Evaluation of Hydronic Forced-Air and Radiant Slab Heating and Cooling Systems

Evelyn Baskin, PhD
Member ASHRAE

ABSTRACT

A contemporary house located in California has a unique HVAC system featuring radiant floor heating and cooling, forced-air hydronic heating and cooling, and a system that ventilates the house at night to reduce air conditioner energy use by pre-cooling building mass. The purpose of this study was to compare the energy consumption and electrical power demand characteristics of the various heating and cooling operating modes. Cooling season testing involved three different operating modes during similar weather conditions and comparable indoor comfort conditions. Heating testing involved operation in two test modes: hydronic radiant floor heating and hydronic forced-air heating, both by heating water with natural gas. Energy performance results reveal that slab pre-cooling caused some of the energy demand to shift from primarily in the afternoon. Coupling slab pre-cooling with nighttime ventilation air significantly shifted the energy demand load from primarily in the afternoon to late night with the load coming mainly from the fan. Also, during comparable outside conditions, there were appreciable energy differences among cooling modes and no identifiable energy advantage was noticed during the heating mode.

INTRODUCTION

In this study, the energy consumption and electrical power demand characteristics of a house during the heating and cooling seasons are assessed. The house is a custom 2484 ft^2 (230.8 m^2) two-story house completed in 2000 and located in Winters, California (see Figure 1), approximately 30 miles (48.3 km) west of Sacramento. Cooling testing comprised operation in three different cooling modes during similar weather conditions while maintaining equivalent comfort levels. Each of the three cooling modes was evaluated for a one-month period during the summer of 2002:

Figure 1 *Test house: front view and back view.*

mode-C1) Hydronic forced-air cooling in response to thermostat setting,

mode-C2) Hydronic forced-air cooling combined with hydronic slab pre-cooling,

mode-C3) Hydronic forced-air cooling combined with night ventilation pre-cooling and supplemented as needed with hydronic slab pre-cooling.

Heating testing was performed from November 2002 to February 2003 and involved operation in two test modes:

mode-H1) Hydronic radiant slab heating (gas hot water heating) and

mode-H2) Hydronic forced-air heating (gas hot water heating).

The energy and electrical power demand are compared among the three operational modes in cooling and between the two modes in heating, considering the indoor and outdoor environmental conditions.

Evelyn Baskin is with Oak Ridge National Laboratory, Oak Ridge, Tenn.

©2005 ASHRAE. THIS PREPRINT MAY NOT BE DISTRIBUTED IN PAPER OR DIGITAL FORM IN WHOLE OR IN PART. IT IS FOR DISCUSSION PURPOSES ONLY AT THE 2005 ASHRAE WINTER MEETING. The archival version of this paper along with comments and author responses will be published in ASHRAE Transactions, Volume 111, Part 1. ASHRAE must receive written questions or comments regarding this paper by **February 16, 2005**, if they are to be included in Transactions.

Figure 2a *Condensing water heater and air handler/FAU (water coil and ventilator).*

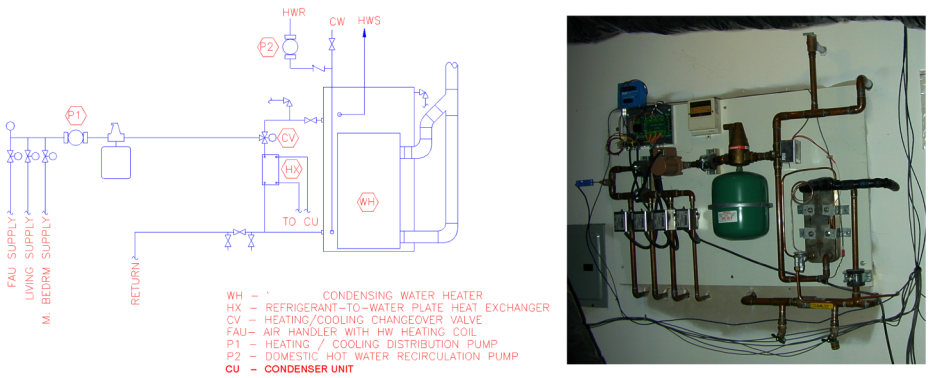

Figure 2b *Hydronic controls and water heater layouts.*

HVAC SYSTEM DESCRIPTION

The HVAC indoor system used in heating and cooling testing includes the following:

- Condensing gas water heater for heating water for combined domestic water and space (radiant and forced-air) heating, as seen in Figures 2a and 2b, along with the air handler and controls.
- A split-system HVAC system
  - Condensing unit consists of a compressor, fan, and a refrigerant-to-water heat exchanger capable of delivering chilled water to the radiant floor tubing or the hydronic fan coil.
  - Hot/chilled water air-handler equipped with a hydronic coil and variable speed fan.
  - Control system and damper that modulate ventilation air through the air-handler fan. Controls allow the occupants to set desired ventilation cooling comfort range.
- Forced air distribution to all major rooms on the first floor and all rooms on the second floor. The system is shown in Figure 3a and is a standard flexible duct layout outside the conditioned space.
- Radiant heating and cooling distribution to all first floor rooms—the main living area (great room, dining room, kitchen, entry, laundry, and baths) as shown on Figure 3b. The floor is a 3.5 in. (8.9 cm) thick concrete slab poured over ~3 in. (7.6 cm) of rock and 3 in. (7.6 cm) of sand. There is a vapor barrier under the slab and the perimeter is insulated with 2 in. (5.1 cm) of extruded polystyrene to a depth of 16 in. (40.6 cm) below the top of the slab. The radiant tubing is tied to welded wire mesh reinforcement and is from 1 to 2 in. (2.5 to 5.1 cm) below the surface of the slab.

The great room, which is a two-story space with a cathedral style ceiling, connects the first and second floors. This results in a thermal connection between the two floors driven by air buoyancy effects. Although the HVAC system has multiple distribution systems, the entire house is controlled as a single zone by a thermostat (set to 80°F [26.7°C] for cooling mode) located on the second floor hallway wall that is open to the open area extending from the great room to the second floor. The owner chose this location because the second floor is not usually occupied during the day, and the downstairs thermostat is not used during the cooling tests. The 80°F (26.7°C)

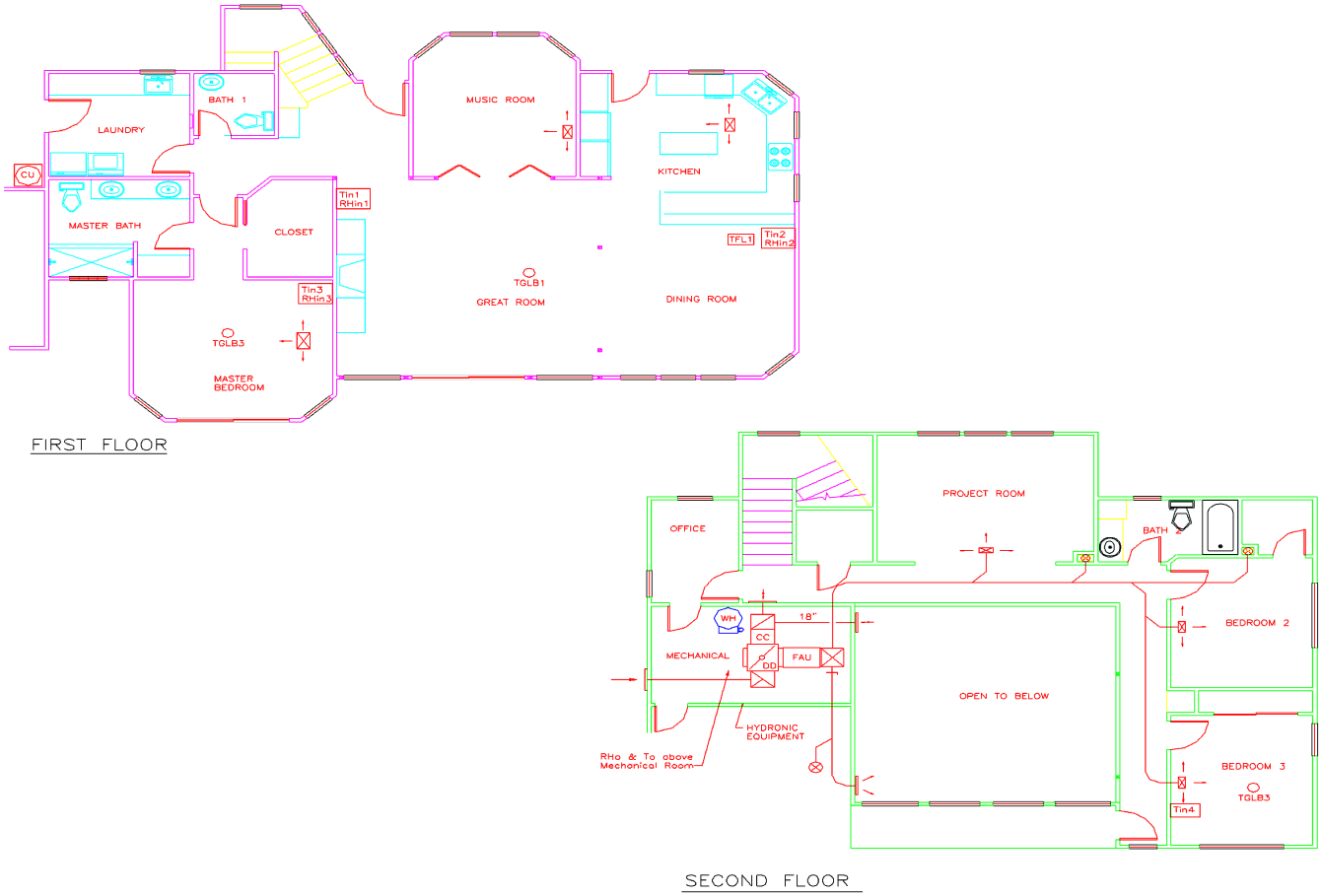

Figure 3a *House floor plan and forced-air distribution system (shown on second floor).*

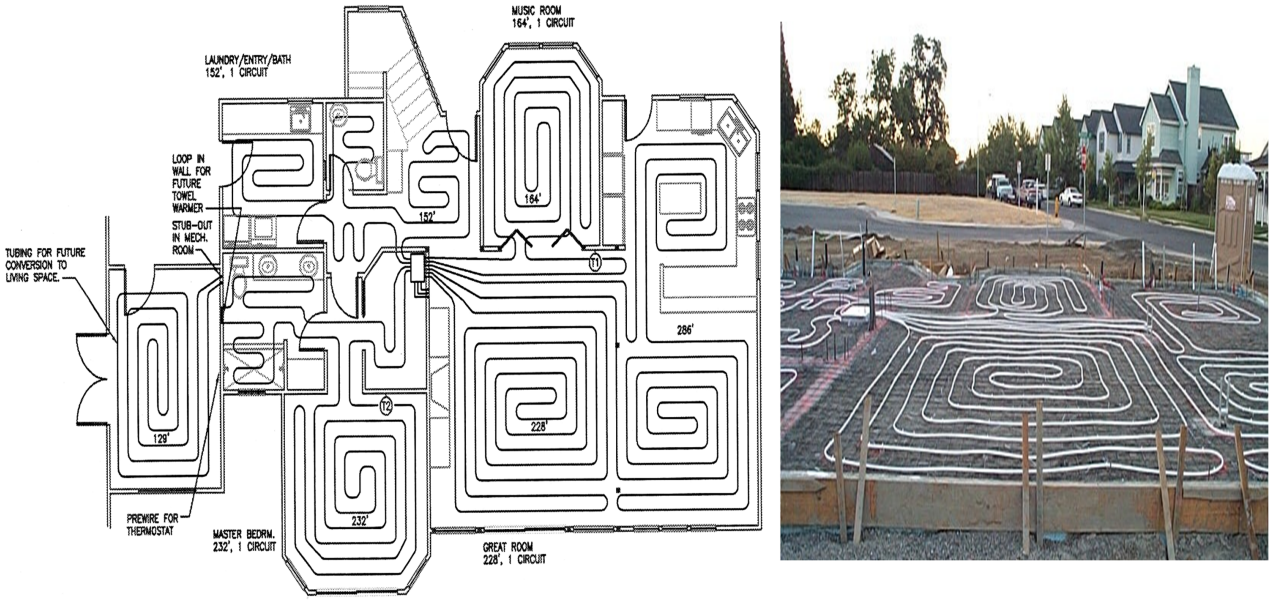

Figure 3b *Home radiant tubing layout.*

Table 1. Heating Thermostat Settings

Schedule	Mode H1 (11/2002 - 12/2002) Thermostat Settings - °F (°C)		Mode H2 (1/2003 – 2/2003) Thermostat Settings - °F (°C)	
Weekday	6:45 AM	65 (18.3)	7:00 AM	68 (20)
	8:00 AM	62 (16.7)	8:00 AM	62 (16.7)
	2:00 PM	68 (20)	3:00 PM	73 (21.1)
	9:00 PM	60 (15.6)	10:00 PM	60 (15.6)
Weekend	9:00 AM	65 (18.3)	9:00 AM	69 (20.6)
	10:00 AM	68 (20)	11:00 AM	72 (22.2)
	10:00 PM	60 (15.6)	11:00 PM	63 (17.2)
	Used woodstove, mostly on Friday and Saturday nights. Disabled outside air ventilation.		Downstairs thermostats maintained by radiant heating.	

for cooling mode setting was selected because it maintains the first floor average temperature of 75°F (23.9°C) during the cooling season.

TESTING MODES AND METHODS

Cooling

The system was operated in three modes during the cooling season test period (June-October 2002). In addition to mechanical cooling, natural ventilation (open windows) was used occasionally. Each operational mode lasted approximately a month, and the cooling modes are defined as:

mode C-1) *Hydronic forced-air* (6/21-7/20): The condensing unit, air handler, and forced-air distribution system were used to meet cooling loads in response to an 80°F thermostat setting.

mode C-2) *Slab pre-cooling and forced-air* (7/21-8/20): Conventional cooling and chilled water cooling of the living area (first floor) concrete floor was used to meet cooling load. Slab cooling was controlled to only occur when indoor temperature failed to drop below 70°F (21°C) by 4 a.m. Hydronic forced-air cooling operated at all times to maintain the 80°F (26.7°C) thermostat setting.

mode C-3) *Slab pre-cooling, forced-air, and night ventilation* (8/31-10/7): The controls operated the air-handler fan and outside air damper to ventilate the house with outside air when the outside air drops 3°F (1.7°C) below the inside air temperature. If the ventilation system failed to lower the indoor air temperature to 70°F (21°C) by 4 a.m., slab cooling was initiated.

Heating

The system was operated in two modes during the heating season test period (November 2002-February 2003). Each operational mode lasted approximately two months as described below:

mode H-1) *Hydronic floor heating* (11/2002-12/2002): Gas-heated water conditions the living area (first floor) concrete floor to meet the heating load in response to the thermostat settings in Table 1.

mode H-2) *Hydronic forced-air heating* (1/2003-2/2003): Gas-heated water is delivered to the hydronic fan coil with heating delivered via the duct system. Thermostat settings are shown in Table 1.

Monitored Parameters

Parameters monitored to assess the energy performance and verify operational performance are:

- House space conditioning load (heating and cooling) and system status
- Ventilation system cooling output and air-conditioning system cooling delivered
- Auxiliary (fan and pump) electrical energy usage and condensing unit energy use
- Outdoor and indoor conditions (temperatures and relative humidity)

ENERGY PERFORMANCE RESULTS (COOLING SEASON)

Indoor and outdoor environmental conditions during the cooling test period (all three modes) are listed in Table 2. The maximum outdoor temperature was the highest during mode-C1 but only 0.5°F (0.3°C) higher than the maximum during mode-C2 and 3.4°F (1.9°C) higher than the maximum during mode-C3. There were 16 more hours when the measured hourly averaged outside temperature was greater than 100°F (37.8°C) during mode-C1 than in mode-C2 and 21 more hours than mode-C3. The number of hours that the hourly averaged temperature ranged between 90°F and 100°F (32.2°C-37.8°C) was identical for modes C1 and C2 and slightly higher for

mode-C3. The averaged outdoor relative humidity was almost equivalent during mode-C1 and mode-C2, but mode-C3 averaged outdoor relative humidity was roughly 9% less than that in the other modes.

Modes C1 and C2 inside average temperatures and relative humidities are similar, in contrast to mode-C3 where indoor temperatures are on average 1.4°F (0.8°C) cooler (night ventilation cooling) and the relative humidity is approximately 9% less than in the other modes. The first floor surface temperature averaged ~72°F (22.2°C) for all testing modes, although the sensor may have been located too close to an exterior wall to represent accurately the average floor surface temperature. Similar average floor surface temperatures can be attributed to similar entering water temperatures (~57°F [13.9°C]) and temperature rise of ~10°F (5.6°C) based on exit water temperature and indoor air temperatures and RHs. Figure 4 shows the averaged daily outside air and floor temperature profiles for each test mode. On average, the outside air and floor temperatures were highest during mode-C1 and lowest during mode-C3 test period.

Table 2. Indoor and Outdoor Environment Conditions During Cooling

	Statistics	Mode-C1	Mode-C2	Mode-C3
$T_{outside}$ °F (°C)	Maximum	106 (41)	105 (41)	103 (39)
	Average	77 (25)	75 (24)	73 (23)
	Hours: 80°F-90°F (27°C-32°C)	190	164	163
	Hours: 90°F-100°F (32°C-38°C)	93	93	108
	Hours: >= 100°F (38°C)	24	8	3
$RH_{outside}$ (%)	Maximum	92	90	90
	Average	49	50	40
T_{inside} °F (°C)	Maximum	83 (28)	83 (28)	84 (29)
	Average	77 (25)	77 (25)	76 (24)
	Minimum	68 (20)	68 (20)	66 (19)
RH_{inside} (%)	Maximum	62	61	57
	Average	51	49	42
	Minimum	22	23	17
T_{floor} °F (°C)	Maximum	76 (24)	76 (24)	74 (23)
	Average	73 (23)	72 (22)	71 (22)
	Minimum	67 (19)	66 (19)	65 (18)

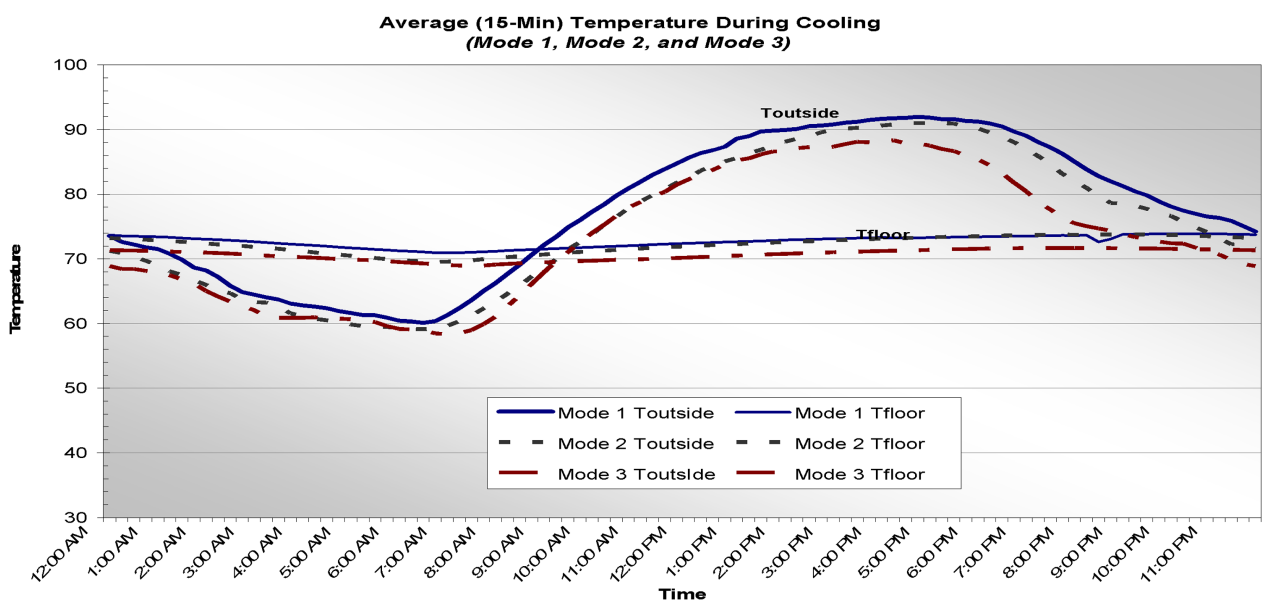

Figure 4 *Fifteen-minute averaged temperature profiles during all test periods for outside air and floor slab.*

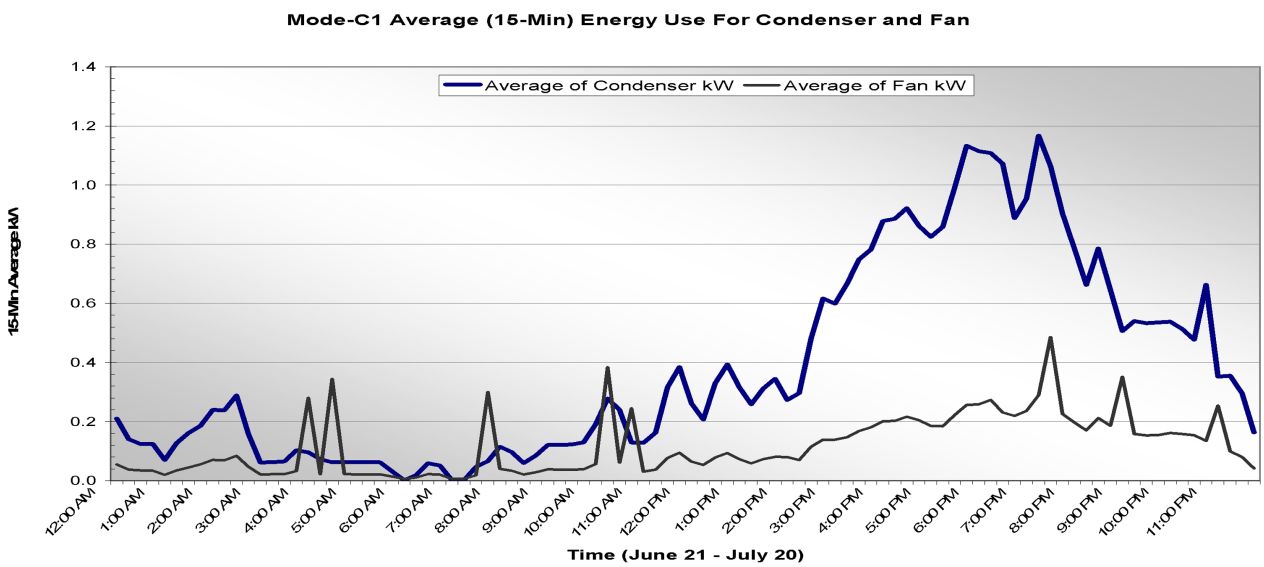

Figure 5a *Fifteen-minute average power use during test period for condenser and fan (mode-C1).*

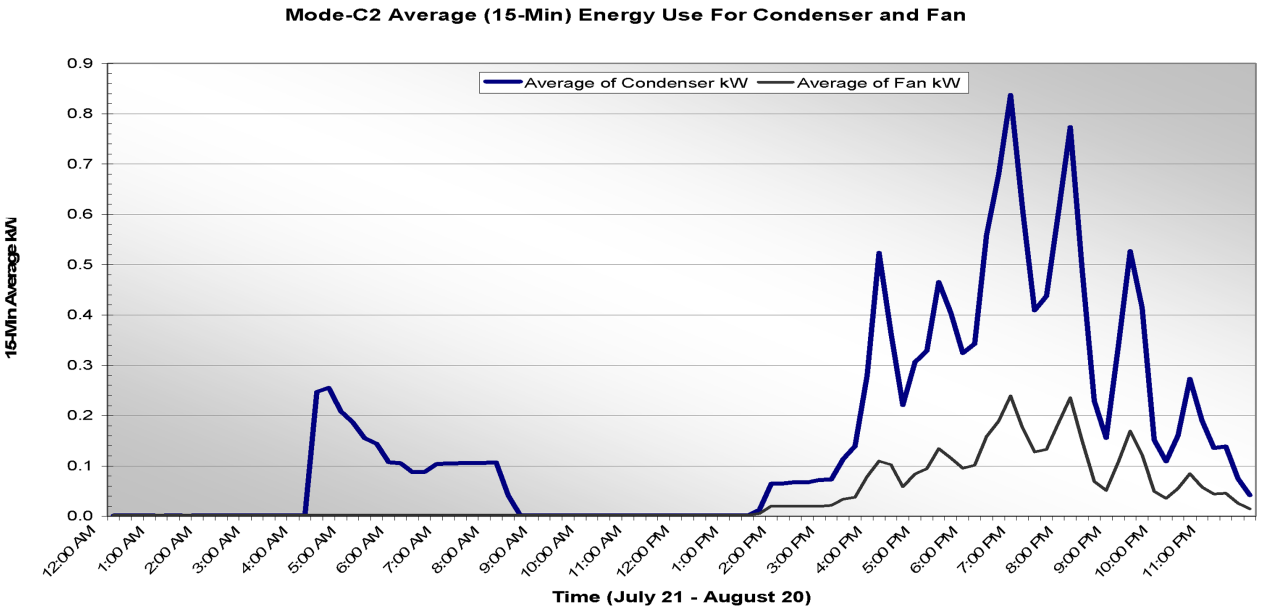

Figure 5b *Fifteen-minute average power use during test period for condenser and fan (mode-C2).*

Figures 5 and 6 illustrate the average demand profile during each mode of operation. The highest hourly averaged condenser energy use occurred between approximately 2:00 and 8:00 p.m. during mode-C1 and mode-C2. Very modest fan energy use took place between midnight and 2:00 p.m. during mode-C2. The fan and condenser operated throughout the day during mode-C1. During mode-C3, 15-minute-averaged fan energy usage was the highest between midnight and noon, which nearly balanced condenser energy use between 4:00 and 8:00 a.m. and between 2:00 and 8:00 p.m. The condenser energy use between midnight and noon during mode-C2 and mode-C3 was used to pre-cool the floor slab on the hottest nights when indoor temperatures did not drop below 70°F (21°C) by 4 a.m. Figure 7 plots the average demand profile for all three modes. It is clear that mode-C1 average 8:00 a.m.-midnight demand is higher than for the other modes. Mode-C3 reveals lower on-peak demand and a greater fraction of energy use between midnight and 10:00 a.m. This energy use is primarily from the fan operating to provide ventilation air.

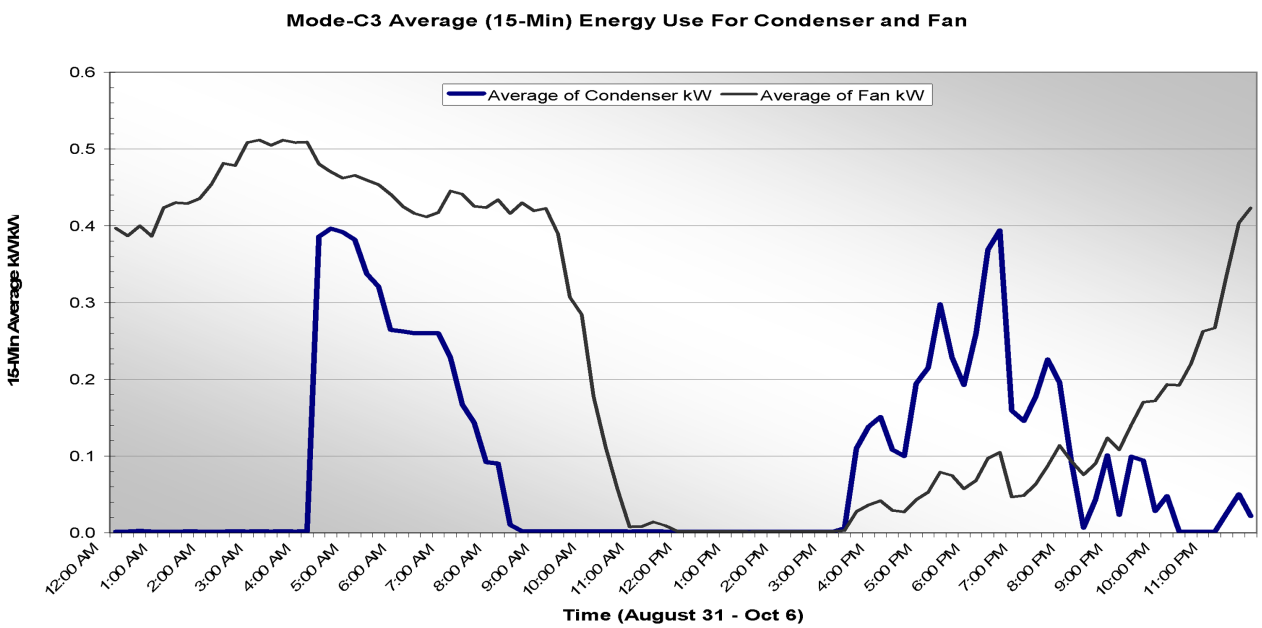

Figure 6 *Fifteen-minute average power use during test period for condenser and fan (mode-C3).*

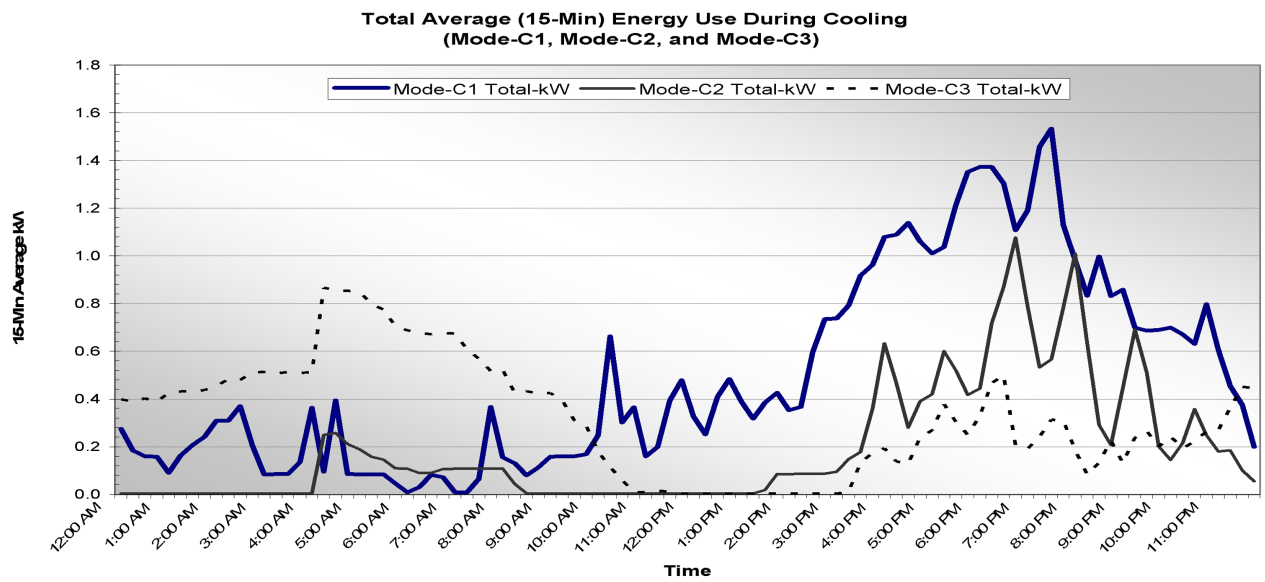

Figure 7 *Fifteen-minute average power use during all cooling test periods (modes C1, C2, and C3).*

The condensing unit has a manufacturer's rated capacity of approximately 24,000 Btu/h (7 kW), but this capacity rating does not include the condenser unit coupled with the refrigerant-to-water flat-plate heat exchanger. The measured circulating pump wattage was 83 W, and energy usage is included in the condenser unit energy usage. Table 3 lists the energy performance results achieved during testing for each mode. Mode-C1 (hydronic forced-air operation) recorded the highest condenser energy use and mode-C3 the lowest. The highest fan energy use was recorded during mode-C3. Overall night ventilation operating "EER" (Btu/W-hour) was nearly three times as high as the mode-C1 EER.

Table 3. Cooling Energy Performance Results

Test	Energy kWh				EER (%Difference vs. Mode 1)		
Operation	Date	Condenser	Fan	Total	System	Vent	Vent + System
Mode-C1	June 21 – July 20	273	83	356	8.7		
Mode-C2	July 21 – Aug 20	112	29	141	9.1 (4.5%)		
Mode-C3	Aug 31 – Oct 7	80	207	287	9.5 (9.6%)	23.5	19.5 (125.4%)

Table 4. Indoor and Outdoor Environment Conditions

Temperature/Solar Gain	Statistic	Mode H1		Mode H2	
		Nov-02	Dec-02	Jan-03	Feb-03
Outside °F (°C)	Maximum	78 (26)	68 (20)	70 (21)	70 (21)
	Average	54 (12)	48 (9)	50 (10)	51 (11)
	Minimum	35 (2)	34 (1)	36(2)	29 (-2)
	Hours: 30°F-40°F (–1°C-6°C)	30	48	26	60
	Hours: 40°F-50°F (6°C-10°C)	222	391	390	246
	Hours: 50°F-60°F (10°C-16°C)	275	233	262	276
	Hours: > 60°F (16°C)	192	25	66	88
Horizontal Solar (Btu/hr-ft^2)	Maximum	3.0	577	590	783
	Average	0	61	65	139
Inside °F (°C)	Maximum	79 (26)	79 (26)	79 (26)	80 (27)
	Average	72 (22)	71 (22)	71 (22)	72 (22)
	Minimum	66 (19)	65 (18)	65 (18)	66 (19)
Floor °F °C)	Maximum	69 (21)	69 (21)	68 (20)	68 (20)
	Average	68 (20)	66 (19)	65 (18)	65 (18)
	Minimum	64 (18)	64 (18)	63 (17)	63 (17)

ENERGY PERFORMANCE RESULTS (HEATING SEASON)

Indoor and outdoor environmental conditions during the heating test period are listed in Table 4. The maximum outdoor temperatures were similar for December 2002 through February 2003, and a milder climate is seen for November 2002. The maximum averaged outside temperature was approximately 8°F (4.4°C) higher during November 2002 than for any other month. The minimum outside air temperatures are very similar throughout the test modes with the lowest air temperature taking place in February. There were significantly more hours when the measured hourly averaged outside temperature was between 30°F and 40°F (–1°C-4°C) during December and February, and the number of hours that the hourly averaged temperature ranged between 40°F and 50°F (10°C) were comparable for November and February. All months in the test periods had practically equivalent hours where the temperature ranges between 50°F and 60°F (10°C-16°C). The horizontal solar gain was virtually nonexistent for November, analogous for December and January, and very high in February, which implies that the heating load should be lower for February. The first floor surface temperatures, maximum and averaged, were slightly higher during radiant slab testing mode (mode-H1), yet the floor temperatures were very similar for both test modes. The inside air temperatures were similar throughout the test period. Figure 8 shows the averaged daily temperature profiles for each test month. On average, the outside air temperature profile curves were highest during November and comparable during December and January. December and January were generally overcast due either to frequent storms or extended foggy weather. February was generally clear with warmer days and colder nights.

Figure 9 illustrates the energy usage profiles during each month of operation. Both months of mode-H1 testing reveal similar average energy profiles. December has significantly higher average demand than November due to colder outdoor temperatures. The profiles for mode-H2 are noticeably different from those of mode-H1. The mode-H2 test period shows two discretely high energy peaks (wakeup and home arrival/dinner), whereas during mode-H1 test period, more sustained increased energy levels occur around the same time of mode-H2 peaking times. The peaks occurred between approximately

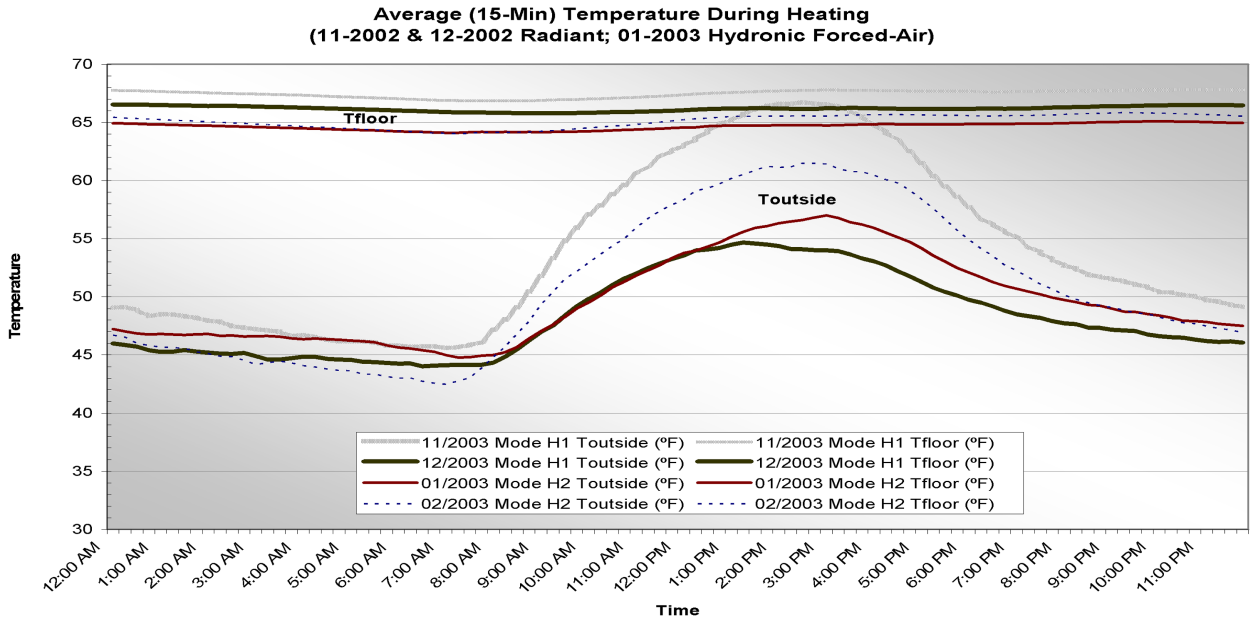

Figure 8 *Fifteen-minute averaged temperature profiles during 24 hours for outside air and floor slab.*

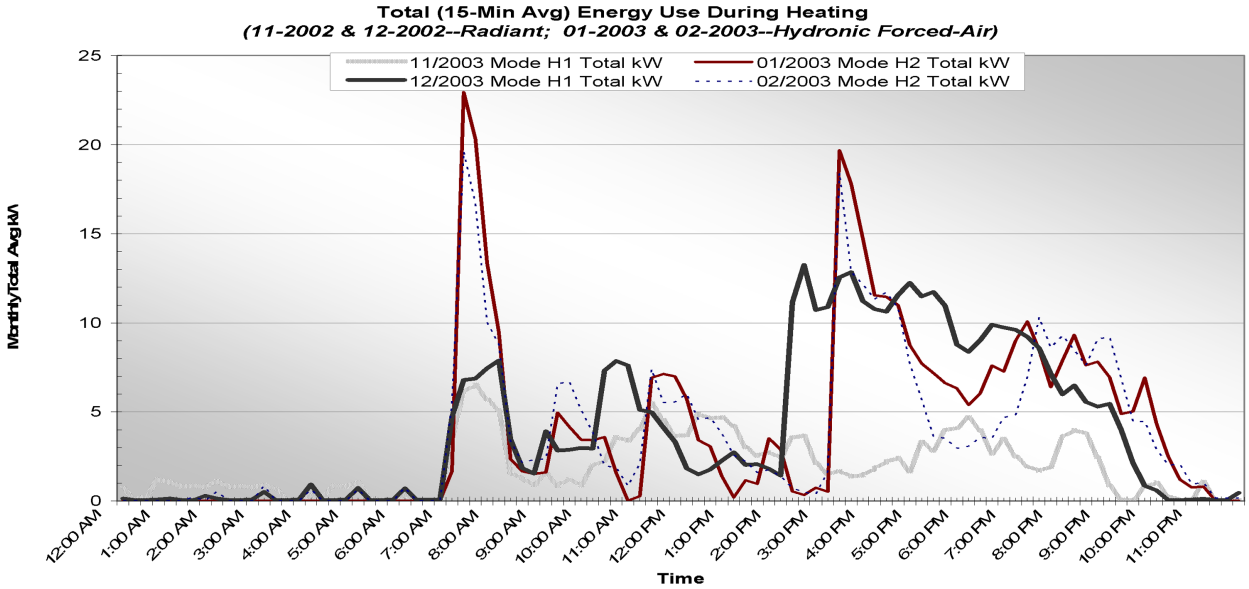

Figure 9 *Total energy use during test periods, mode-H1 and mode-H2.*

7:00 and 9:00 a.m. and 3:00 and 6:00 p.m. during mode-H2. During mode-H1, the major energy use occurs between 7:00 a.m. and 10 p.m. without any significant peaks, but during December, the energy consumption is much higher between 2:30 p.m. and 10:00 p.m. due to the colder outside air temperatures.

Table 5 lists the energy performance results achieved during each testing mode for heating. The gas consumption includes domestic hot water usage, which was assumed to be uniform through modes H1 and H2. During mode-H1 (December) the highest gas and electric energy consumption was recorded in December, while the lowest was recorded in

Table 5. Energy Performance Results

Test	Energy {Btu (kWh)}	Energy Use (kWh)		
Mode H1 (Radiant)	Gas	Cond + Gas	Fan	Total
Nov-02	2517600 (737.9)	188.4	2.6	191.0
Dec-02	5300950 (1553.6)	393.3	5.0	398.3
Mode H2 (Hydronic)				
Jan-03	4314200 (1264.4)	351.5	40.1	391.6
Feb-03	4002550 (1173.1)	329.4	40.0	369.4

November, due to the milder outside air temperatures. During similar outside air temperatures, mode-H1 (December) and mode-H2 (January) total energy consumption is comparable. It should be noted that the measured duct leakage (using the Delta-Q method (Walker et al.) was found to be 8.1% of the total airflow. This is considerably lower than the 25-30% leakage common to new construction. If the Table 5 total energy usage for January were increased by approximately 15-20%, mode-H1 relative performance would be clearly superior.

CONCLUSIONS

Cooling performance results reveal that slab pre-cooling caused some of the electric demand to shift from the on-peak periods (2 to 8 p.m.) to early morning off-peak periods (4 to 8 a.m.). This is due to the ability of the slab cooling to reduce on-peak cooling loads. Coupling slab pre-cooling with nighttime ventilation significantly shifts the energy demand profile from primarily in the afternoon to the nighttime with most of the off-peak load coming from the fan. The combined benefits of slab pre-cooling and nighttime ventilation significantly increase system overall performance and contribute to an "inverted" demand profile relative to mode-C1 (forced-air) operation. Heating performance results indicate approximate equivalence for the hydronic forced-air heating mode relative to the radiant floor heating mode during similar outside environmental conditions. The low duct leakage (8% of system airflow) affected the result because a more typical "leaky" duct system would result in a performance advantage for the radiant floor heating.

REFERENCE

Walker, I.S., M.H. Sherman, J. Wempen, D. Wang, J.A. McWilliams, and D.J. Dickerhoff. Development of a New Duct Leakage Test: Delta Q. LBNL 47308. Lawrence Berkeley National Laboratory. Berkeley, CA.