07 kWh/DDh (see Figure 6). The electrical consumption consists of the circulating pumps for the radiant system and the fan energy for the furnace.

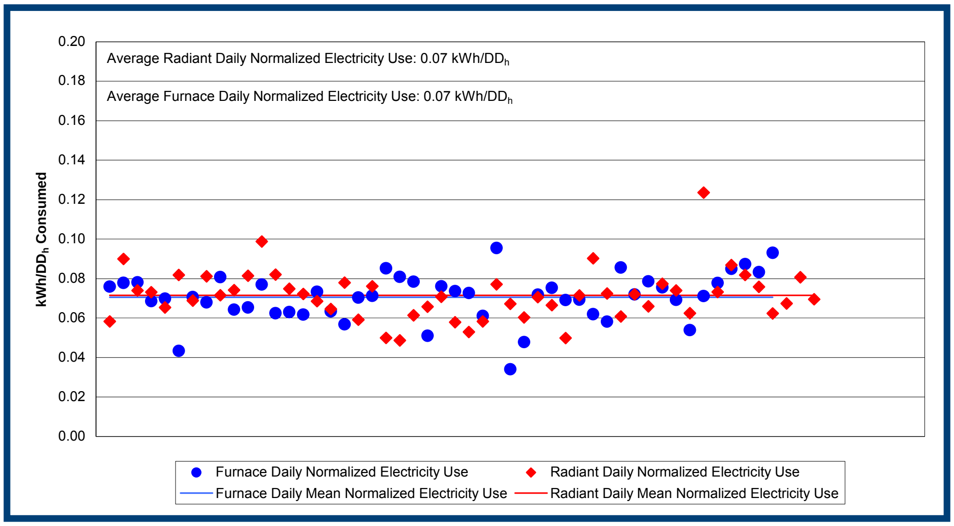

Figure 4 Furnace and radiant system electric consumption per heating degree day (daily data used)

Gas consumption differed, however; the furnace used an average of 5.56 kBtu/DDh and the boiler an average of 7.11 kBtu/DDh. On the basis of simply reporting each system's actual gas consumption during the periods monitored, the numbers represent a 27 percent difference in fuel consumed. Given such large variation, we closely reviewed other parameters measured during the test period as well as the operating conditions for each unit. These parameters included the following:

- Operating efficiency of the boiler.
- Difference in basement temperatures during the operation of each system.

Operating efficiency. The operating efficiency of the boiler was calculated at 75 percent, or 11 percent below the manufacturer's AFUE rating of 86 percent. In reviewing a small amount of one-minute data that had been collected, we found that the boiler was in fact short-cycling. The burner cycled on for approximately four to five minutes and then turned off for approximately two minutes over typical three-hour periods of boiler operation. A back calculation of the firing rate used burner-on time, the volume of gas consumed, and the utility's estimate of the heat value of the natural gas, indicating that the actual firing rate of the burner was closer to 45,000 Btu/hour rather than the lowest manufacturer's recommended setting of 35,000 Btu/hour.

Although the furnace was oversized in comparison to the heat load of the house (37,200 Btu/hour output versus the calculated house heat load of 26,800 Btu/hour), oversizing proved to have a much smaller impact on furnace operation than on boiler operation in the given radiant floor system. There was no evidence of furnace short-cycling. One-minute data collected early in the monitoring phase indicated average furnace-burner on-times of seven minutes with an average off-time of approximately 44 minutes when outdoor temperatures were in the mid-30s F. The manufacturer's rated efficiency of the furnace (90 percent AFUE) provided the basis of comparison.

To account for differences in the operating conditions of the two systems, two adjustments to the boiler's efficiency normalized the conditions and permitted a fair comparison of the systems. The first adjustment accounted for the short-cycling of the boiler by adjusting its observed efficiency of 75 percent to the manufacturer's rating of 86 percent. The second adjustment dealt with the difference in the rated AFUEs of the boiler and the furnace by adjusting the boiler efficiency from the observed 75 percent to match the furnace's AFUE of 90 percent. These adjustments were calculated in the following manner:

- Adjustment from boiler's measured efficiency to boiler's rated AFUE:
  kBtu/DDh86% = (0.75/0.86) * kBtu/DDh75%

- Adjustment from boiler's measured efficiency to furnace's rated AFUE:
  kBtu/DDh90% = (0.75/0.90) * kBtu/DDh75%

  kBtu/DDh86% = kBtu/DDh with boiler operating at 86 percent efficiency

  kBtu/DDh90% = kBtu/DDh with boiler operating at 90 percent efficiency

The negligible difference in electrical consumption at the different efficiencies did not require adjustment.

Basement temperatures. A second issue regarding conditions during the operation of the two systems was the difference in basement temperatures. Under the forced-air system, the average basement temperature was 66 degrees F; under the radiant system, the average basement temperature was 69 degrees F. The mean outdoor ambient air temperature was 38 degrees F for both systems. Although there was no thermostat in the basement and the area was not intentionally heated, the boiler, it may be argued, should be given "credit" for maintaining a three-degree F higher temperature.

The difference in basement temperatures was taken into account as follows:

kBtu/DDh Basement adjusted = kBtu/DDh75% minus kBtu/DDh 3 degrees F warmer basement air temperature

kBtu/DDh75% = kBtu/DDh with boiler operating at 75 percent efficiency

The heat required to maintain a three-degree F higher basement temperature in radiant mode was derived from a heat load calculation of basement losses (walls, windows, and floor) to the outdoors in accordance with the method described in the 1997 ASHRAE Fundamentals Handbook.[18]

[18] American Society of Heating, Refrigerating, and Air Conditioning Engineers, (ASHRAE), Fundamentals, 27.11, 1997.

Based on the calculated coefficients, the heat required to maintain the average three-degree F higher basement temperature during radiant mode was 3.1 kBtu/day.[19] The boiler, operating at 75 percent efficiency, would have had to burn 4.1 kBtu/day of natural gas to maintain this elevated temperature. Therefore, we subtracted 4.1 kBtu from the daily Btu consumption of the boiler in any calculations that accounted for differences in basement temperature.

The adjustments for differences in system efficiency and basement temperatures between radiant and furnace modes resulted in six possible scenarios as follow for gas energy consumption:

- Boiler as it performed during the study at 75 percent efficiency.
- Boiler efficiency of 75 percent and basement temperature differences taken into account.
- Boiler efficiency adjusted from 75 to 86 percent.
- Boiler efficiency adjusted from 75 to 86 percent and basement temperature differences taken into account.
- Boiler efficiency adjusted from 75 to 90 percent.
- Boiler efficiency adjusted from 75 to 90 percent and basement temperature differences taken into account.

Table 4 and Figures 7 and 8 present the results of these adjustments for the radiant system.

Table 4. Comparison of System Energy Consumption after Radiant System Adjusted for Differences in Equipment Efficiency and Basement Temperature

	Monitored Gas Energy Consumption ($kBtu/DD_h$)	Adjusted Gas Energy Consumption ($kBtu/DD_h$)				
		B * E 75% **	E 86%**	B * E 86%**	E 90%**	B * E 90%**
Radiant System	$7.11_{75\%\ Eff.}$	6.93	6.20	6.05	5.92	5.78
Forced Air System	$5.56_{90\%\ Eff.}$	5.56	5.56	5.56	5.56	5.56
Statistically Differentiable Means	Yes	Yes	Yes	Yes	Yes	No

* B: Data is adjusted to account for extra energy used to elevate Basement air temperature during radiant mode.

** E xx%: Boiler efficiency used in calculation.

Statistical analysis was performed to verify the significance of the differences between the calculated results. The measurement error involved in computing

[19] Based on mean outdoor air temperatures of 38°F in both radiant and furnace modes as well as mean basement air temperatures of 69°F in radiant mode and 66°F in furnace mode.

the daily kBtu/DDh for each system was estimated to be +/-7 percent[20] as reflected in the error bars in Figures 7 to 8. The following elements were included in the error calculation:

- Accuracy of gas meter: +/-2 percent.[21]
- Accuracy of reading gas: +/-1 percent.[22]
- Accuracy of heat value of natural gas: +/-5 percent.[23]
- Accuracy of outdoor temperature sensor : +/-3 percent.[24]
- Accuracy of datalogger recording: Negligible due to thousands of firing cycles over the course of the test periods.[25]

A one-tailed t-test compared the means of each set of energy consumption data for the radiant system (e.g., normalization of efficiencies and basement temperature) with the means of each data set for the furnace. The test revealed that the differences in mean energy consumption per degree day between the two systems were statistically significant for all cases except the final one, in which the boiler's efficiency was adjusted to the equivalent of the furnace's rated AFUE of 90 percent and differences in basement temperature were normalized. Nonetheless, with both systems operating at the same efficiency and under identical basement conditions, no significant difference in energy consumption between the two systems was discernible.

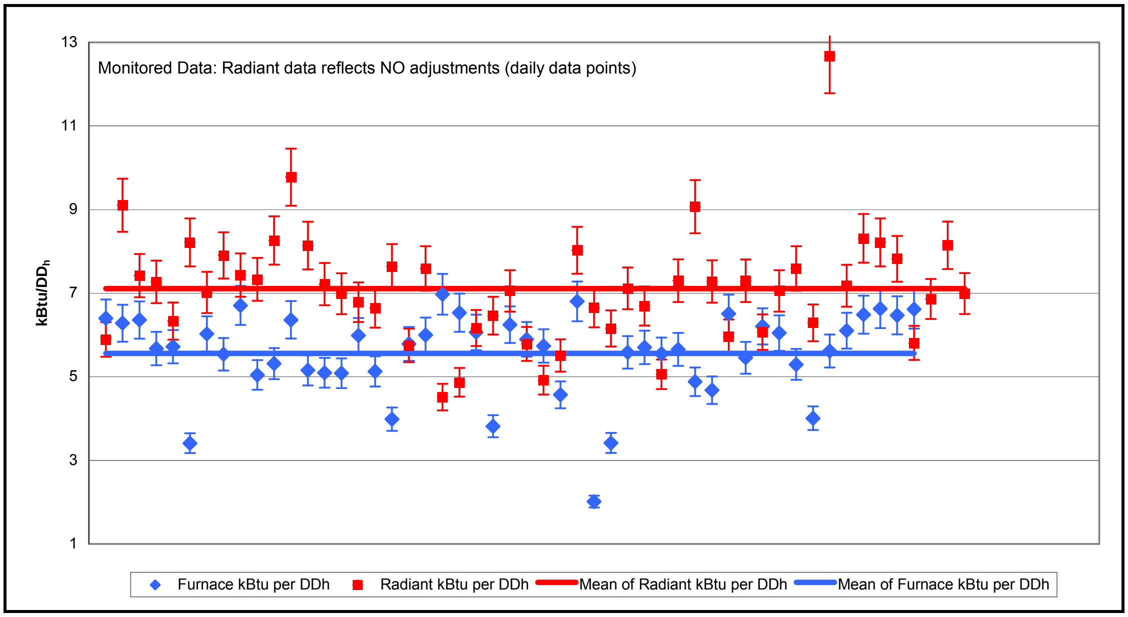

Figure 5 Furnace and radiant system natural gas consumption per heating degree day (no adjustments to data) (daily data used)

[20] The measurement error of 7% was calculated as the root sum of the squares of the individual measurement errors.
[21] Source: Estimate from New York State Department of Public Service
[22] Source: estimate, NAHB Research Center engineers
[23] Source: Niagara Mohawk
[24] Source: sensor manufacturer

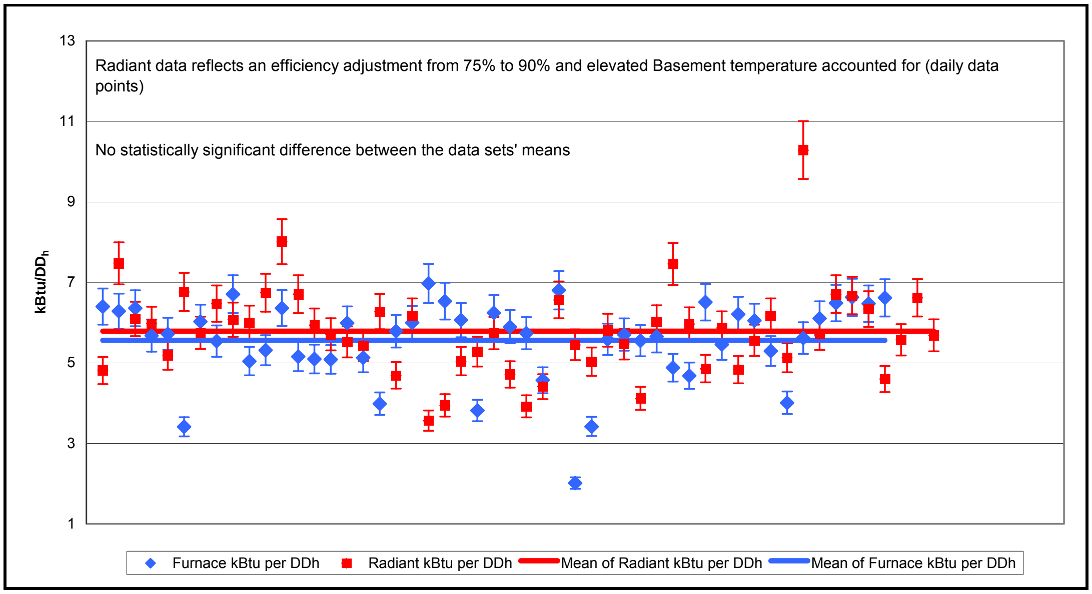

Figure 6 Furnace and radiant system natural gas consumption per heating degree day (boiler efficiency to 90% and basement temperature differences accounted for) (daily data used)

2. Was there a significant difference in thermostat setpoints between the forced-air and radiant floor heating systems?

The thermostat settings for the forced air and radiant systems were 70 degrees F and 68 degrees F, respectively. Given that the radiant system was a dual-zone system (first and second floor), the two system thermostats were set at 68 degrees F. With the settings established, the occupants were asked to leave them unchanged for the remainder of the heating season.[26]

Recorded indoor temperatures during the operation of both systems ranged from about 69 to 74 degrees F.[27] When the furnace system was enabled, the second floor (74 degrees F) was warmer than the first floor (72 degrees F), probably because of increased temperature stratification between the two floors when the blower operated. Under the radiant system, the opposite was true, with the first floor (73 degrees F) slightly warmer than the second floor (72 degrees F), probably because prioritization of the first-floor pump accounted for 98 percent of the runtime of the first- and second-floor pumps.

Average indoor temperatures over the entire test period were also calculated for each system.[28] The average indoor temperature for the forced-air system was

[25] This error is assumed to be randomly distributed across the whole data set and therefore can be neglected when determining each individual data point.
[26] The rationale for this test protocol was to provide a consistent and known benchmark for heating system operation. Had the occupants been allowed to vary the settings based upon comfort level at different times, it would have been difficult to distinguish between an altered thermostat setting and over-/under-heating due to system performance.
[27] Because uncalibrated, off-the-shelf mercury bulb thermostats were used, thermostat settings and measured air temperatures are different. Actual dry bulb temperature was monitored by sensors tied into the datalogger and positioned near the thermostats on the first and second floors.
[28] These values represent the average of hourly air temperatures measured by sensors located near the first and second floor thermostats.

73 degrees F; the average temperature during operation of the radiant system was 72 degrees F. Because the accuracy of the humitter used to monitor temperature and humidity is +/- 1 degree F at 68 degrees F, it is not possible to conclude that the temperature differences are significant. However, the temperature measurements do indicate that the house was warmer during operation of both systems than the thermostat settings would indicate. While mercury-bulb thermostats generally are not as accurate as digital thermostats, assumptions regarding the correlation of comfort and temperature should not be based on thermostat settings alone.

3. Was there a significant difference in room air temperature stratification between the forced-air and radiant floor heating systems?

Indoor temperatures were monitored at eight locations in the home throughout the test period. One sensor was placed near each thermostat on the first and second floors; two sets of three sensors located one, four, and seven feet from the floor were also placed on the first and second levels of the home.[29] Under the radiant system, the average difference between the high and low sensors on the first and second floors was one degree F and zero degree F, respectively. During furnace operation, the average difference was three degrees F on the first floor and one degree F on the second floor. Thus, the radiant system showed a narrower band of temperature stratification than did the furnace.

However, it should be noted that ASHRAE Fundamentals indicates that 98 percent of the population would be comfortable with a three-degree F temperature difference between head and ankles.[30]

The data were analyzed as follows to compare the evenness of temperatures throughout the home:

- Hourly average temperatures were calculated for each of the eight locations.
- The daily average temperature at each location was computed from the hourly averages.
- The difference between the maximum and minimum daily average temperature across all eight sensors was computed for each system.

The analysis showed that indoor temperatures were substantially more even during operation of the radiant system. The average difference between maximum and minimum daily average temperatures was three degrees F under the radiant system and six degrees F under the forced-air system (see Figure 9). The results lend support to the greater comfort afforded by a radiant system, which warms surfaces and produces a more even distribution of air temperature.

[29] These 6 thermistors protruded approximately 3" from the wall. They may have displayed more uniform temperatures due to radiation from the wall than if they had been placed in the center of the room. The thermistors are accurate within +/- 1^{o} F.
[30] American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., *1997 ASHRAE Handbook of Fundamentals*, (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1997)

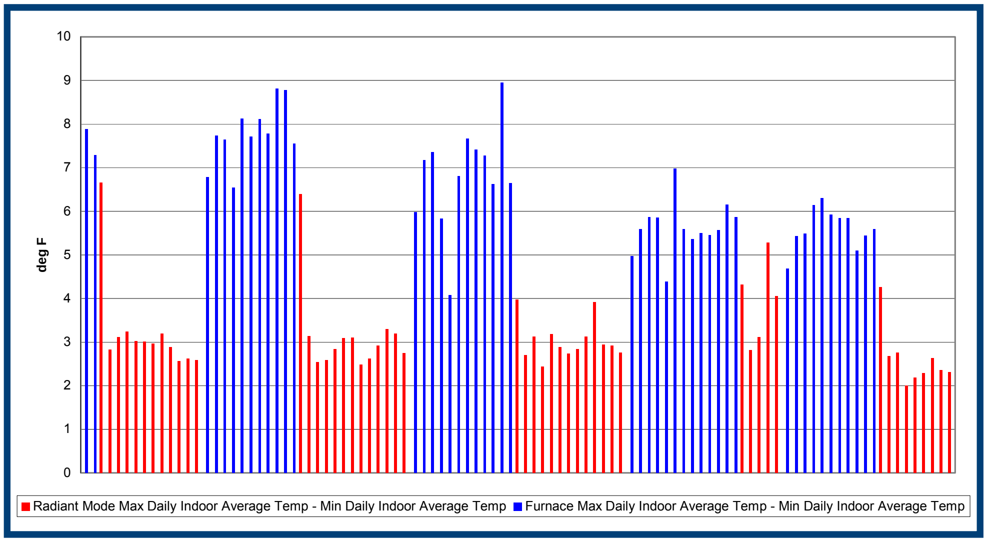

Figure 7 Difference between maximum and minimum daily average indoor air

4. Were there noteworthy operational issues with either system (e.g., short/long cycles, overheating, inability to meet load)?

Overshooting thermostat setpoint. During radiant system operation, we observed a slight overshooting of the thermostat setpoint. In the two to three hours following shut-off of the circulating pump, the first-floor temperature tended to climb approximately one to two degrees F. The occupants did not report any discomfort, however. Nor did they complain that the house was too warm. We observed no overshooting during operation of the forced-air system. Once the blower shut off, the indoor temperature slowly declined until it reached the thermostat setpoint. However, temperatures on the second floor were typically higher than the thermostat setpoint, indicating a degree of overheating. Again, the occupants did not report any discomfort.

Short-cycling: As stated, analysis of the one-minute data for the boiler and the furnace indicated that the boiler was in fact short-cycling during the test period. The average total on-period for the circulating pumps was approximately three hours. Within that period, however, the burner cycled on for approximately three minutes and then turned off for approximately two minutes until the water temperature in the boiler cooled to about 155 degrees F. The average outdoor temperature during the test periods for both systems was 38 degrees F--significantly warmer than the minus five-degree F design temperature for Schenectady.

After several discussions with the boiler manufacturer, the HVAC contractor, and the Radiant Technology Institute, we made adjustments to the boiler, reducing the firing rate to approximately 38,000 Btuh input and lowering the aquastat setting to 160 degrees F. On-site observation over several hours indicated that the burner remained on for approximately four minutes and turned off for about two minutes—a slight improvement, but still a very short cycle time. The outdoor temperature was 27 degrees F. The furnace, operating at approximately 40,000 Btuh input, did not short-cycle. Average cycle time for the furnace during the warmer-than-normal winter season was seven minutes; average system off-time was 44 minutes. The figures appear within reason, especially given that the outdoor temperature averaged 38 degrees F during the forced-air test periods.

2.5 Occupant Reactions and Comfort

To document comfort associated with the heating systems, the homeowners kept a log noting comfort issues during the operation of each system. Although they were not told which system was operating, they could identity each system by the noise (or lack of it) from the blower and differences in comfort levels in different areas of the house. Though the occupants initially selected the thermostat setpoints at their own comfort level, they later reported that they were warmer and more comfortable during operation of the radiant system. During the second period of radiant system operation, they said, "We knew the other (radiant) system came on because now we can use the whole house again!" Despite fairly small differences between average indoor temperatures under the operation of each heating system, the homeowners intentionally spent more time upstairs where average temperatures were 74 degrees F during operation of the forced-air system. Table 5 shows average basement, first-floor, and second-floor temperatures during operation of each system. The average temperatures were calculated by using the data collected from the temperature sensors located near the thermostats and from one sensor suspended about one foot from the basement ceiling.

Table 5: Average Indoor Temperatures during Operation of Forced-Air and Radiant Systems

	Forced Air °F	Radiant °F
Basement	66	69
First Floor	72	73
Second Floor	74	72

The occupants' reports lend support to the claim that occupants feel warmer at slightly lower air temperatures during operation of the radiant system. At an average temperature of 74 degrees F on the second floor during operation of the forced-air system, the homeowners felt approximately "equal comfort" as at 72 degrees F during operation of the radiant system. Likewise, they reported feeling "less comfortable" when the first-floor average temperature was 72 degrees F during operation of the forced-air system.

However, it is difficult to draw any firm, scientifically based conclusions regarding comfort on the basis of the monitoring performed in the Schenectady house. The humitters used to monitor indoor temperature and humidity have an accuracy of +/- one degree F at 68 degrees F. Given that two humitters measured first- and second-floor conditions, the accuracy of the temperature difference between floors drops to +/- two degrees F. To verify claims regarding greater comfort at lower temperatures and consequent energy savings, a more rigorous study involving a larger population would be necessary.

In addition to their comfort perceptions, the homeowners clearly preferred the warmer floors that were characteristic of the radiant test periods. Subfloor temperatures were measured in four locations throughout the home. =During operation of the forced-air system, average subfloor temperatures ranged from 69 to 74 degrees F; during operation of the radiant system, temperatures ranged from 73 to 80 degrees F. The occupants did not report any hot or cold spots on the floor or any drafts during the operation of either system.

At the conclusion of the study, the homeowners were required to choose between the radiant and forced-air furnace so that one of these heating systems could be used in another Habitat for Humanity home. The homeowners chose the radiant system. Their only reservation was that the system would make the future installation of a central air-conditioning system more costly.

2.6 Conclusions

Several points should be highlighted regarding this evaluation of a radiant heat system:

1. The radiant system evaluated constitutes only one type of in-floor hydronic radiant system among several options. In addition to the “dry” system with aluminum plates used in this study, other options include direct staple-up systems, tubing installed on top of the subfloor, or tubing embedded in a concrete slab or lightweight concrete. Each of these systems would have performed differently in the Schenectady home, and each offers advantages and disadvantages depending on various construction and design considerations.

2. The results reported above are specific to the particular home and the circumstances surrounding the given system’s construction and installation. The small home was well insulated and had an extremely tight (0.28 ACHnat) building envelope. All of these factors resulted in a particularly low heat load of 26,800 Btuh. The same type of “dry” system installed in a larger home is likely to have performed differently as would the same type of forced air system.

3. The gas-fired sealed combustion boiler used as the heat source for the radiant system is also only one of several options. Other possibilities include a modulating boiler, a conventional tank water heater, or a tankless water heater. Again, the use of a different type of heat source for the radiant system would have likely produced different results.

4. Both the furnace and the boiler were the smallest available given the other considerations taken into account in designing the study. Yet, both were oversized for the application. In addition, outdoor temperatures were unusually mild during the winter of the test period. Both systems rarely operated at design conditions.

2.7 Lessons Learned

1. The importance of careful sizing, design, and commissioning of a hydronic radiant system was highlighted. Communication between the radiant system designer and the equipment manufacturer is essential to ensure that the distribution system is compatible with the operating requirements of the heat source. Likewise, the installer must verify that operating conditions meet design specifications. Any changes or assumptions made in the field should be verified with the system designer and the equipment manufacturer.

2. The cast-iron boiler used in conjunction with the Schenectady home's radiant distribution system proved to be more "sensitive" to oversizing than did the furnace. The boiler (Btu output 12 percent higher than the calculated heating load) short-cycled throughout all test periods and had fairly long total cycle periods. Average burner-on times were four to five minutes over the typical two-and-one-half- to three-hour periods. The short-cycling contributed to a calculated operating efficiency of 75 percent versus the rated AFUE of 86 percent. For the furnace (Btu output 27 percent higher than the calculated heating load), burner- on-times were more reasonable, averaging seven minutes. Outdoor temperatures were significantly warmer than the minus five-degree F design temperature throughout the winter during operation of both the radiant and forced-air systems. Average outdoor temperatures for both the furnace and boiler test periods were 38 degrees F.

Figure 8 Example of an Installed AAV

3. The use of a cast-iron boiler with a low-temperature radiant distribution system requires careful consideration and coordination between the radiant system designer and the boiler manufacturer. The boiler manufacturer's specification of a minimum high-limit water temperature setting of 180 degrees F and the primary loop recommended to ensure return water temperature of 130 degrees F were not well matched to the radiant distribution system, which called for supply temperatures of 130 to 140 degrees F. Return water temperatures in the secondary loop were approximately 24 degrees F lower than the supply temperatures. With primary loop water temperatures at 165 degrees F mixing with secondary loop water, the boiler needed little time to reach its high-limit setting of 180 degrees F. The 165-degree F water temperature in the primary loop also contributed to heat unnecessarily given up to the basement.

4. On the basis of the evaluation, the radiant system of interest did not consume less energy than the forced-air system, even when the data were normalized to place both systems on an equal footing (radiant system adjusted to 90 percent efficiency

and basement temperature differences taken into account). Assumptions regarding greater energy efficiency cannot be made on the basis of presumed lower thermostat settings or reduced temperature stratification.

5. The evaluation did corroborate claims of greater occupant comfort with the radiant heating system. The occupants liked the warm floors, reported greater comfort, and chose to keep the radiant system after the study concluded.

6. The evaluation also verified that the radiant system produced more even temperatures throughout the house compared with the forced-air system. During operation of the radiant system, temperature swings averaged three degrees F; during forced-air system operation, temperature swings averaged six degrees F.

7. Room air temperature stratification was less during operation of the radiant system than during operation of the forced-air system. For the radiant system, first-floor temperature differences at one and seven feet off the floor were zero degree F while the second-floor temperature difference was one degree F. For the forced- air system, the differences were three degrees F and one degree F, respectively.

8. The installed cost of the radiant system ($8,279) was almost twice as high as that of the forced-air system ($4,280). Lower installed costs were possible for both systems, which could have taken advantage of natural draft heating equipment with lower efficiencies. For the radiant system, elimination of the aluminum plates would have reduced the cost by approximately $500 but might have compromised performance. Even with more moderately priced equipment and materials, the radiant system would likely still cost approximately 30 to 50 percent more than a forced-air system.

9. Lack of occupant complaints does not mean that any heating system is operating optimally. The occupants were entirely comfortable during operation of the radiant system and did not complain of high heating bills.

2.8 Industry Needs

The evaluation has identified several needs of the residential heating industry, in general, as well as of the radiant heating industry, in particular.

1. With respect to small, high-efficiency, sealed combustion heating equipment, the options are limited, especially in the case of moderately priced equipment. The same holds true for both forced-air and hydronic heating equipment.

2. Tank or tankless water heaters are potential candidates for a moderately priced heat source in small homes with low heat loads. However, more guidance is needed in designing and sizing either tank or tankless water heaters for a space heating application. Code officials also often need more information about the use of water heaters for space heating.

3. Through both literature and classes, the Radiant Panel Association (www.radiantpanelassociation.org) provides useful guidelines for the design and

installation of a radiant heating distribution system, e.g., different types of available systems, sizing and layout of tubing, floor temperatures, and so forth.[31] However, more concise, readily available industry information is needed on the selection of heating equipment, matching equipment to the radiant distribution system, and the requirements for various flooring materials. Greater coordination is needed between and among radiant manufacturers and designers, heating equipment manufacturers, and related material manufacturers, e.g., flooring material manufacturers. More guidance on controls, piping and component configuration, recommended flow rates, and commissioning would also be helpful.

3.0 AIR ADMITTANCE VALVES (AAVs)

3.1 Description

Air Admittance Valves are mechanical devices designed to relieve vacuum pressure and maintain trap seals without the need for additional vent piping. AAVs are one-way valves that open only under negative pressure (e.g., when a toilet is flushed). Allowing air into the waste pipe in this manner promotes flow in the drain and equalizes pressure within the system, thereby protecting water trap seals. When air pressure is neutral, gravity closes the valve, preventing the escape of sewer gas under conditions of equal or positive pressure.

The use of AAVs can reduce the amount of pipe required to vent a typical plumbing system, increase plumbing labor efficiency, allow greater flexibility in the layout of fixtures, and eliminate maintenance associated with flashing around roof penetrations for conventional vent stacks. Even though most building codes have provisions for AAVs, the building industry continues to resist adoption of AAV products.

To assess the building industry's concerns with AAV issues, the evaluation of air admittance valves addressed the following:

- Documenting relevant building code requirements and associated permitting procedures.
- Obtaining feedback from code officials and trade contractors regarding the installation and performance of the valves.
- Construction-phase monitoring to provide information on impacts on plumbing and other trade contractors.
- Recording labor and material costs associated with installation of AAVs for comparison with conventional venting systems.

[31] John Siegenthaler, P.E., *Radiant Basics – A Course in Hydronic and Electric Radiant Panel Heating Components, Installation Specifying and Sequencing*, Radiant Panel Association, 2002. *Standard Guidelines for the Design and Installation of Residential Radiant Panel Heating Systems*, Radiant Panel Association, reprinted September 2000.

The brand of AAVs used for the evaluation was Studor, although other brands are also available. Studor AAVs are available in two sizes. The "mini" is suitable for installation on one-and-one-quarter-, one-and-one-half-, and two-inch waste lines, and the "maxi" can be connected to three- or four-inch pipe. The valves must be located in a vertical position in an accessible location where air can circulate freely. They are typically installed in areas such as an under-sink cabinet, a recessed box on the wall, or at least six inches above insulation in the attic.

When installed as a branch vent, the Studor AAV must be at least four inches above the center of the horizontal waste line that serves the fixture. When installed as a stack vent, the AAV must be at least six inches above the flood level of the highest fixture.

In a system where air admittance valves are used, codes still require one vent to open air. The International Residential Code (IRC) allows sidewall venting, for instance, through a gable end. A Studor Recess Box may be used for termination through a sidewall. The box has cutouts to allow for one-and-one-half-, two-, and three-inch pipe. The box is covered by a painted aluminum grille or register that prevents nesting, bugs, or the accumulation of debris.

When sidewall venting is used, codes specify distance requirements from window or door openings and property lines. The purpose of the requirements is to prevent sewer gas migration into a home through ventilation openings. The IRC requires the vent to terminate at least two feet above and 10 feet horizontally outward from an opening. It also must be at least 10 feet above the ground and 10 feet from the property line.

The use of air admittance valves can potentially reduce long pipe runs often necessary in a conventional venting system and thus keep not only material costs in check but also labor costs associated with rough plumbing. The use of sidewall venting eliminates the need for any vent stack penetrations through the roof and can provide durability benefits by eliminating a common source of roof leaks. Thus, the combination of air admittance vents and sidewall venting can reduce construction costs, improve durability of the roofing system, and eliminate one aspect of home maintenance.

3.2 Design and Preconstruction

3.2.1 Design Considerations

Studor personnel provided assistance in designing the plumbing vent system and specified Studor "mini" vents for the kitchen sink, the tub-shower, and each lavatory. The first- and second-floor toilets and the washing machine vent to open air at the east gable. These fixtures are located close to the main vent that runs from the sewer line in the basement to the gable. Figures 11 and 12 show pipe riser diagrams for both a conventionally vented system and a system using air admittance valves.

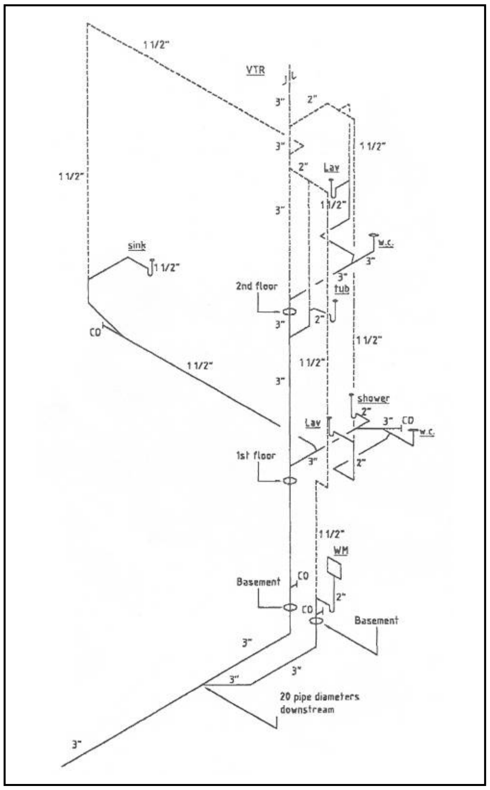

Figure 11 Conventional venting

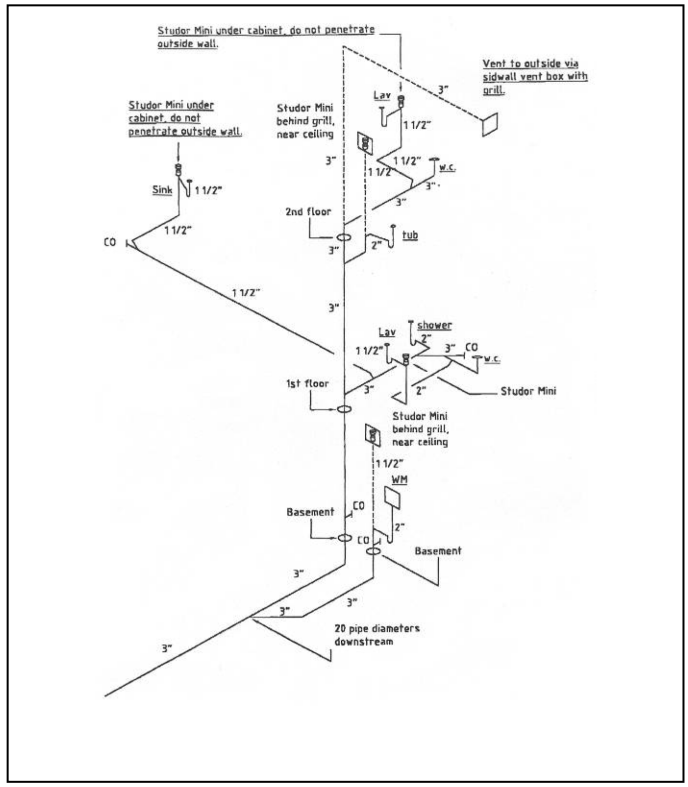

Figure 12 Studor venting

Although New York State had officially adopted the 2000 International Residential Code, which allows the use of both air admittance valves and sidewall venting, the new code did not take effect until September 2002. Therefore, it was necessary to apply for a variance through the New York State Department of State (DOS) for the use of both the AAVs and sidewall venting. Research Center staff attended a hearing in Albany, NY to testify and submit documentation on AAVs.

In addition to the code compliance issues, the Schenectady Building Department and the plumbing contractor had reservations about the use of AAVs. The city objected to the AAVs because they rely on private venting systems to provide venting for the public sewer system. With the AAVs, the net free vent area would be reduced since only one vent stack to the outdoors would be required.

The city was also concerned about the possibility of excessive back pressure due to a clog in the house or public sewer line. The NAHB Research Center staff countered that the building would still have one four-inch vent to the outdoors--as in the conventional design--and that the Studor vents have been tested under pressure fluctuations as high as a 30-inch water column.

The plumbing contractor's concerns were based on experience. He had replaced several mechanical plumbing vents after dirt accumulated on the seal and prevented them from opening or closing. Research has shown that dirt accumulation is not likely with AAVs since they have been inspected and tested after being in place for 25 years. Moreover, dust covers helped protect the vents.

Other questions that arose during the variance process included the following:

How does air downstream from a fixture get released when, for instance, a bathtub drains on the second floor?

Most of the drain line will not be filled with water. Water will run in a sheet down the sidewalls; air will be released at the center. In addition, one vent to the open air is located in the main stack.

How is the failure of an air admittance valve detected, and how difficult is valve replacement?

A sewer gas smell will be noticeable in the house, or water will not drain efficiently. Given that the valves must be accessible and thus located, for example, under a cabinet or in a recessed box on the face of the wall, they are easy to replace.

What is the life expectancy of air admittance valves?

Vents have been tested through 1 million cycles or the equivalent of approximately 80 years.

New York State granted the variance with respect to the use of the vents and sidewall venting, with the condition that the vent to open air is located on the east side of the home to avoid any potential problems associated with prevailing winds.

3.3 Construction Phase

3.3.1. Cost Estimates

The plumbing contractor estimated that the use of air admittance valves saved approximately four hours in labor and about $50 in materials. The material savings were associated with the following locations:

Kitchen sink--7’of 2” Schedule 40, and (3) 2” fittings
Tub/shower--5’ of 2” Schedule 40, and (2) 2”/4” fittings
Bathroom sinks (2)--30’ of 2” Schedule 40, and (8) 2”/4” fittings

Because the home is small with the first- and second-floor bathrooms stacked, the material and labor savings were not large. Even the washing machine, which was located in the basement, did not require extensive additional piping under conventional venting procedures. Given that the city of Schenectady did not allow house traps, the main sewer line had to be vented. Therefore, a four-inch vent ran from the basement to the attic to provide the one required vent to open air. Consequently, it would have been a relatively short run to connect the washing machine to the four-inch vent.

The most advantageous location for an AAV in the Schenectady home was the kitchen sink. Because of double corner windows above the sink, it is likely that a loop vent would be used; that is, a 2-inch line run around the inside perimeter of the cabinet. Conventional theory holds that the extra piping allows plenty of room for air in the line, thereby providing the same function as a vent.

At $50/hour, the labor savings at the rough-in stage totaled $200, or $250 for both labor and materials.

The list price of the Studor materials follows:

4 Mini-Vents @ $27.55 each
4 Connectors @ $1.95 each
1 Recess Box and Grille @ $14.15

The total material cost for the Studor materials was $132.15. Therefore, the total savings for the venting portion of the plumbing system amounted to $117.85.

3.3.2 Impact on Other Trades

The air admittance valves did not significantly affect the work of trades other than the plumbing contractor. Drywall contractors were affected to a minor extent. In places where a recessed box was required to house the air admittance valve, the drywall had to be cut around the box., but the work involved no extra cost.

Venting through the sidewall affected the work of both the roofing and siding subcontractors. As mentioned, sidewall venting enhanced the durability of the metal roofing system and eliminated the need for the careful installation and sealing of a boot around the plumbing vent in a standing-seam metal roof. According to the roofing contractor, the installation of a boot on a metal roof would take about two person-hours and cost approximately $75 in materials.

The siding contractor was required to install the box where the vent terminated at the gable and trim around the box. Such a task was routine for the siding crew; it was no different than trimming around a window or light fixture. Installing the box and fitting siding around it took an extra 15 to 30 minutes, with no extra charge.

With all trades taken into account, the total savings related to using Studor Vents was an estimated $293.

3.4 Post-Construction

The Air Admittance Valves have been installed in the Schenectady home for approximately two years, with no complaints or reports of failure by the homeowners.

3.5 Conclusions

3.5.1 Code Approval

Although numerous building and plumbing codes in the United States permit the use of air admittance valves, many local ordinances prohibit them. In such cases, builders must apply for a variance.

The time involved in seeking a variance depends a great deal on the support, or lack thereof, of local building department officials.

3.5.2 Acceptance

Field personnel, e.g., plumbing contractors, code enforcement officials, and plumbing inspectors, continue to resist the use of air admittance valves. Reasons include the following:

Lack of familiarity with the valves and mistaken association with earlier mechanical “cheater vents”.

Isolated reports of problems with the performance of the valves.

Relatively small cost or labor savings associated with use of the vents, especially in moderately sized new homes, thereby reinforcing the tendency to stay with tried-and-true methods.

Municipalities’ reliance on private plumbing venting for preventing excessive back pressure in public sewer systems.

3.5.3 Cost Savings

Cost savings associated with use of the air admittance valves totaled approximately $293. Considering the total cost of the home, the amount is not large. However, builders typically achieve large savings by adding up savings on many smaller measures. Furthermore, savings would be greater on a larger home where plumbing fixtures may be more spread out along long runs.

3.5.4 Labor Savings

Labor savings for the Schenectady home amounted to approximately four hours.

3.5.5 Other Advantages

The primary advantage of using air admittance valves in the Schenectady home relates to kitchen and bath sinks with windows above or in the path to the main vent stack. The use of the valves was also advantageous given the two-inch-by-four-inch framing of the exterior walls. To run two-inch pipe horizontally through the wall for a conventionally vented system would have required cutting studs and installing headers in certain areas.

The primary advantage of the use of sidewall venting was elimination of penetrations in the standing-seam metal roof.

On the basis of the Schenectady project, air admittance valves can be an effective method of venting a residential plumbing waste system. In new construction, builders can achieve labor savings. However, the amount of savings depends on the size and layout of the home. AAVs would be particularly useful in larger homes and in renovation work where wall cavities may not be open for venting through the roof.

4.0 PROJECT PARTICIPANTS AND SOURCES OF INFORMATION

SOURCES

Radiant Systems

Radiant Panel Association
P.O. Box 717
1433 West 29th Street
Loveland, CO 80539
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Fax: 970-613-0098
www.radiantpanelassociation.org

Radiant Technology Institute
RTI Pex Piping Systems
11A Farber Drive
Bellport, NY 11713
631-286-0900
800-784-0234
http://www.radiant-tech.com

Furnace Manufacturer

Carrier Corporation
P.O. 4808, Carrier Parkway
Syracuse, NY 13221-4808
800-227-7437
800-Carrier
www.carrier.com

Boiler Manufacturer

Slant/Fin Corporation
100 Forest Drive
Greenvale, NY 11548
516-484-2600
800-775-4552
www.slantfin.com

Air Admittance Valves

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www.schenectadybuilders.com

NAHB Research Center, Inc.
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