Adirondack Alternate Energy Passive Solar Houses at Hyspot and Kilmer

Final Report 10-27

November 2010

New York State
Energy Research and
Development Authority

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Final Report

Prepared for the

**New York State
Energy Research and
Development Authority**

Albany, NY
www.nyserda.org

Gregory Pedrick
Project Manager

Bruce Brownell
ADIRONDACK ALTERNATE ENERGY
Edinburg, NY

Prepared by:

Hugh Henderson
CDH ENERGY CORP.
Cazenovia, NY

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EXECUTIVE SUMMARY

The performance at two Adirondack Alternate Energy (AAE) high-performance, passive solar houses were evaluated by installing detailed monitoring equipment and collecting data for 24 to 37 months. The two houses were located outside of Saratoga Springs, NY. Both houses are highly insulated and include concrete slab that provides thermal mass. The house design includes a central plenum that draws air from the top of the house and forces it through ductwork imbedded in the slab. The houses were blower-door tested and shown to be very tight (ACH_{50} near 1). One house was heated and cooled by a ground water heat pump. The other was heated by a wood stove with electric heat for backup.

The data logging system was installed at each home and monitoring started in July 2007 and continued through August 2010. The collected energy use and space conditions data showed that the houses were very efficient and had low energy use. Space temperatures were maintained at reasonable levels.

Still, the lack of mechanical ventilation in the homes resulted in high humidity levels in the winter as well as high levels of occupant generated CO_2 (typically 1,500-2,000 ppm) whenever the house was closed. CO_2 levels in a properly ventilated house would be closer to 1,000 ppm. The measured data confirmed that door openings and normal infiltration were not an adequate means to provide sufficient fresh air to the space.

For future versions of the house, we recommend that:

- Ventilation should be provided by adding a fresh air duct into the central plenum. Ventilation flow can be induced with the plenum fan or by using a continuously operating bathroom exhaust fan.
- An energy efficient Brushless Permanent Magnet (BPM) motor should also be used to minimize the fan power requirements – which can account for 2,000-3,000 kWh per year. Two speed controls would greatly limit high speed operation to times when the house is stratified; otherwise the fan would run on low speed (the variable-speed DC motor that has previously been retrofitted at one of the houses is not very energy efficient).

- Cooling with in-slab ductwork is problematic and poses a condensation risk. Constant operation of the heat pump fan is also incompatible with good humidity control in the summer. We recommend using a high-efficiency ductless heat pump in the main zone. This system is a good option since installation costs are low and the central plenum will serve to uniformly distribute the “localized” heating and cooling throughout the house.

FORWARD

COMMENTS FROM BRUCE BROWNELL, OWNER

ADIRONDACK ALTERNATE ENERGY

Monitoring has been one of the important contributors to the level of performance for which AAE Low Energy Requirement Homes are noted. Extensive monitoring started when we had done 60-70 passive homes in 1977-79 with a two house performance study by Brookhaven Nat. Labs. Subsequently, we were involved in several others;

- 1974-75: AAE had 130 families live in monitored building for 3-to-4 days each across two winters. Measured energy use and comments were recorded.
- 1980: General Electric study 10-to-12 weeks, unpublished.
- 1981-82: N.Y.S. power pool, through Niagara Mohawk- eight homes on line- proved it can use off-peak power only at night to heat and cool.
- 1983-84: Harvard School of Medicine- Indoor Air Quality study-four homes.

Another equally important contributor is our intense year long collaboration with our clients and their contractors during the building process and subsequent follow up over the years with many relevant conversations about the client's AAE home. We have throughout 40 years, more than 360 homes across 15 eastern states, housing roughly 1,000 people, representing over 9,000 house years. Their most common comment is “we have an unparalleled level of human comfort”. Additionally, the collective comments from a layperson's perspective tend to fall in the health arena:

- We used to get the kids up two-three hours before the bus because of their asthma. Now it is much improved.
- These two boys, after 20 years, are going to have to go off to college and the real world. Neither they or I ever had a cold.
- Numerous frequent mentions of great improvement in aches, pain, stiffness, skin rashes, etc., etc.

- A huge relief in family stress, as:

  — The house can be left in winter and it will not freeze.
  — At a power outage- no problem- start the wood stove.
  — The sun never sends you a bill.
  — It doesn't matter if heating oil or gas prices double.

These collective values are the rewards AAE, its employees, and clients share that are unique and priceless. This monitoring effort should fine tune these facts. This decade will see large improvements in our great performance with the advent of:

- "Super windows" at R 10 and light selective, two-three times better.
- Off-peak power availability with the smart grid- Improved simple controls.
- Increased efficiency with heat pumps (perhaps air source) and more efficient DC motors.
- Integrating PV and solar hot water in our homes as a standard feature.

The future is very bright for passive solar.
BRB
11/8/2010

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Adirondack Alternate Energy (AAE) won a competitive award from NYSERDA Program Opportunity Notice 1062 (agreement #9987) to fund the installation of meters and instrumentation for long term monitoring at two of its passive solar houses built near Saratoga, NY. The AAE high performance house design is based on more than 30 years of experience building more than 350 highly efficient, passive solar houses in the Northeast.

AAE subcontracted with CDH Energy Corp. to complete the monitoring effort. CDH worked with AAE and NYSERDA to develop a monitoring plan, install the sensors and monitoring equipment, and continue monitoring for 24 months. Data collection at the Hyspot Road house started in June 2007. Monitoring at the Kilmer Road house did not start until August 2008. Data collection continued at both houses until August 2010.

During the monitoring period, CDH posted the collected data to a website where users could review the detailed data and make plots and tables for various periods. The database was updated nightly, throughout the monitoring period, with the newest data. The website is available at: www.cdhenergy.com/dataaccess.php (Click on "Adirondack Alternate Energy", user/pass: adirondack/solar).

DESCRIPTION OF HOUSES

Hyspot House

The Hyspot House is a 1,584 ft^2 residence built with 2x6 framing and exterior foam board insulation applied in two inch layers. Each layer is separately taped and joints are staggered. The walls and roof have four inches of polyisocyanate insulation. The six inch concrete slab is poured on top of four inches of polyisocyanate insulation. The house has casement or sliding windows and is air tight (about 1 ACH_{50}).

The house has about 200 sq ft of south-facing glass, including 180 of vertical glass and 20 sq ft of skylights on a tilted roof surface.

The house had two adult occupants plus two very large dogs (approximately 150 lbs each). The master bathroom had a large Whirlpool Tub.

A main feature of the house is 30x30 inch central air plenum designed to draw air from the top of the house and push it down through galvanized ductwork buried in the slab. The ductwork supply grills discharge at the perimeter of the house on both the first and second floors (2^{nd} floor ducts are located in the stud cavity).

At this house, the supply fan in the 2½-ton Versatec heat pump (Model VLV030) serves to circulate air through the ductwork. The water source heat pump extracts heat from a ground well to heat and cool the building. A variable speed Grundfos groundwater pump operates to provide water for heat pump operation as well as to meet the occupant's water needs. Domestic Hot Water (DHW) is provided by a 15 kW tankless water heater.

The heat pump is an "upflow" unit that is installed next to the plenum. Therefore, the round discharge from the unit is ducted with two 90º elbows to direct the supply air down into the floor. The measured power for the supply fan was 340 Watts, or an estimated 0.35-0.45 W/cfm.

A blower door was used to measure the air tightness of the Hyspot house on July 17, 2007. The Measured air tightness was 1.4 air changes per hour at 50 Pa. The equivalent leakage area (ELA) was calculated to be 20 sq in. During the test, the bathroom fan was taped off, though it was determined later that the fan was not vented to outdoors. See Appendix A for details of the blower door test.

Figure 1. Photos of Hyspot House

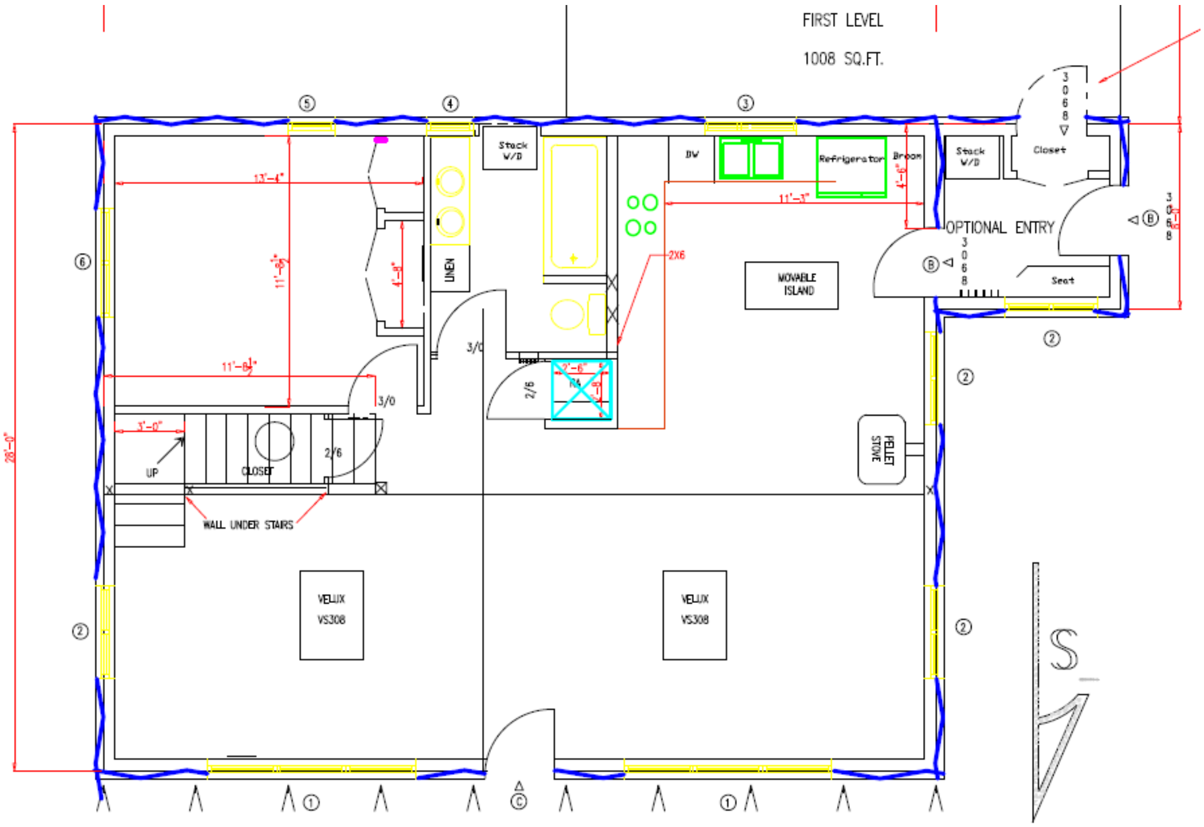


Figure 2. First Floor Plan for AAE House

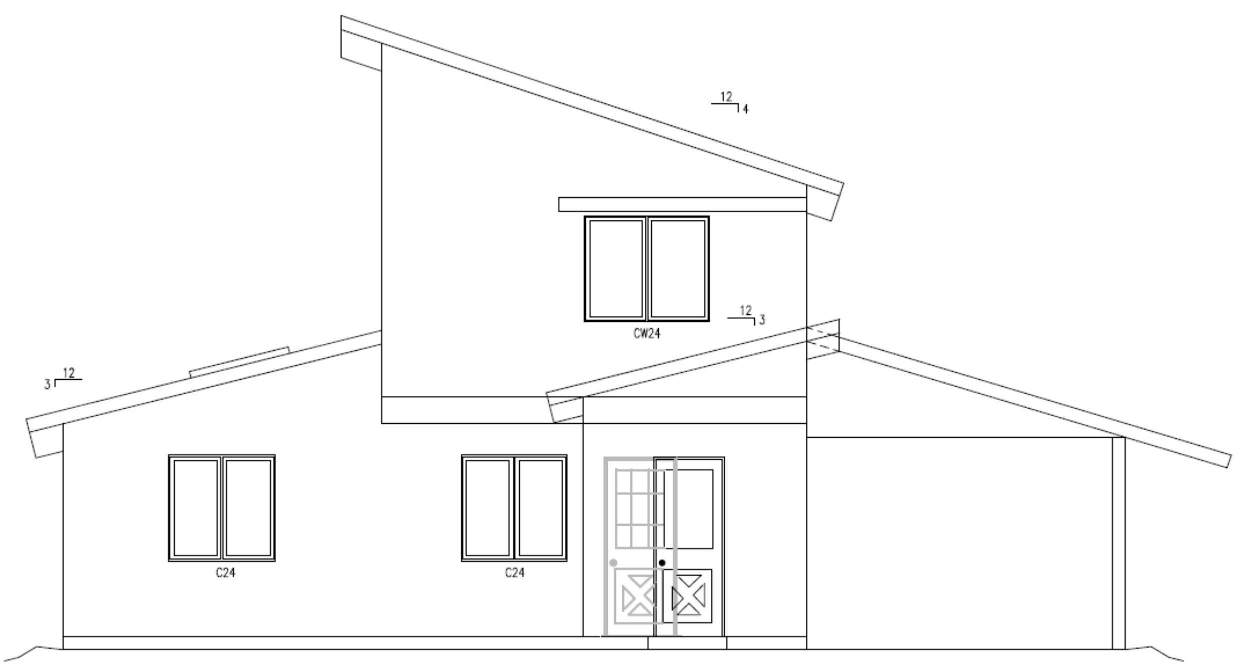


Figure 3. East Elevation for AAE House

Versatec Water-Source Heat Pump

Air Plenum (looking up towards top of house)

Supply Duct from Slab up to 2nd Floor

Supply Duct Leaving Bottom of Plenum (entering slab)

Supply duct leaving slab (South side, 1st floor)

Figure 4. HVAC System Details at Hyspot House

Figure 5. Evidence of Mold on the Main Door in the House (July 2007)

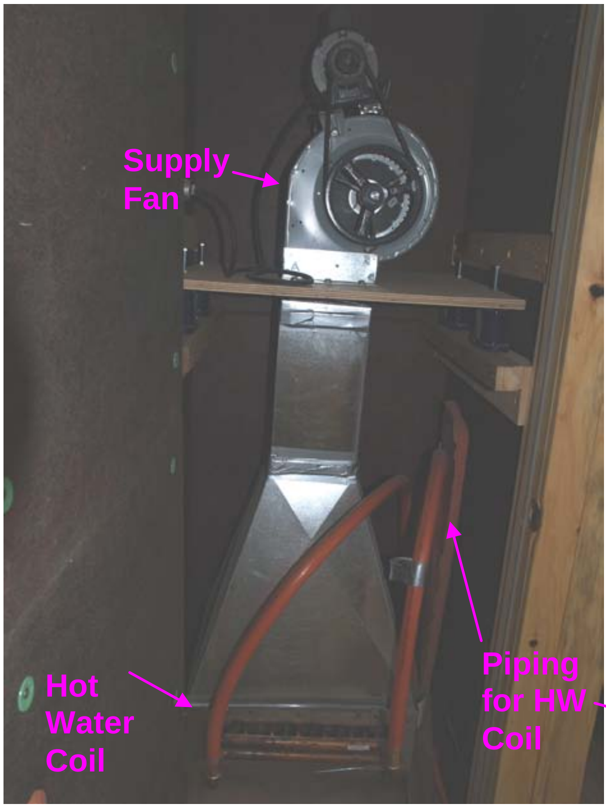
Kilmer House

The physical layout of the Kilmer house is identical to Hyspot house, except it has a 250 sq ft three-season room on the back (North) side of the house. This house is primarily heated by a wood stove in the main living area. During the second season, another wood stove was added in the three-season room and this became the primary heating source for the home.

The vertical air plenum in the house also has a supply fan, as well as a hot water (HW) coil, that heats the air entering the slab ductwork. This system was rarely or never used. The hot water tank is a 20-gallon electric water tank.

The house had a family with two adults and two children living in it for most of the monitoring period.

A blower door was used to measure the air tightness of the Kilmer house on May 27, 2008. The measured air tightness was approximately 1.1 air changes per hour at 50 Pa for the main part of the house. The equivalent leakage area (ELA) was calculated to be 19 sq in. See Appendix A for details of the blower door test.



Air Plenum with Supply Fan and HW Coil

Wood Stove in Main Part of Home

20-gallon DHW Tank

Figure 6. Photos of Kilmer House

Summary House Comparison

Table 1. Summary of Characteristics

	Hyspot	**Kilmer**
Floor Area	1,584 sq ft	1584 sq ft + 250 sq ft (three-season room)
Heating System	2½-ton Versatec Water-Source Heat Pump (Model VLV030)	Two Wood Stoves (main and three-season room) HW Coil in Plenum
Cooling System	Heat pump	none
Domestic Hot Water (DHW)	15 kW tankless	20 gallon electric tank
Equivalent Leakage Area	20 sq in	29 sq in (all areas)
ACH at 50 Pa	1.5	1.7 (all areas)

MONITORING APPROACH

The monitoring system was based around a Campbell Scientific CR10X data logger in both houses. The CR10X is a fully programmable, expandable logger capable of performing a variety of measurements and interfacing with many different types of sensors. The data logger sampled all sensors once per second and calculated averages and totals for each 15-minute record, as appropriate. The logger was called, and data was downloaded each night by phone modem. The data was loaded into a database at CDH Energy for automatic verification and processing.

Table 2 lists the measured data points and Figure 7 shows their locations at the Hyspot house. Table 3 lists the measured data points and Figure 8 shows their locations at the Kilmer house. Appendix B provides full details on the monitoring systems. The rational for installing these points is given below.

Energy Consumption

At both houses, whole house energy use (**WT**) and DHW energy use (**WDHW**) was measured with a power transducer. At Hyspot, the power use of the heat pump (**WHP**) and ground water pump (**WP**) were also measured.

Space and Duct Conditions

At both houses space conditions were measured at the top of the plenum, since all air was pulled to this point it was thought to represent average conditions. Sensors were installed to measure indoor temperature (**TAI**), indoor relative humidity (**RHI**), and the concentration of Carbon Dioxide (**CO2**). The temperature of air entering the floor slab (**TSE**) and leaving the in-floor ductwork (**TSL**) were also measured at both houses.

North and South Wall Temperatures

Sensors were installed on the inside of the sheathing in the stud cavities on both the North wall (**TWALL**) and South wall (**TWLS**). These points were intended to quantify the differences between the walls and determine if the impact of solar gains could be discerned. The outdoor temperature (**TAO**) was measured by putting a probe just outside the north wall at each house. No conclusive results resulted from the wall measurements.

Door Opening Sensor

At both houses a sensor was added to detect when the main door of the house was open or shut. The sensor was used to determine the number of door openings (**CDR**) and the duration (**SDR**) of each event.

Heat Pump Sensors (Hyspot)

In addition to power meters, a sensor was added to measure the temperature of water entering (**TCW**) and leaving (**TWO**) the heat pump at the Hyspot house.

Wood Stove Sensors (Kilmer)

At Kilmer a sensor was added to measure the temperature in the flue of the wood stove (**TEXH**). This sensor detected when the stove was used. Because of concerns that the wood stove might depressurize the house, a building pressure sensor was installed (**PB**). However this sensor was never able to consistently provide a realistic signal.

Table 2. Summary of Monitored Data Points – Hyspot House

Channel Type	Logger Channel	Name	Description	Eng Units	Instrument
Pulse	P1	WT	Total House Power	kWh/kW	Ohio Semitronics WL40R - 053
Pulse	P2	WDHW	Domestic Water Heater Power	kWh/kW	Ohio Semitronics WL40R - 049
Pulse	C6	SDR	Door Photo Sensor	min	Newark 89F1404/89F1401
Pulse	C6	CDR	Door Photo Sensor	count	Newark 89F1404/89F1401
Pulse	C7	WP	Well Pump Power	kWh/kW	Ohio Semitronics SWH - 2100
Pulse	C8	WHP	Heat Pump Power	kWh/kW	Ohio Semitronics SWH - 2100
Analog	A2	TCW	Water Entering Heat Pump	°F	Watlow Type T-TC
Analog	A3	TWLS	South Wall Sheathing Temperature	°F	Watlow Type T-TC
Analog	A4	TAI	Indoor Temperature	°F	Watlow Type T-TC
Analog	A5	TSE	Supply Temperature (into slab)	°F	Watlow Type T-TC
Analog	A6	TSL	Supply Temperature (from slab)	°F	Watlow Type T-TC
Analog	A7	TAO	Outdoor Temperature	°F	Watlow Type T-TC
Analog	A8	TWALL	North Wall Sheathing Temperature	°F	Watlow Type T-TC
Analog	A9	TWO	Water Leaving Heat Pump	°F	Watlow Type T-TC
Analog	A10	RHI	Indoor RH	%	Vaisala HMD60U
Analog	A11	CO2	Carbon Dioxide Concentration	ppm	Telaire Ventostat 8102

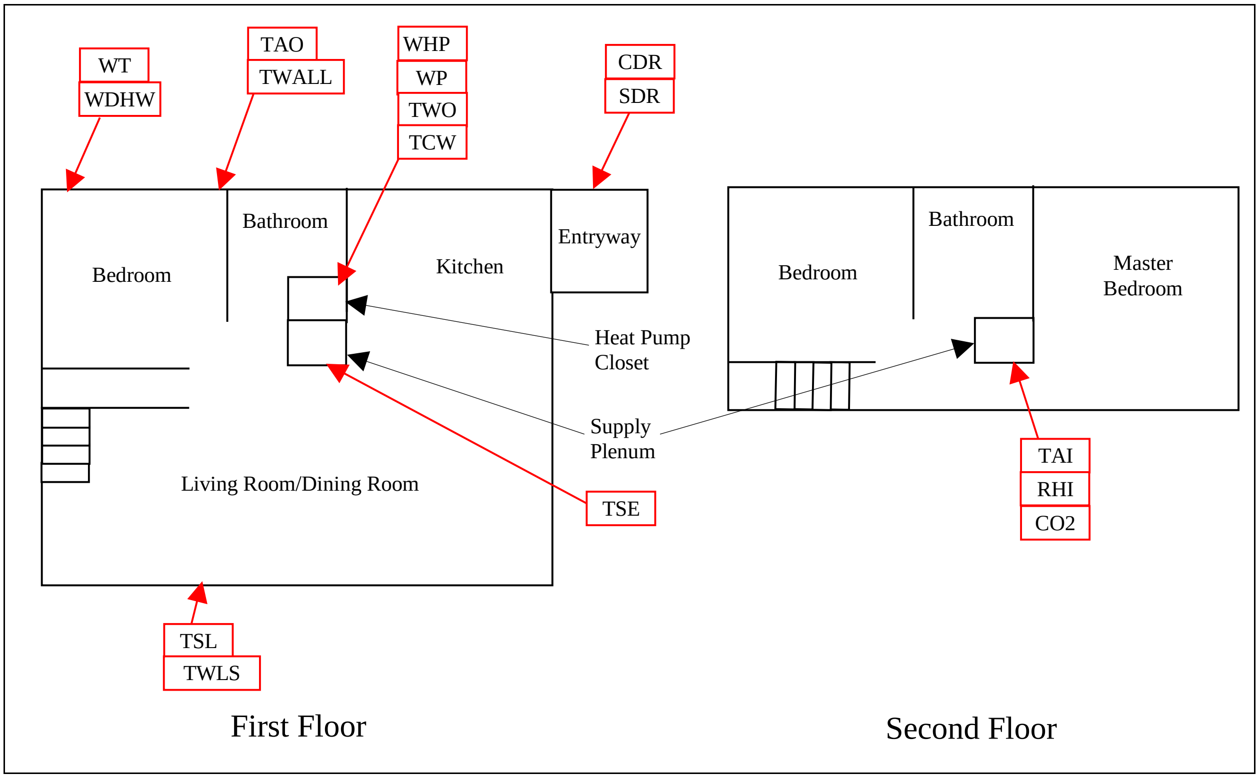


Figure 7. Sensor Locations in Hyspot House

Table 3. Summary of Monitored Data Points – Kilmer House

Channel Type	Logger Channel	Name	Description	Eng Units	Instrument
Pulse	P1	WT	Total House Power	kWh/kW	Ohio Semitronics WL40R - 053
Status	C1	SF	Supply Fan Status/Runtime	min	Veris H800
Status	C7	SDHW	Domestic Hot Water Heater Status/Runtime	min	Veris H800
Status	C8	SDR/CDR	Door Photo Sensor	min/count	Newark 89F1404/89F1401
Analog	A2	TWLS	South Wall Sheathing Temperature	^F	Watlow Type T-TC
Analog	A3	TAI	Indoor Temperature (at fan inlet)	^F	Watlow Type T-TC
Analog	A4	TSE	Supply Temperature (into slab)	^F	Watlow Type T-TC
Analog	A5	TSL	Supply Temperature (from slab)	^F	Watlow Type T-TC
Analog	A6	TAO	Outdoor Temperature	^F	Watlow Type T-TC
Analog	A7	TWALL	North Wall Sheathing Temperature	^F	Watlow Type T-TC
Analog	A8	TEXH	Temperature of Wood Stove Flue	^F	Watlow Type T-TC
Analog	A9	RHI	Indoor RH	%	Vaisala HMD60U
Analog	A10	CO2	Indoor CO_2	PPM	Ventostat 8102
Analog	A11	PB	Building Pressure	in	Setra 264
Analog	A12	TT	Tempering Tank Temperature	^F	Watlow Type T-TC

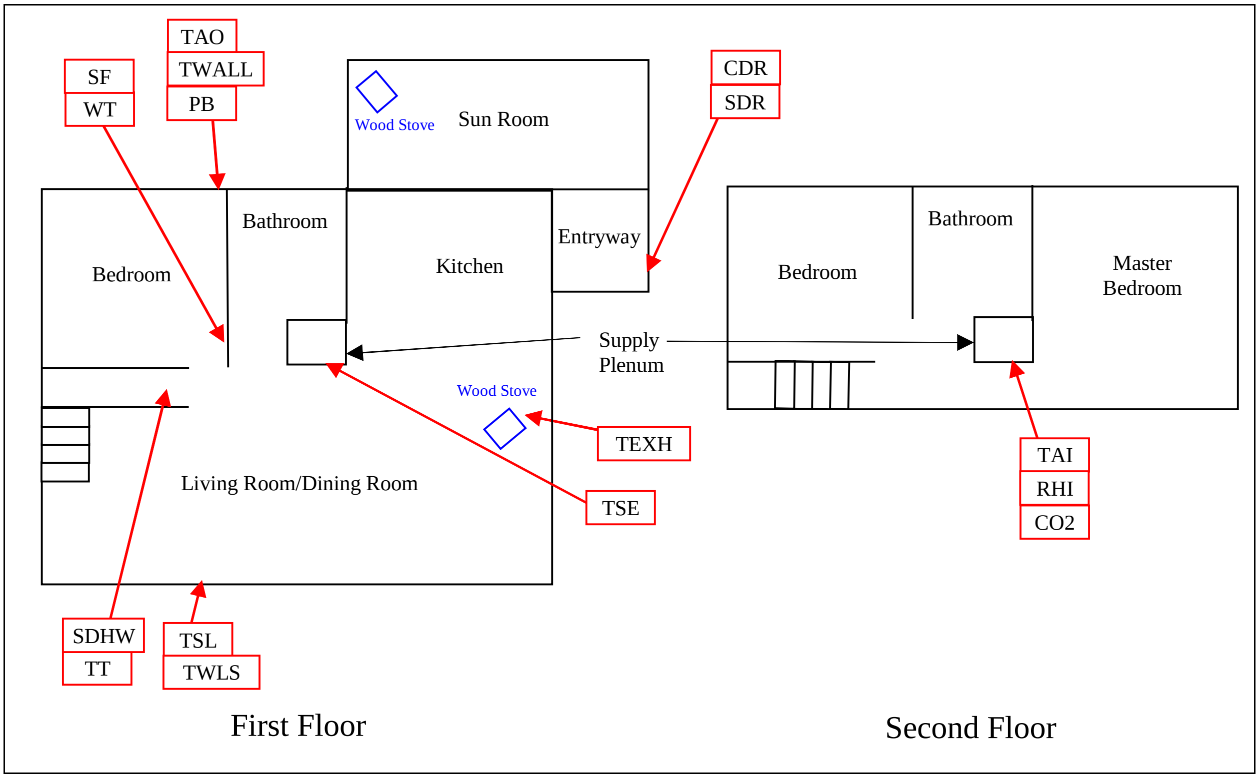


Figure 8. Sensor Locations in Kilmer House

Major Events During Monitoring Period

Table 4. Summary of Major Events During Monitoring Period - Hyspot

May 23, 2007

- All thermocouples installed
- Door Photo Sensor Installed
- 50 Amp CTs installed for Whole House Power and Domestic Water Heater Power
- RH and CO_2 sensors installed at top of Plenum
- Data Logger wired for Data Collection on installed points.

June 15, 2007

- Un-calibrated CO_2 sensor replaced with calibrated sensor.
- 100 Amp CTs installed to correct Total House Power Reading
- Heat Pump Power and Well Pump Power sensors installed and Heat Pump Power was verified.
- Supply fan power read for Heat Pump Statuses.
- Phone line connected and capability to collect data via modem was verified.
- Official data collection begins.

July 17, 2007

- Replaced CO_2 sensor with original sensor (now calibrated).
- 100 Amp CT installed to correct Domestic Water Heater Power. Measurement was verified.
- Attempted to install Heating, Cooling and Supply Fan statuses but determined it's not feasible due to unit/thermostat wiring.
- Performed Blower Door Test.

July 30, 2007

- CDH suggested that homeowners open a window for ventilation

January 15, 2010

- Time Delay Relay added by AAE staff to hold heat pump on for at least two hours

August 5, 2010

- End of data collection

Table 5. Summary of Major Events During Monitoring Period - Kilmer

May 29, 2007
- All thermocouples installed, except for Tempering Tank Temperature
- Wire for Door Photo Sensor Run to Entryway door.
- RH and CO_2 sensors installed at top of Plenum.

August 10. 2007
- 50 Amp CTs installed for Whole House Power.
- Status Sensor installed for Supply Fan.
- Data Logger wired for Data Collection on installed points.

May 27, 2008
- Installed Building Pressure, Tempering Tank Temperature
- Fused Power Transducers and connected CTs. Installed 50Amp CT for Domestic Water Heater Power.
- Performed Blower Door Test.
- Official data collection begins.

August 11, 2008
- Replaced CT on Total House Power.
- Replaced DHW power transducer with DHW status sensor.
- Remote communications established.

October 7, 2009
- AAE staff installed energy-efficient DC motor with controls to vary speed based on stratification (based on shaft, outdoor and slab temperatures)

August 5, 2010
- End of data collection

MEASURED DATA – HYSPOT HOUSE

Data collection at the Hyspot House officially began on July 17, 2007. During the previous two site visits the data logger and most sensors were installed. This section primarily analyzes the data gathered from 07/17/2007 to 12/31/2009. Some 2010 data is also included in the analysis.

Energy Use Summary

Table 6 shows the total monthly electric use for the Hyspot house, including Domestic Hot Water (DHW), the Heat Pump unit and other loads. Space heating and cooling only account for about 2,500 kWh per year, or about $330 in this house. The DHW represents about 950 kWh, or about $125 per year. The implied hot water use (inferred from the energy input) in this two person home is only about 15 gallons per day[1]. The remaining energy use for lights and appliances is 7,200 to 7,500 per year.

[1] A family of four is typically assumed to use about 60 gallons per day.

Table 6. Monthly Electric Use Over the Monitoring Period

Date	Percentage of Good Data (%)	Total Heat Pump Electric Use (kWh)	DHW Heater Electric Use (kWh)	Other Electric Use (kWh)	Total House Peak Demand (kW)	Total House Electric Use (kWh)
Jul 2007	100%	363.0	44.2	681.2	26.5	1,089
Aug 2007	100%	237.1	85.7	622.2	11.1	945
Sep 2007	100%	145.6	52.6	526.5	7.4	725
Oct 2007	100%	44.8	50.1	434.8	19.0	530
Nov 2007	100%	269.9	79.7	566.3	26.6	916
Dec 2007	100%	485.8	106.5	830.8	26.6	1,423
Jan 2008	100%	477.7	93.6	910.9	20.6	1,482
Feb 2008	100%	445.8	77.6	836.5	25.0	1,360
Mar 2008	100%	315.5	91.3	711.4	25.0	1,118
Apr 2008	100%	62.1	77.8	450.0	23.8	590
May 2008	100%	44.8	83.5	460.5	21.1	589
Jun 2008	100%	121.0	77.9	677.4	24.8	876
Jul 2008	*100%*	*104.7*	*54.5*	515.3	8.0	674
Aug 2008	*97%*	*37.8*	*54.0*	390.8	6.5	483
Sep 2008	*100%*	*48.4*	*68.5*	427.6	27.8	545
Oct 2008	*100%*	*98.8*	*63.6*	592.0	9.0	754
Nov 2008	*100%*	*286.2*	*91.9*	747.4	27.5	1,126
Dec 2008	*100%*	*488.4*	*99.3*	841.9	23.1	1,430
Jan 2009	*100%*	*571.5*	*102.1*	867.0	10.4	1,541
Feb 2009	*100%*	*367.6*	*109.9*	729.4	29.1	1,207
Mar 2009	*100%*	*286.8*	*98.4*	704.0	26.7	1,089
Apr 2009	*100%*	*124.0*	*80.2*	609.8	20.6	814
May 2009	*100%*	*49.9*	*75.1*	586.5	10.4	711
Jun 2009	*100%*	*23.2*	*66.9*	351.5	28.1	442
Jul 2009	*100%*	*0.0*	*73.4*	357.8	22.2	431
Aug 2009	*100%*	*135.5*	*65.1*	400.3	9.6	601
Sep 2009	*100%*	*9.3*	*64.9*	342.9	6.8	417
Oct 2009	*100%*	*214.3*	*75.7*	470.0	15.8	760
Nov 2009	*100%*	*171.6*	*73.5*	676.1	10.2	921
Dec 2009	*100%*	*556.0*	*91.8*	1,170.3	14.2	1,818
Jan 2010	*100%*	*602.9*	*99.2*	1,148.6	23.8	1,851
Feb 2010	*100%*	*523.4*	*64.3*	991.4	12.3	1,579
Mar 2010	*100%*	*289.6*	*87.0*	855.7	9.6	1,232
Apr 2010	*100%*	*114.4*	*83.3*	1,140.0	26.5	1,338
May 2010	*100%*	*305.1*	*79.7*	775.1	18.6	1,160
Jun 2010	*100%*	*361.9*	*58.3*	486.2	9.1	906
Jul 2010	*100%*	*488.9*	*64.7*	556.7	9.9	1,110
Annual 2008	**100%**	**2,531**	**934**	**7,562**	**27.8**	**11,026**
Annual 2009	**100%**	**2,510**	**977**	**7,266**	**29.1**	**10,752**

Table 7 shows a breakdown of the heat pump electric use for the compressor in heating and cooling modes and for the supply fan. Heating operation of the compressor accounts for the majority of the heat pump power use while there is fairly modest energy use for cooling. The months with highest cooling energy use for the monitoring period was July 2007 with 363 kWh and then June and July 2010. The energy use for these months was evenly split between the compressor and fan because the fan was set to run continuously. The extra heat added by the supply fan resulted in the high compressor energy use. In August 2007 and then for the Summer of 2008 the fan was set to cycle on and off with the compressor, so overall cooling energy use was much lower in these periods.

Table 7. Breakdown of Monthly Electric Use for the Heat Pump

Date	Compressor Cooling Electric Use (kWh)	Compressor Heating Electric Use (kWh)	Supply Fan Electric Use (kWh)	Total Heat Pump Electric Use (kWh)
Jul 2007	181.0	0.4	179.5	363.0
Aug 2007	182.0	2.8	48.2	237.1
Sep 2007	57.0	20.2	65.3	145.6
Oct 2007	2.7	25.1	16.9	44.8
Nov 2007	0.0	217.2	52.6	269.9
Dec 2007	0.0	391.1	94.6	485.8
Jan 2008	1.1	384.3	92.1	477.7
Feb 2008	0.0	359.5	86.1	445.8
Mar 2008	0.0	254.2	61.2	315.5
Apr 2008	0.0	49.9	12.2	62.1
May 2008	3.9	32.0	8.9	44.8
Jun 2008	90.9	0.0	28.6	121.0
Jul 2008	76.0	0.0	25.0	104.7
Aug 2008	23.0	0.0	7.8	37.8
Sep 2008	31.1	0.0	10.3	48.4
Oct 2008	0.0	78.8	19.4	98.8
Nov 2008	0.0	230.6	55.5	286.2
Dec 2008	0.0	393.3	94.9	488.4
Jan 2009	0.0	462.5	108.8	571.5
Feb 2009	0.0	297.6	69.9	367.6
Mar 2009	0.0	232.2	54.6	286.8
Apr 2009	0.0	99.4	24.5	124.0
May 2009	17.6	20.3	11.0	49.9
Jun 2009	16.5	0.7	5.5	23.2
Jul 2009	0.0	0.0	0.0	0.0
Aug 2009	98.7	2.1	31.2	135.5
Sep 2009	2.7	4.4	2.1	9.3
Oct 2009	25.4	144.7	42.0	214.3
Nov 2009	0.0	137.9	33.6	171.6
Dec 2009	0.0	449.3	106.7	556.0
Jan 2010	0.0	419.2	183.5	602.9
Feb 2010	0.0	310.2	213.2	523.4
Mar 2010	0.0	138.3	151.1	289.6
Apr 2010	0.1	37.9	76.4	114.4
May 2010	60.8	9.6	234.6	305.1
Jun 2010	131.4	0.0	230.3	361.9
Jul 2010	245.2	3.0	240.3	488.9
Annual 2008	**226**	**1,782**	**502**	**2,531**
Annual 2009	**161**	**1,851**	**490**	**2,510**

Table 8 shows the same data as Table 7 but grouped by season. The table also includes runtimes in the heating and cooling modes. On an annual basis the home uses about 7 kWh per square foot per year. Table 9 and Figure 9 summarize the annual breakdown.

Table 8. Summary of Electric Use by Season or Quarter

Season	Total Heat Pump Electric Use (kWh)	Supply Fan Electric Use (kWh)	DHW Heater Electric Use (kWh)	Total Cooling Runtime (hrs)	Total Heating Runtime (hrs)	Total House Electric Use (kWh)	Electric Use per Square Foot (kWh/ft^2)
Summer 2007	745.7	293.0	182.5	322.4	14.4	2,758.2	1.78
Fall 2007	800.5	164.1	236.3	2.6	409.3	2,868.7	1.85
Winter 2008	1,238.9	239.5	262.6	0.9	644.1	3,960.3	2.56
Spring 2008	227.9	49.7	239.2	75.1	52.8	2,055.0	1.33
Summer 2008	190.9	43.0	177.0	105.5	0.0	1,701.6	1.10
Fall 2008	873.4	169.8	254.8	0.0	453.4	3,309.6	2.14
Winter 2009	1,225.9	233.4	310.4	0.0	637.9	3,836.6	2.48
Spring 2009	197.1	41.1	222.2	27.5	78.2	1,967.0	1.27
Summer 2009	144.8	33.4	203.4	80.5	4.1	1,449.3	0.94
Fall 2009	941.9	182.3	241.0	20.0	471.4	3,499.4	2.26
Annual 2008	**2,531.1**	**502.0**	**933.6**	**181.5**	**1,150.3**	**11,026.4**	**7.12**
Annual 2009	**2,509.7**	**490.2**	**977.0**	**128.0**	**1,191.6**	**10,752.3**	**6.95**

Table 9. Summary of Annual Electric Use and Costs

	Energy Use (kWh)				
	Cooling	Heating	DHW	Other	Total
2008	285	2,246	934	7,562	11,026
2009	201	2,309	977	7,266	10,752
	Costs				
	Cooling	Heating	DHW	Other	Total
2008	$37	$292	$121	$983	$1,433
2009	$26	$300	$127	$945	$1,398
	Percentage				
	Cooling	Heating	DHW	Other	Total
2008	3%	20%	8%	69%	100%
2009	2%	21%	9%	68%	100%

Note: Assuming $0.13 per kWh

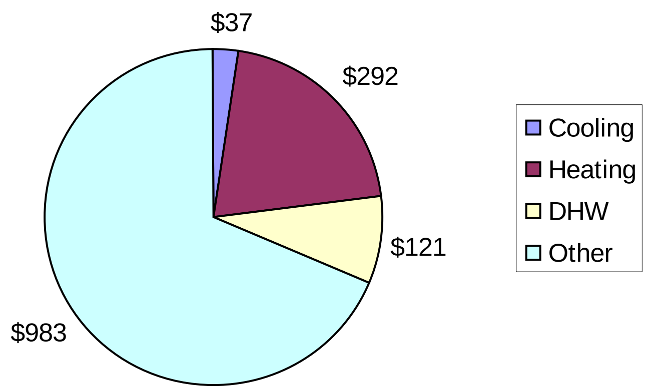


Figure 9. Breakdown of Annual Electric Costs (at $0.13/kWh)

Overall Performance Trends

Figure 10 includes shade plots that show the runtimes for the supply fan, the cooling mode, and the heating mode. The shade plot qualitatively denotes the operation with shades of gray. Each day is represented as a vertical stripe on the plot. Successive days are denoted along the x-axis. Missing data are shown as white.

The runtime of the equipment is inferred from the heat pump power data along with the air temperatures entering and leaving the heat pump. When the air leaving the heat pump is warmer than the inlet, and consuming power, the heat pump is in heating. The opposite temperature difference criteria is used to determine cooling. Periods with modest power use are attributed to supply fan operation.

The supply fan operated continuously from June through July 22nd in 2007 and then briefly in September 2007 (and then again starting in January 2010).

During the cooling season, the heat pump operates primarily during the day. The heat pump operates frequently during night time hours in the heating season.

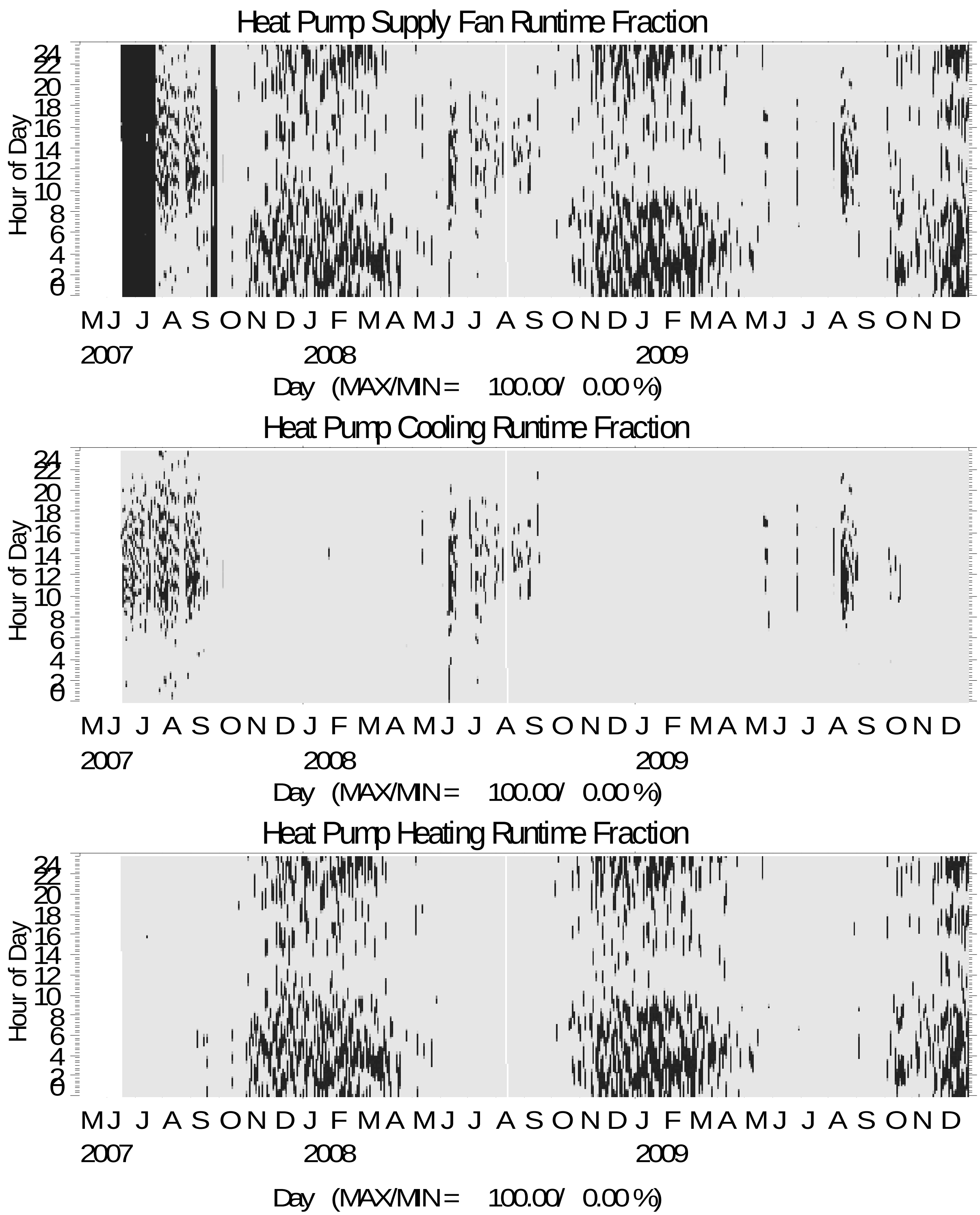


Figure 10. Shade Plots of Heat Pump Supply Fan, Heating and Cooling Runtime Fractions

The heat pump in this house forces supply air through air ducts that are embedded in the concrete slab. Figure 11 shows a plot of the temperature difference through the slab with respect to ambient temperature. In either heating or cooling, the temperature difference is typically 10°F.

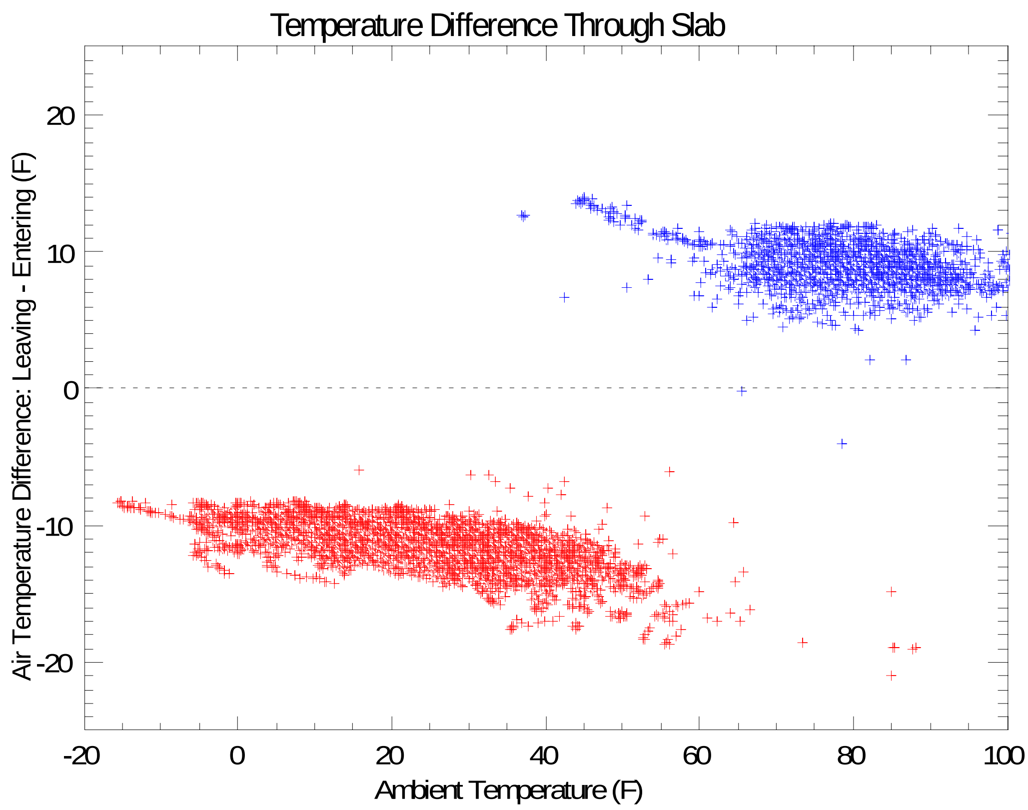


Figure 11. Temperature Difference Leaving and Entering the Slab during Heat Pump Operation

Figure 12 shows the load line for total house power. The rise in electric use associated with both heating and cooling is evident. The data shows a change point in the electric use at 62.9°F. The load line slope for the house is 1.03 kWh/°F-day for cooling and 0.806 kWh/°F-day for heating. The scatter of the heating data is might be due to occupant behavior (e.g., hot tub use).

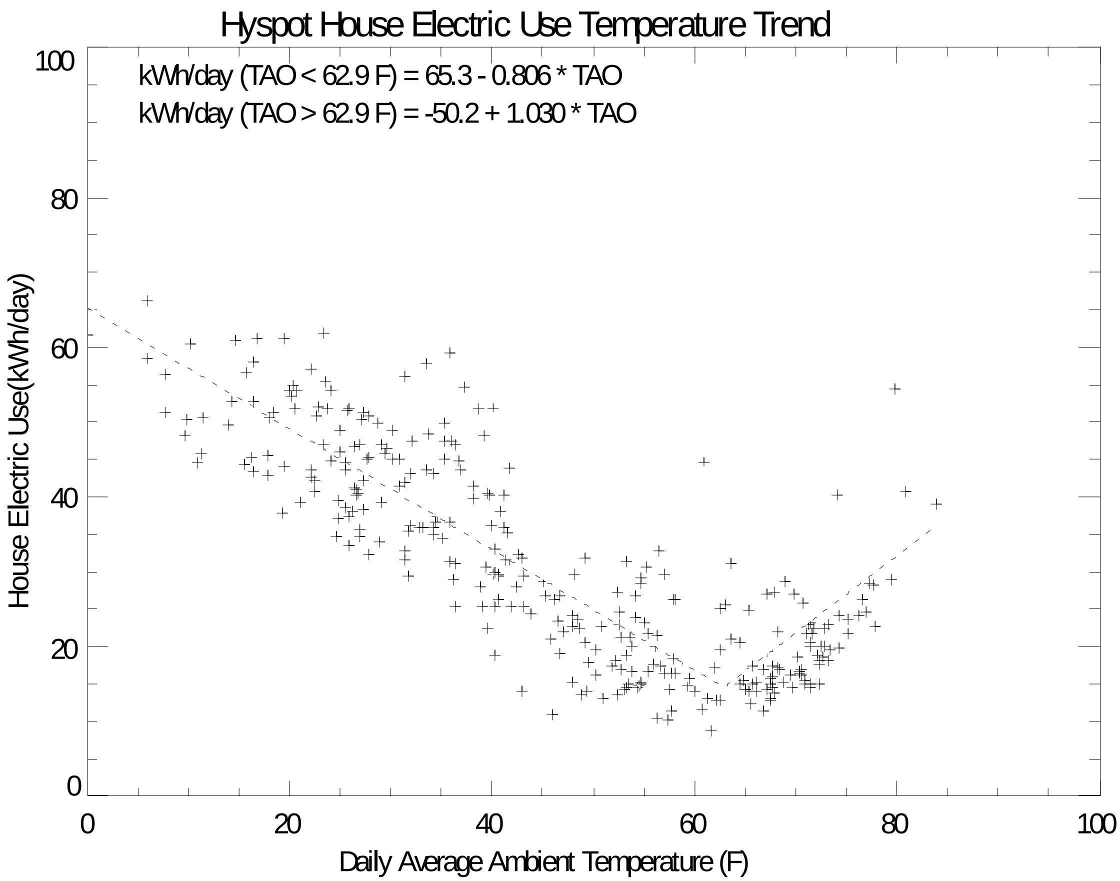


Figure 12. Load Line for Hyspot House

Cooling Operation

Figure 13 shows the Cooling Runtime for the Hyspot house. The house is operated to generally require cooling above 60° F ambient, though there is considerable scatter. There were several days with more than 8 hours of runtime. The maximum runtime was 11.5 hours. These peak runtime occurred during days where the average temperature exceeded 75°F.

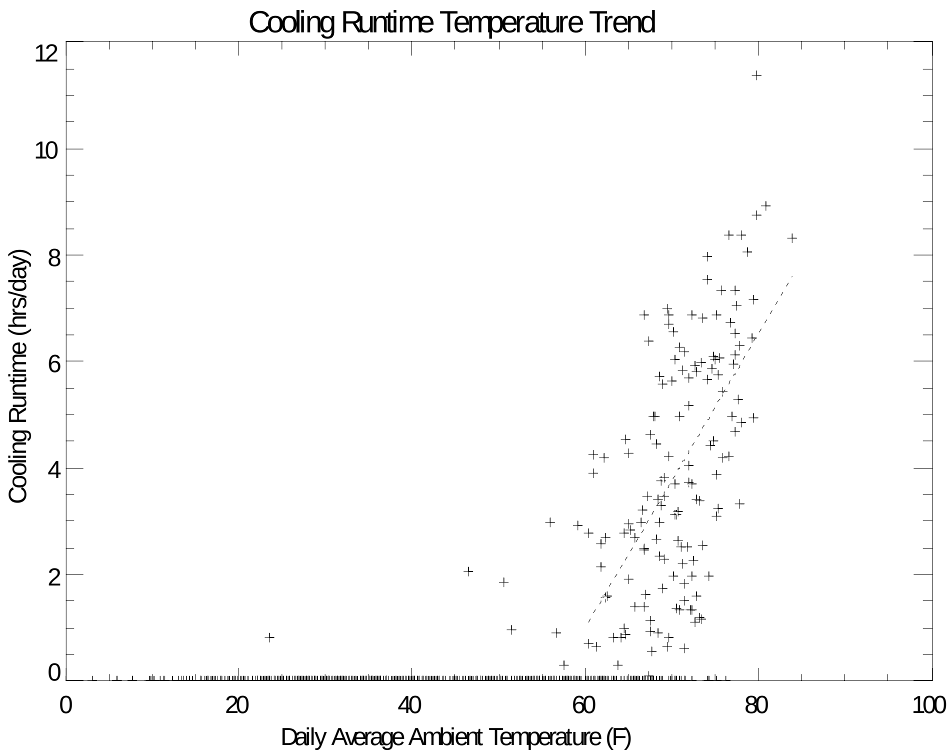


Figure 13. Cooling Runtime Load Line

Figure 14 shows operating conditions for the peak day for the summer of 2007 (August 2). The temperature rose from a morning low of 76°F to an afternoon high of 96°F[2]. The heat pump operated for 8.25 hours on this day. During this period, the supply temperature at the supply vents (out of the slab) was typically 55°F and the temperature leaving the heat pump (into the slab) was 47°F. The temperature entering the heat pump, which is pulled from the top of the house, was about 77°F. The dew point in the house was about 50-60°F for this day.

[2] Not counting the hours when the sun hit the temperature sensor in the late afternoon.

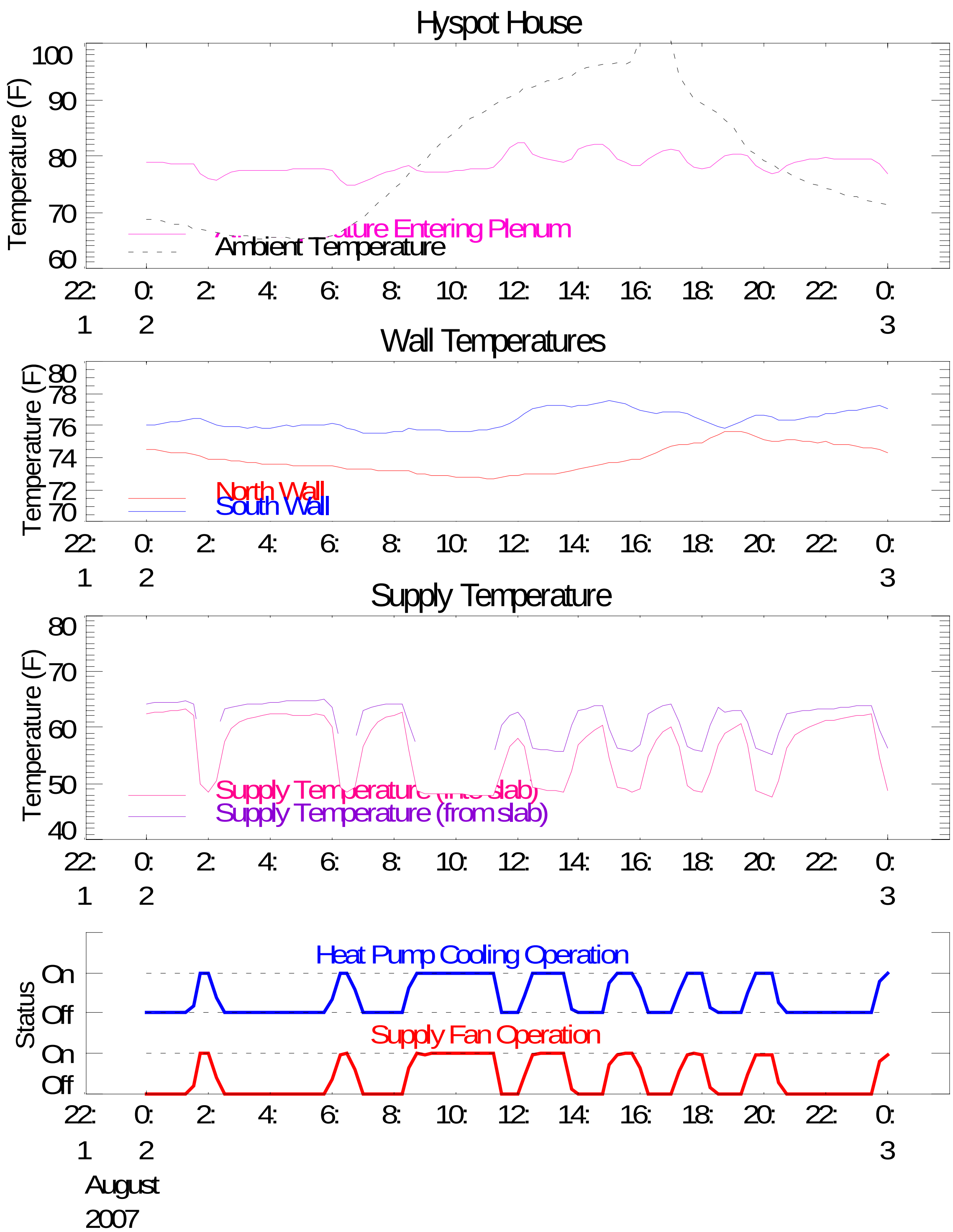


Figure 14. Peak Day Cooling Profile: August 2, 2007

Figure 15 shows the same data for July 10, 2007, a similarly hot day when the controls were set for constant fan operation. There is very little variation in the supply plenum temperature with constant fan operation as the air in the house is well circulated. During the compressor off periods from 3 to 6 pm, there is evidence of stored cooling in the slab (i.e., the temperature leaving the slab was lower than the entering temperature).

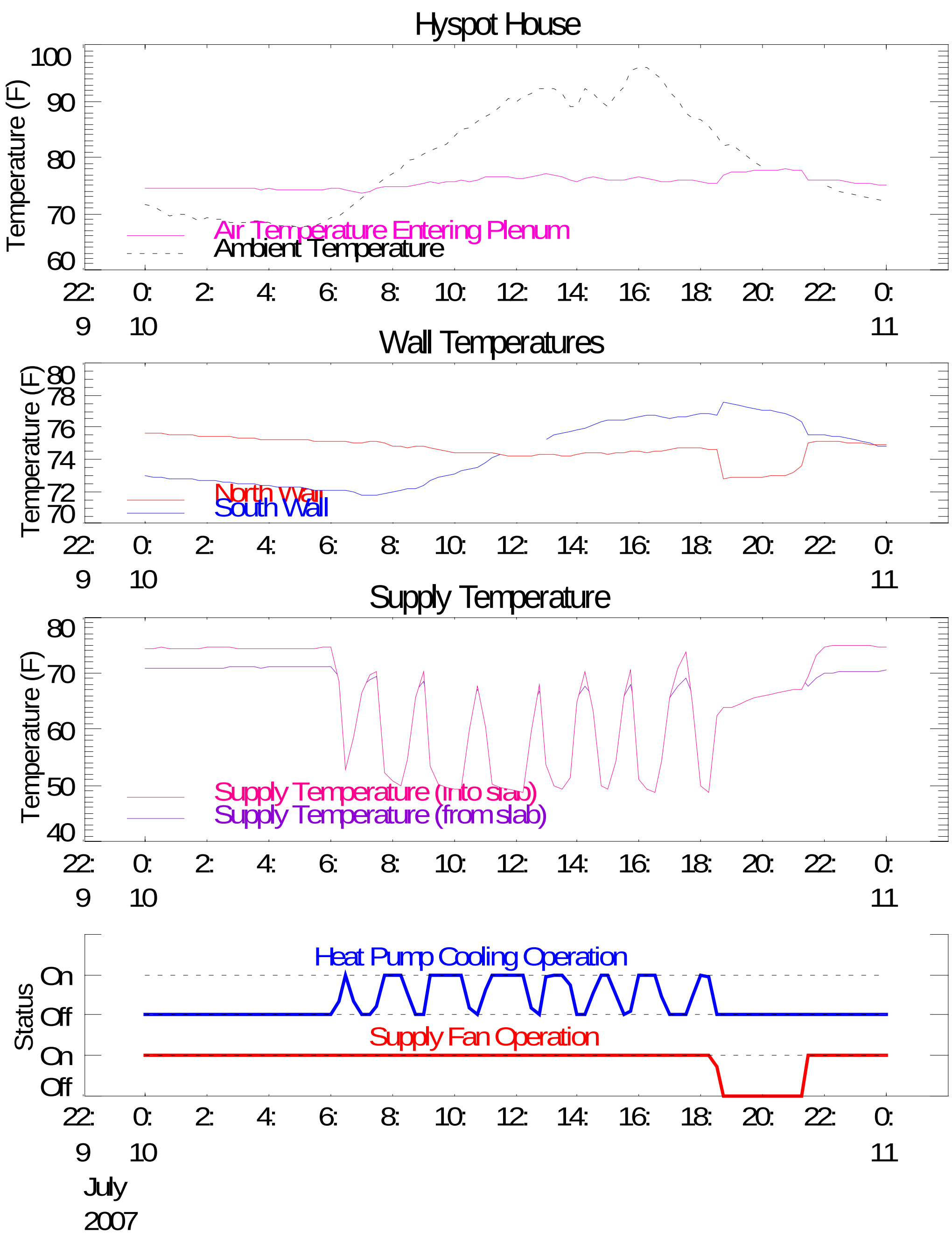


Figure 15. Peak Day Cooling Profile with Constant Fan Operation: July 10, 2007

Heating Operation

Figure 16 shows the variation of heating runtime with ambient temperature for the Hyspot house. The house needs heating below 60°F. On the coldest days the heat pump ran for nearly 15 hours. There is considerable scatter, possibly due to operation of a whirlpool tub or other occupant behaviors. The maximum heating operation day occurred on a weekend when the occupants were home for the entire day.

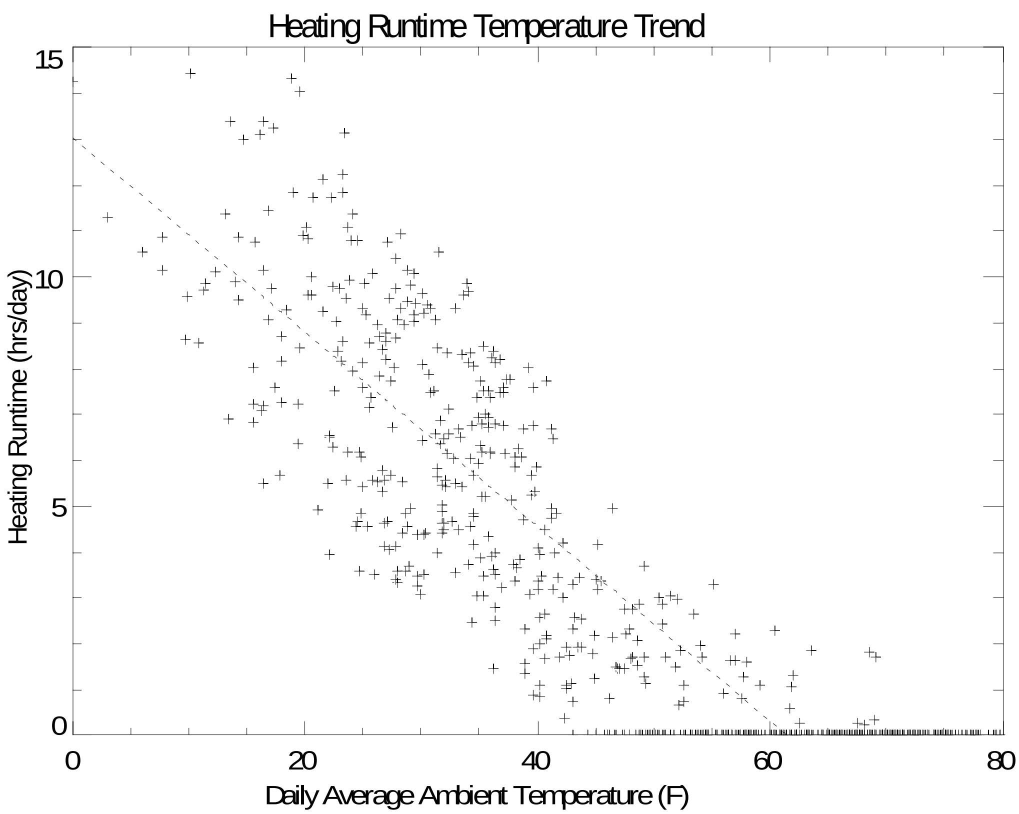


Figure 16. Heating Runtime Load Line

Figure 17 shows the heat pump operation and various house temperature sensors on January 23, 2008, when ambient temperature dropped to -8°F. The supply temperature into slab was 96°F and the exit temperature was 84°F during heat pump operation (i.e., a 12°F drop through the slab). This heat was eventually released to home as radiation (and convection) from the floor.

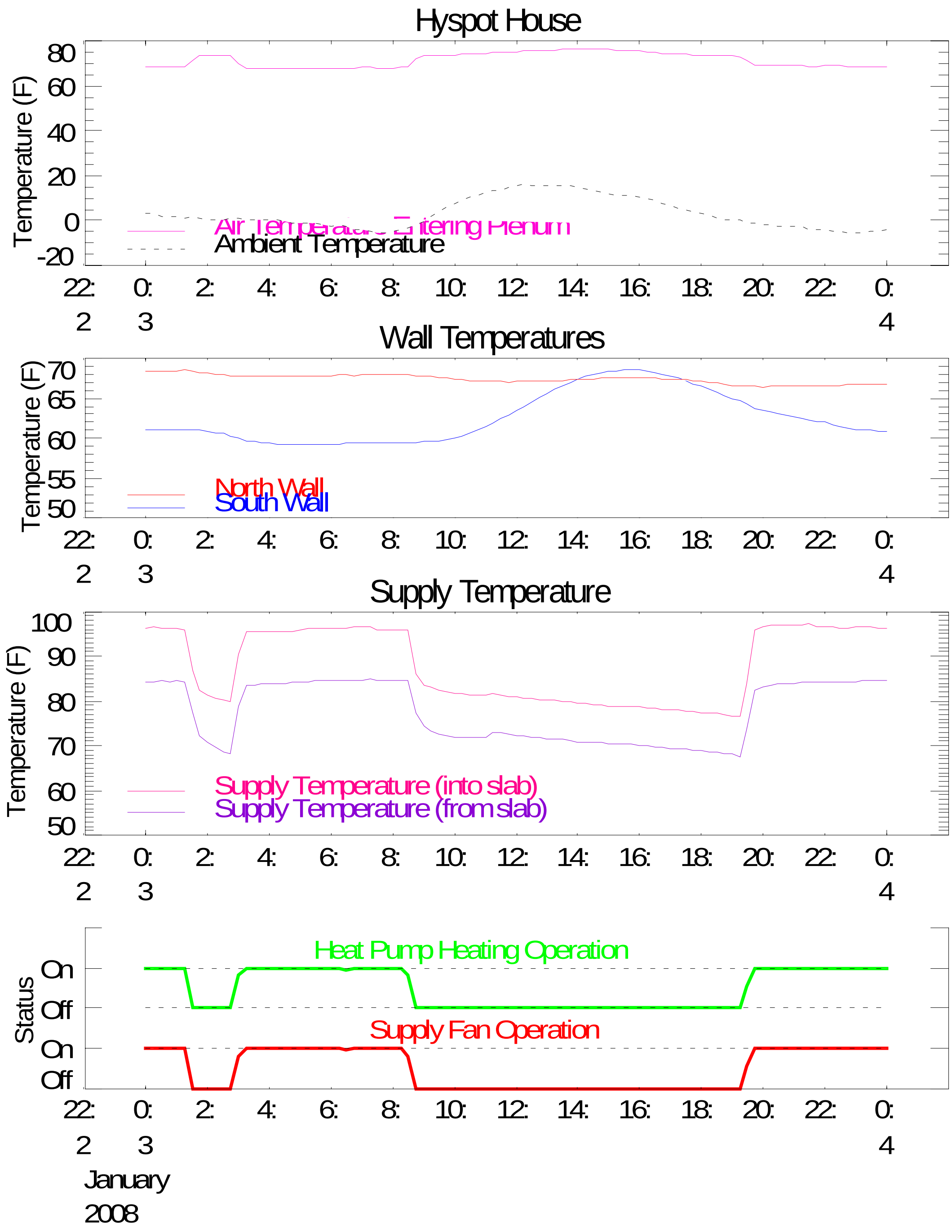


Figure 17. Peak Heating Profile: January 3, 2008

Humidity Trends

Summertime humidity control was reasonably good except when the supply fan was operated continuously. Operation of air conditioners in the constant fan mode has been shown to result in poor dehumidification performance[3] Figure 18 shows the indoor-outdoor humidity comparison for the house throughout the year. The indoor humidity varies slightly across the year: from a low of 50 gr/lb in the winter to a high of 85 gr/lb in the summer when the house is in the cooling mode. Data for constant supply fan operation are shown as a different color on the plot (red). The indoor humidity was typically much higher with constant fan operation due to off-cycle moisture evaporation from the evaporator coil. Indoor humidity decreases very little in the winter because of occupants in the space. This confirms that there is very little infiltration (or ventilation) to remove moisture from the space.

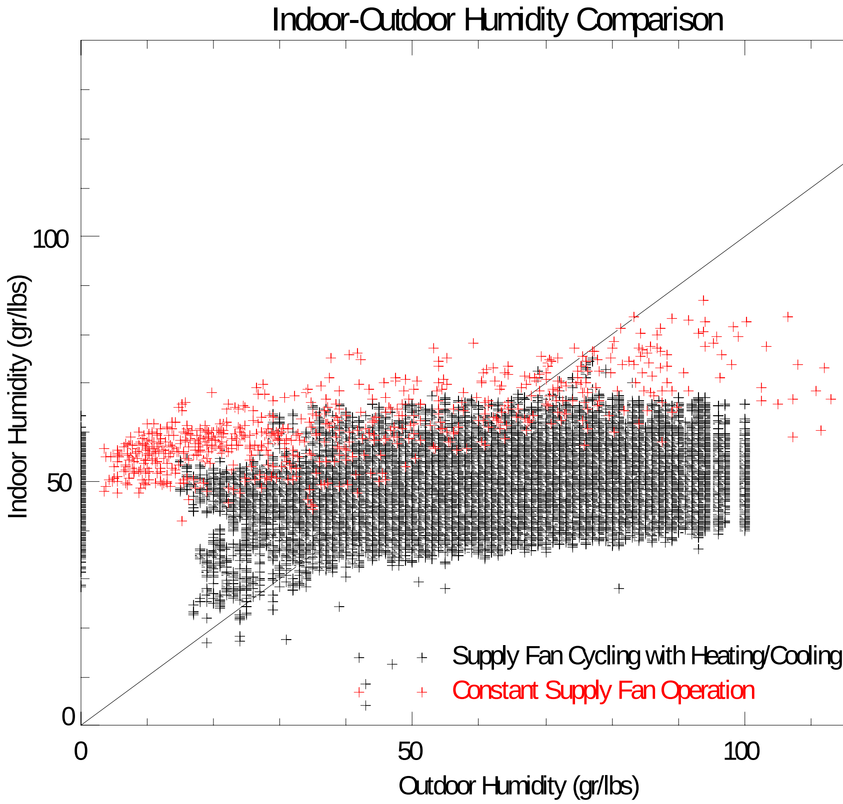


Figure 18. Comparison of Indoor and Outdoor Humidity Levels

[3] Moisture stored on the cooling coil evaporates back into the air stream when the compressor cycles off but the fan stays on. See the summary article: Shirey, D. and H.I. Henderson. 2004. 'Dehumidification at Part Load. ASHRAE Journal. Vol. 46, No. 4. April. (http://www.fsec.ucf.edu/en/publications/pdf/FSEC-GP-151-06.pdf). The full research report is available at http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1537-05.pdf.

In wintertime, the humidity remained high for all three years of monitoring period. Figure 19 shows the humidity in the house for January and February of 2008, 2009, and 2010. The second year humidity levels were lower than the first year, which might imply that moisture introduced during construction was being released from interior wood finishes during the first winter of occupancy. However, the humidity increases back up again for the 3rd year, which seems to imply that other factors might have a larger impact on space humidity levels. The periodic spikes may be related to the operation of the whirlpool tub.

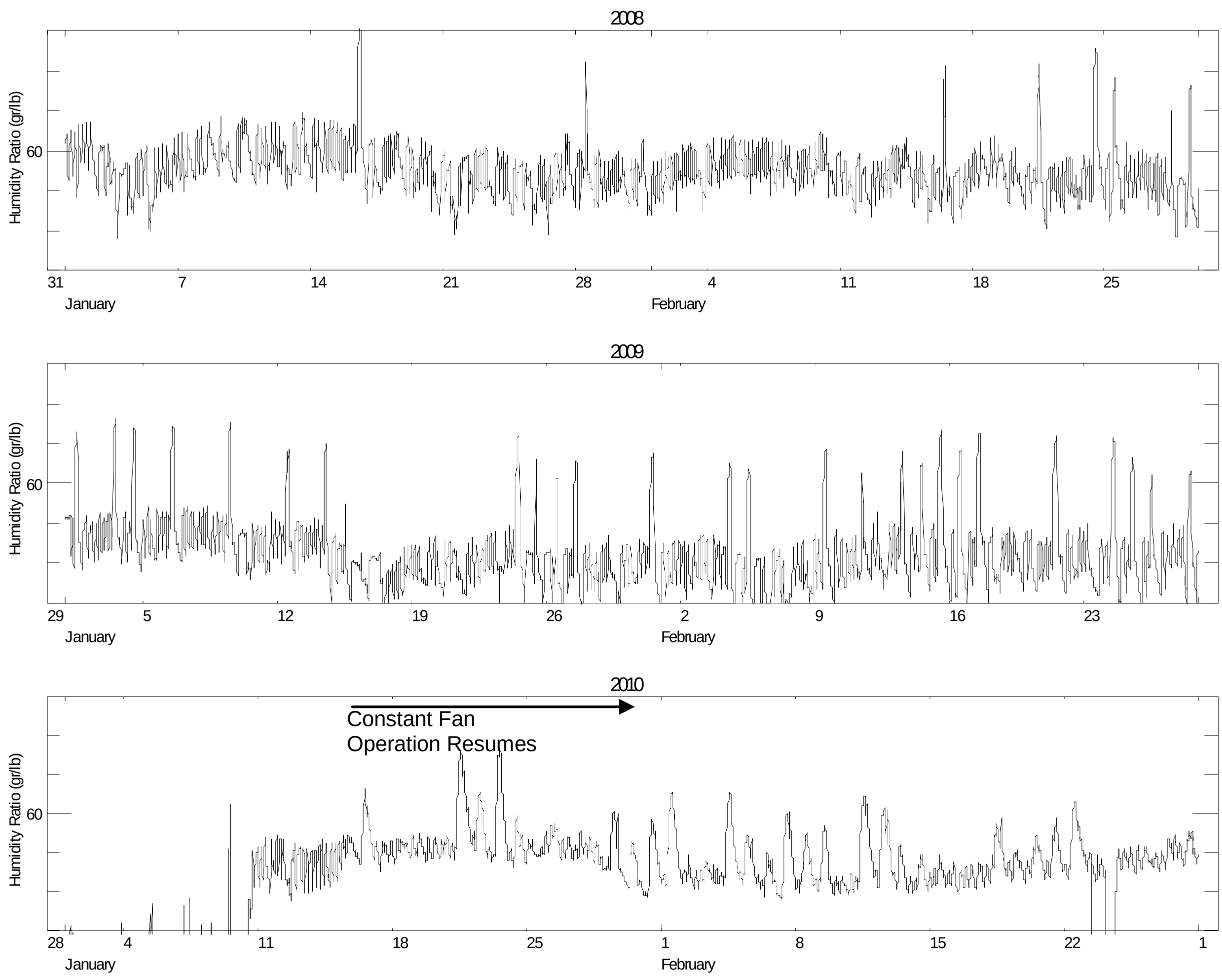
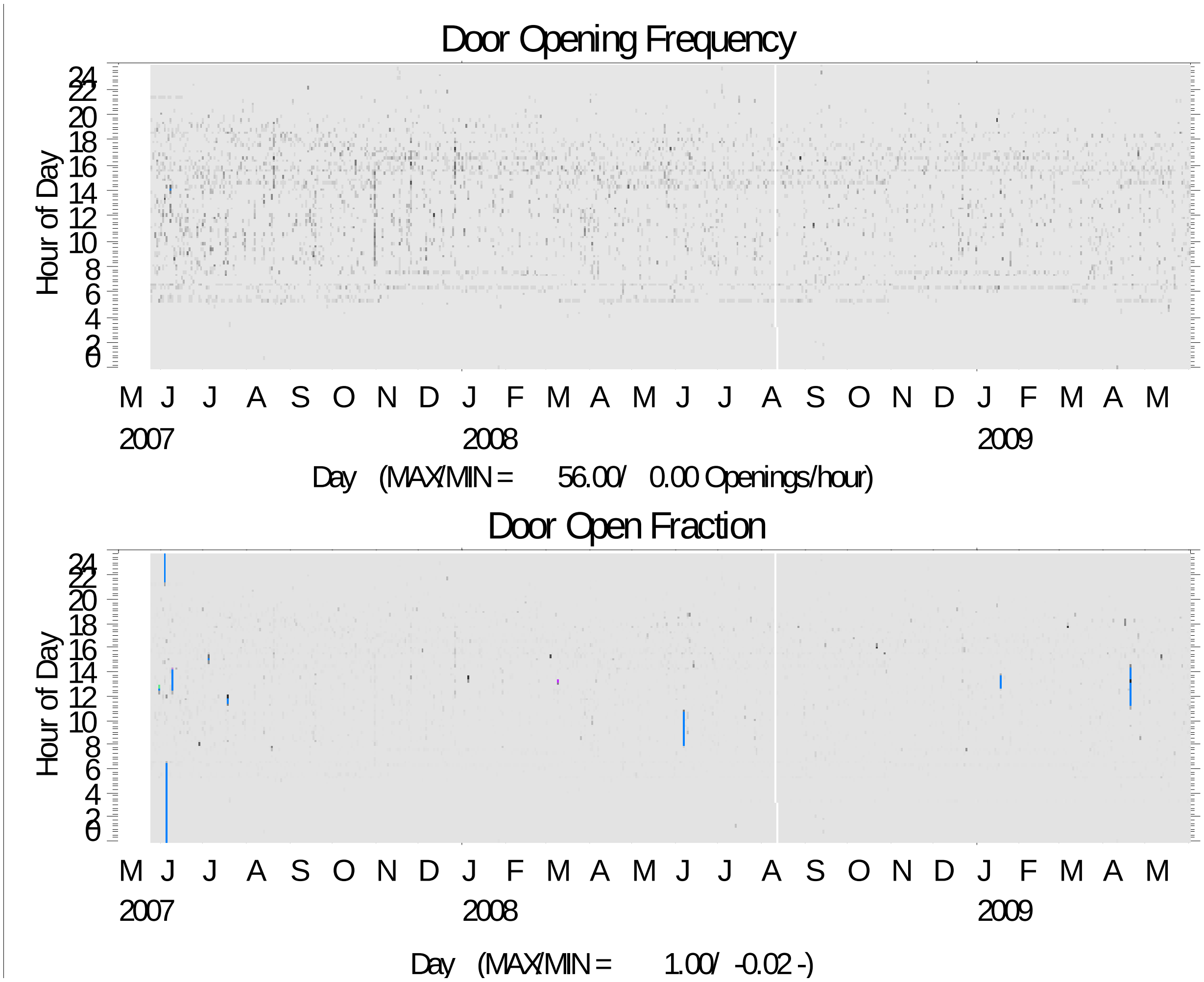


Figure 19. Comparing Space Humidity Levels for Three Different Winters

Door Openings and Carbon Dioxide Levels

A sensor was installed to measure when the main door was open. This data was used to determine the number of door openings and also the total time the door was open. The shade plots in Figure 20 qualitatively show this data. There are consistent door openings at 5 am and 7 am each day, corresponding with one occupant arriving home from the night shift and the other leaving for the day shift. From November through March both morning door openings move back approximately one hour, due to the shift in daylight savings time. There are typically some openings throughout the day, though they begin to decrease after 4 pm. The door opening fraction is zero for most of the time with only a few isolated periods where the door is open for a prolonged period (probably because the door was slightly ajar).



FigurH 0. 6hade Plots of Door Opening Frequency and Closed Fraction

Figure 21 shows the carbon dioxide level plotted against the duration of door openings. The plot implies that the door activity has very little impact of the amount of fresh air entering the space – as evidenced by the lack of any trend with CO_2 levels. If more fresh air were provided by the door activity we would expect CO_2 levels to approach ambient levels of approximately 370 ppm. Similarly, the number of door openings, shown in Figure 22, did not show a discernible impact on CO_2 levels. CO_2 levels were often "pegged" at the sensor's upper limit of 2000 ppm due to the lack of ventilation in this house.

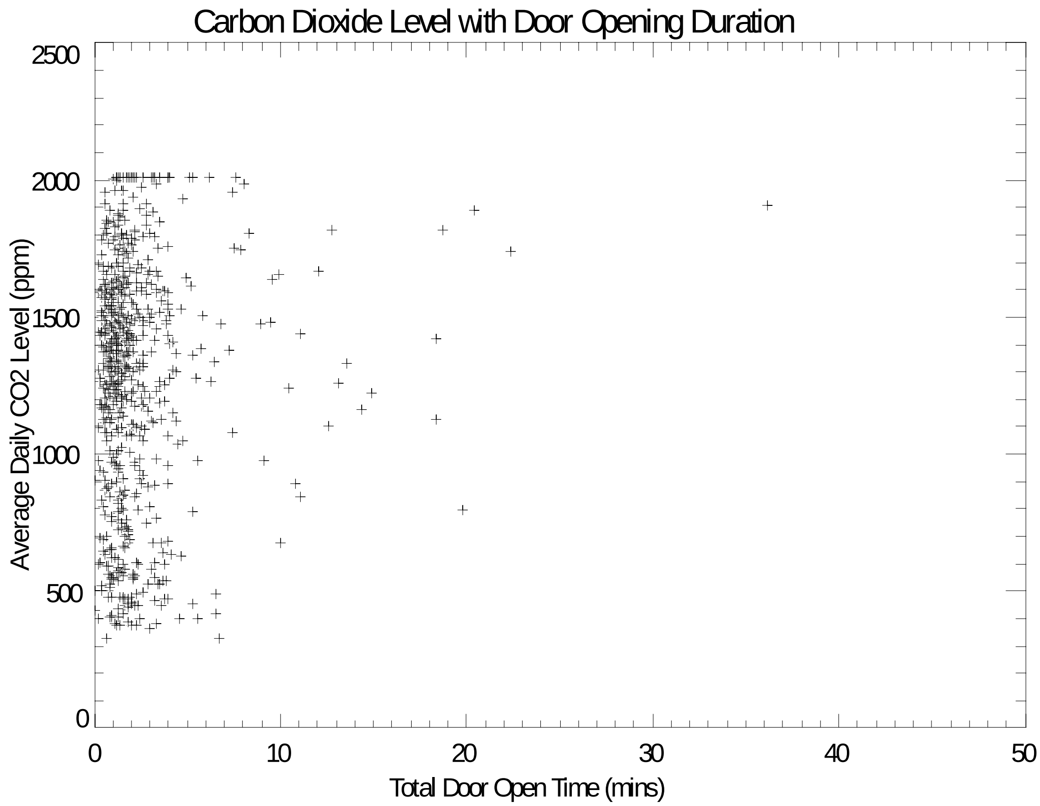


Figure 21. Daily Carbon Dioxide Level with Total Door Opening Duration

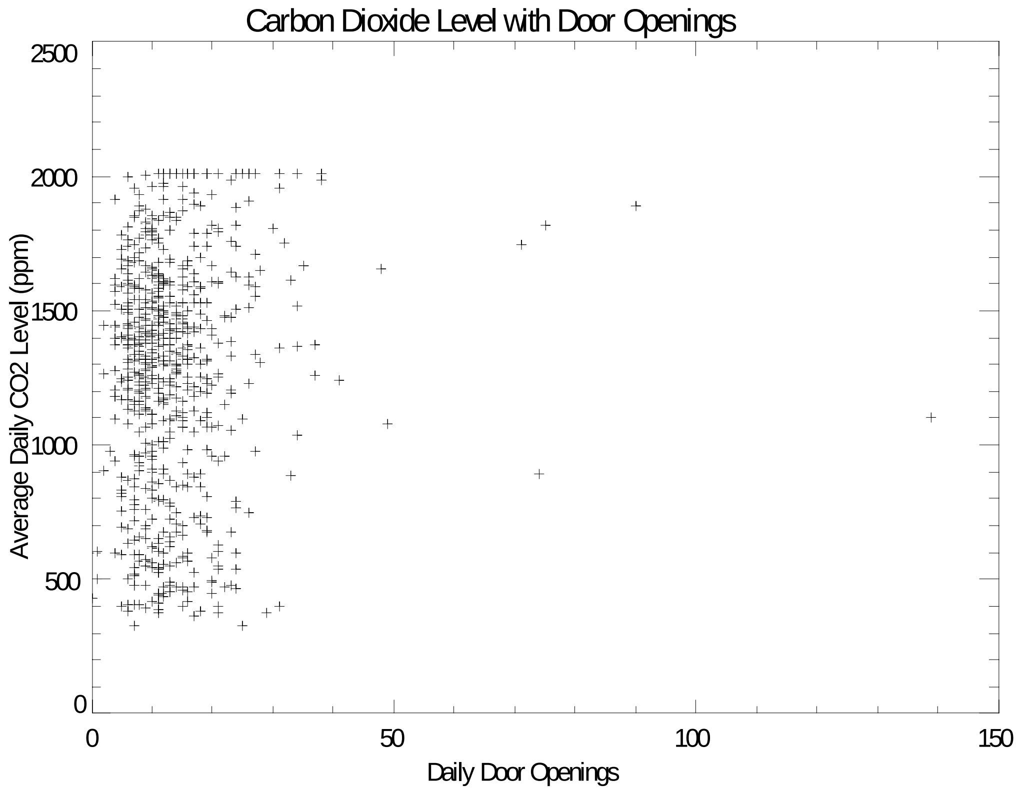


Figure 22. Carbon Dioxide Level with Total Door Opening Counts

Impact of Thermostat Time Delay Controls

On January 15, 2010 a time delay relay was added to the heat pump to keep it operating for a minimum ON time of 2 hours. At the same time the fan was put back into continuous operation (see Figure 23). The shade plot does confirm that the heat pump ran for at least 2 hours after January 15. However, heat pump cycle times were typically 1-2 hours even before the change was made; therefore, the control change had only a modest impact.

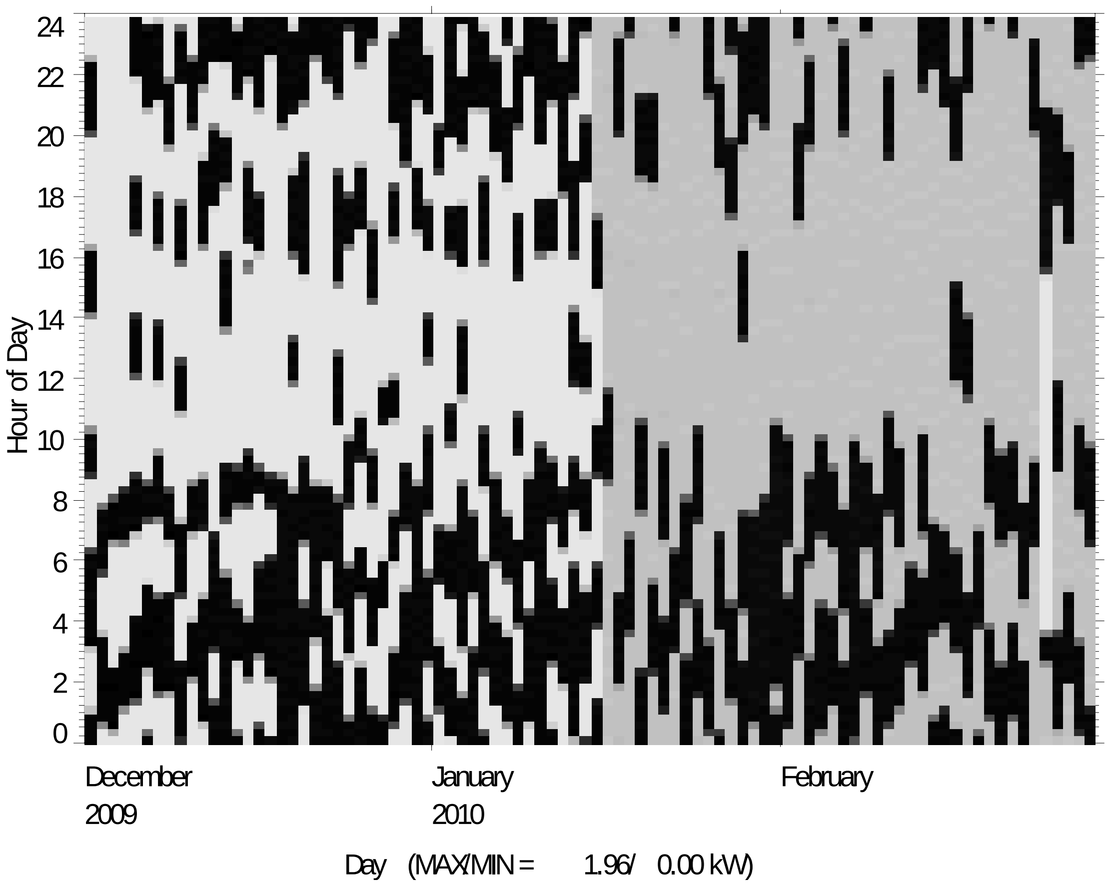


Figure 23. Shade Plot of Heat Pump Power From December 2009 to February 2010

The indoor temperatures (at the top of the Plenum) are shown in Figure 24. Since the supply fan cycled on an off with the compressor, the temperature at the top of plenum increased by about 5ºF during each heat pump off cycle. After January 15, the temperature variation was much smaller due to constant fan operation. The slightly longer (2 hour) on times did not appear to cause excessive temperature fluctuations in the space.

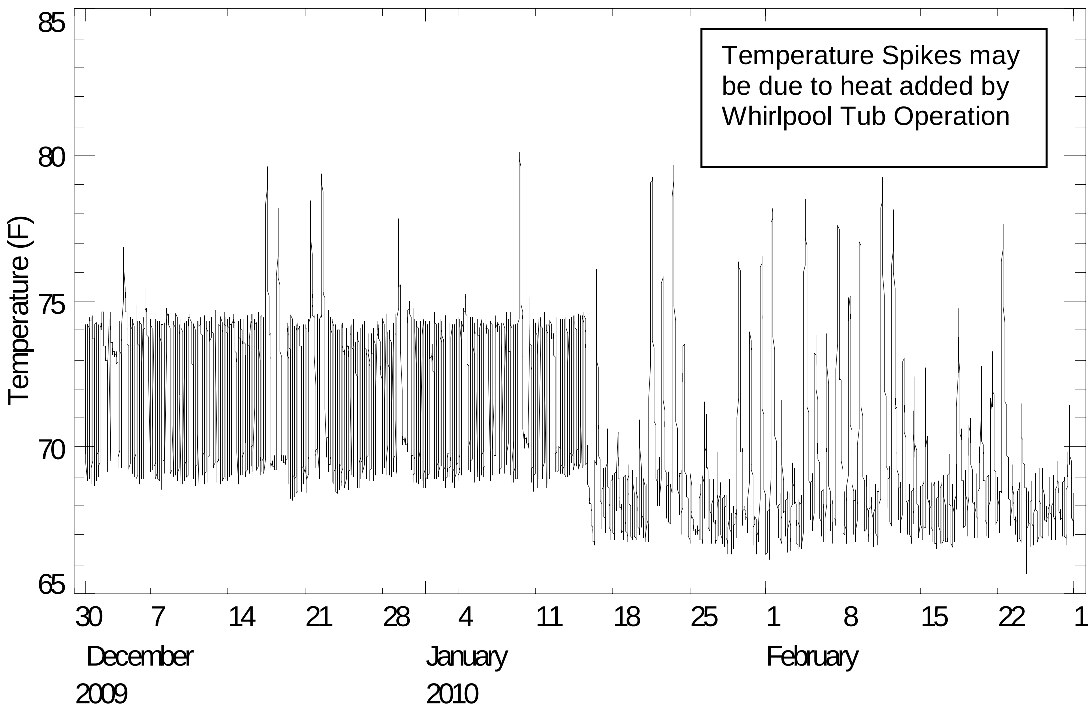


Figure 24. Indoor Temperatures Observed From December 2009 to February 2010

MEASURED DATA – KILMER HOUSE

Data collection at the Kilmer House officially began on August 11, 2008 after the third and final site visit corrected communication issues and verified power readings. During the first two site visits the data logger and most sensors were installed. This section reflects the data gathered from 08/11/2008 to 07/31/2010.

Energy Use Trends

Table 10 summarizes the monthly electric use for the Kilmer house over the 24 month period. Total Power Use was about 11,000 kWh per year. Domestic Hot Water Heater (DHW) consumption accounts for 35% of the total electric use. The peak demand for the house frequently reaches 10-12 kW when the DHW elements, stove, drier and other loads operate at the same time. The DHW tank uses about 9 to 13 kWh per day on average for this family of 4, which equates to 40-50 gallons of hot water per day after accounting for tank standby losses (observed to be about 3 kWh/day). A breakdown of electric costs is shown in Figure 25.

Table 10. Measured Monthly Electric Use

Date	Percent Good Data (%)	Domestic Hot Water Use (kWh)	Other Electric (kWh)	Total Electric Peak (kW)	Total House Electric Use (kWh)	Wood Stove Runtime (Hrs)
Aug 2008	66%	240	369	8.7	609	0
Sep 2008	100%	359	574	10.0	932	0
Oct 2008	100%	398	699	10.2	1097	107
Nov 2008	100%	297	706	10.0	1003	423
Dec 2008	100%	371	894	9.8	1266	660
Jan 2009	100%	367	799	9.4	1166	708
Feb 2009	100%	372	685	9.4	1057	640
Mar 2009	100%	397	717	9.4	1113	444
Apr 2009	100%	393	633	12.9	1026	185
May 2009	100%	412	603	10.0	1015	32
Jun 2009	100%	222	345	9.7	566	0
Jul 2009	94%	303	498	9.3	801	0
Aug 2009	100%	363	631	9.5	994	0
Sep 2009	100%	340	520	8.4	861	21
Oct 2009	100%	322	599	10.0	921	150
Nov 2009	100%	318	627	8.7	945	230
Dec 2009	100%	309	763	9.4	1072	327
Jan 2010	100%	371	733	8.9	1104	33
Feb 2010	100%	258	598	9.6	857	0
Mar 2010	100%	373	558	9.2	931	122
Apr 2010	100%	357	469	9.0	826	115
May 2010	100%	305	593	9.2	898	44
Jun 2010	100%	307	477	8.4	784	0
Jul 2010	100%	267	474	9.9	741	0
Annual 08-09	**97%**	**4,130**	**7,521**	**12.9**	**11,652**	**3,197**
Annual 09-10	**100%**	**3,890**	**7,045**	**10.0**	**10,935**	**1,040**

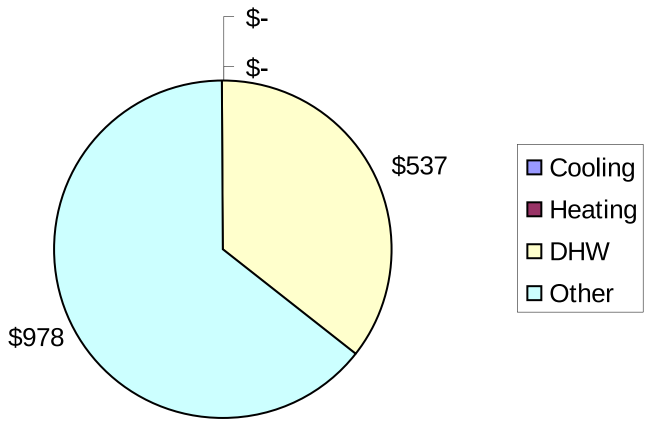


Figure 25. Breakdown of Annual Electric Use at Kilmer (at $0.13/kWh)

Figure 26 and Figure 27 are shade plots that qualitatively show when energy use occurred over the 24-month period. Each day is shown as a vertical stripe on the plot. Successive days are shown along the x-axis. Darker shades of gray indicate more energy consumption. Light gray indicates no use. White indicates missing data.

Figure 26 shows the total house electric use and Figure 27 shows energy for the DHW tank alone. DHW operation – which occurs in the early morning and to a lesser extent at night – is the predominate component of the house load.

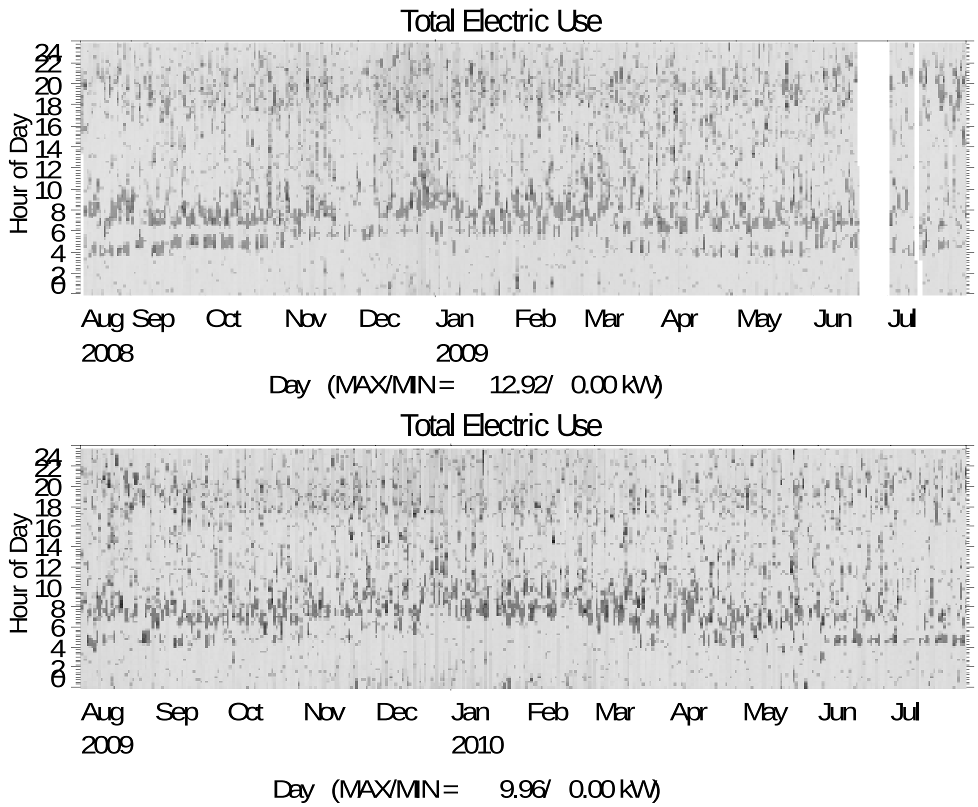


Figure 26. Shade Plots Showing Patterns of Energy Use – Total House

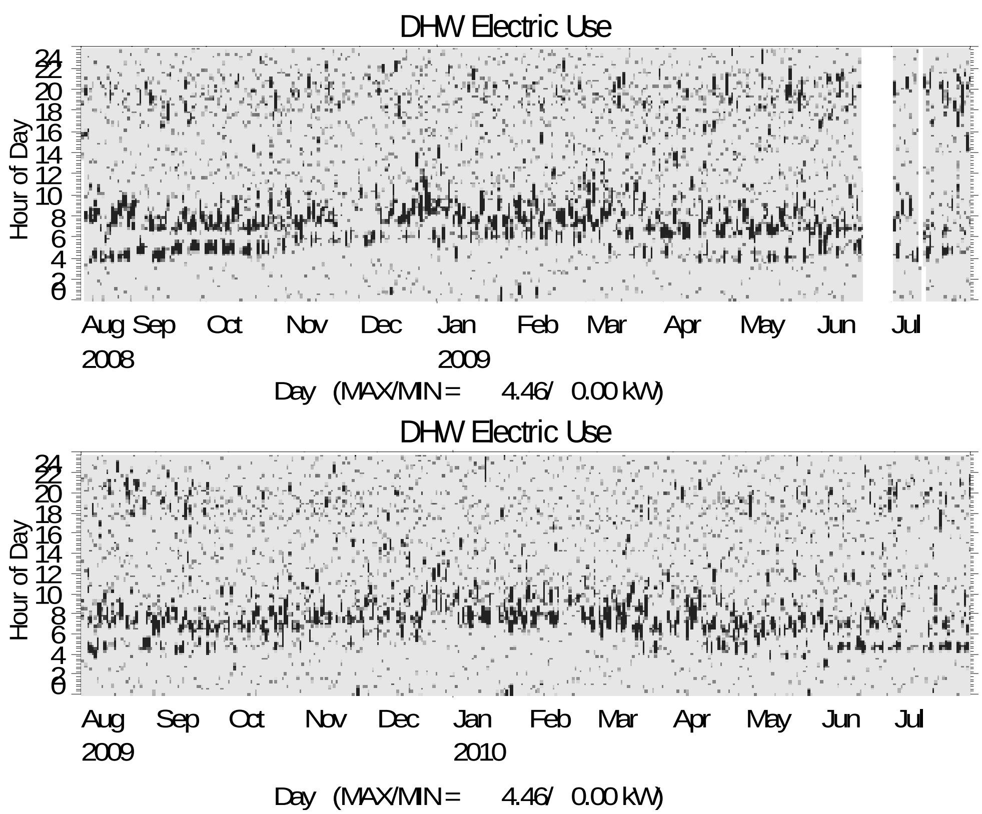


Figure 27. Shade Plots Showing Patterns of Energy Use – DHW Tank

Figure 28 shows how daily energy use changes with ambient temperature. The house is primarily heated by a wood stove. The backup heating system is available to circulate hot water from the DHW tank to a hot water coil in the fan plenum. The data in Figure 28 shows very little variation in total energy use with ambient temperature, which implies the backup heating system was rarely (if ever) used. The modest variation of total house use with temperature is explained by longer operation of lighting during evenings in the winter.

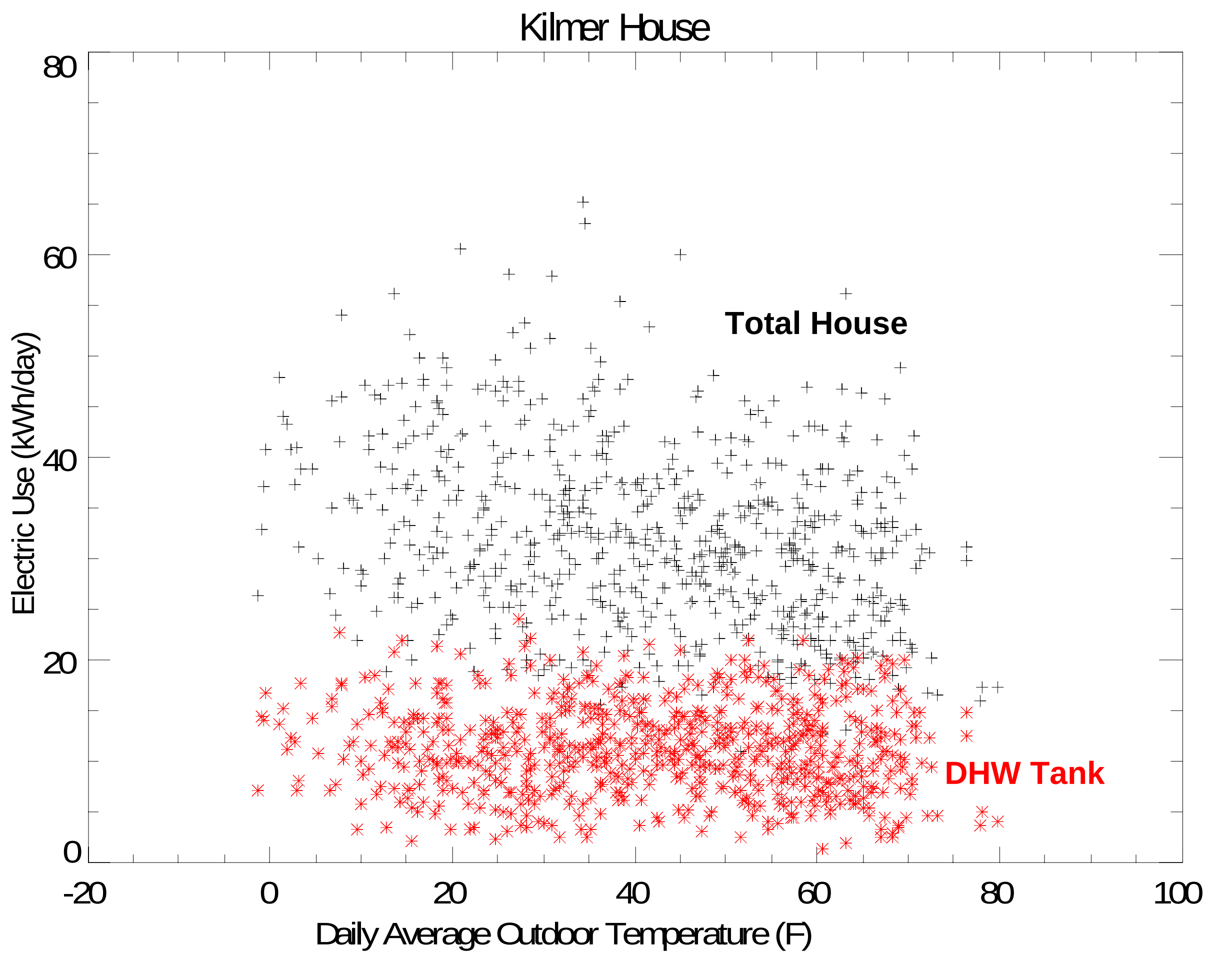


Figure 28. Variation of Electric Use with Temperature at the Kilmer House

Wood Stove Operation

Figure 29 is a shade plot showing the temperature in the wood stove flue. The dark gray areas qualitatively show when the wood stove operated (i.e., was hot). Operation was essentially continuous from November to April for the first heating season. For second season the homeowners installed another woodstove in the 3-season room and use that stove instead of the main stove. As a result the main stove was not used for the coldest part of the 2nd winter season.

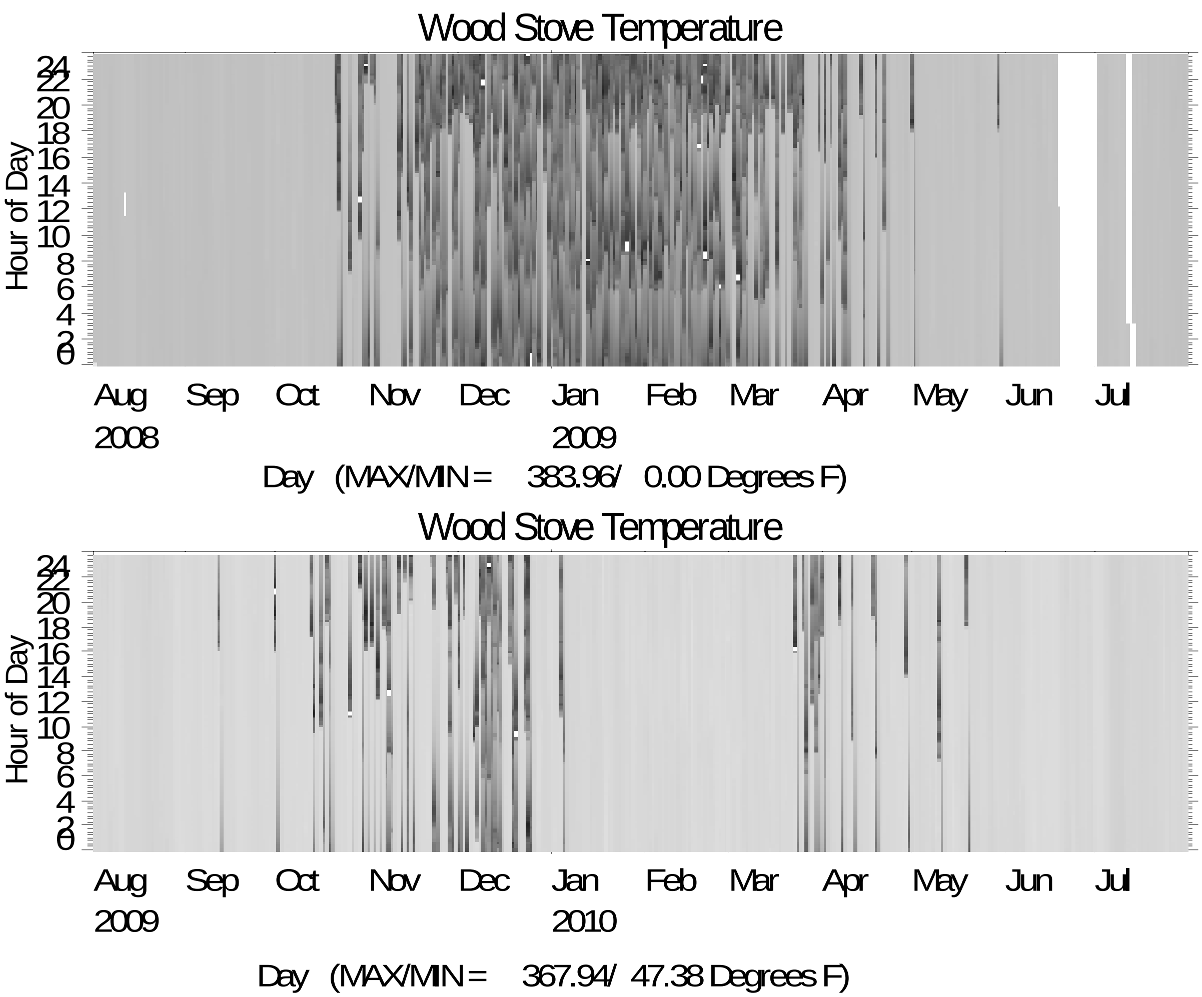


Figure 29. Shade Plots Showing When Wood Stove Operation Occurred

The wood stove did not have a discernable impact on the ventilation rates in the house, as evidenced by the measured CO_2 levels in Figure 30. CO_2 levels are low in the Summer, Spring and Fall when the windows are open. However, times with more (or less) wood stove operation do not appear to affect CO_2 levels.

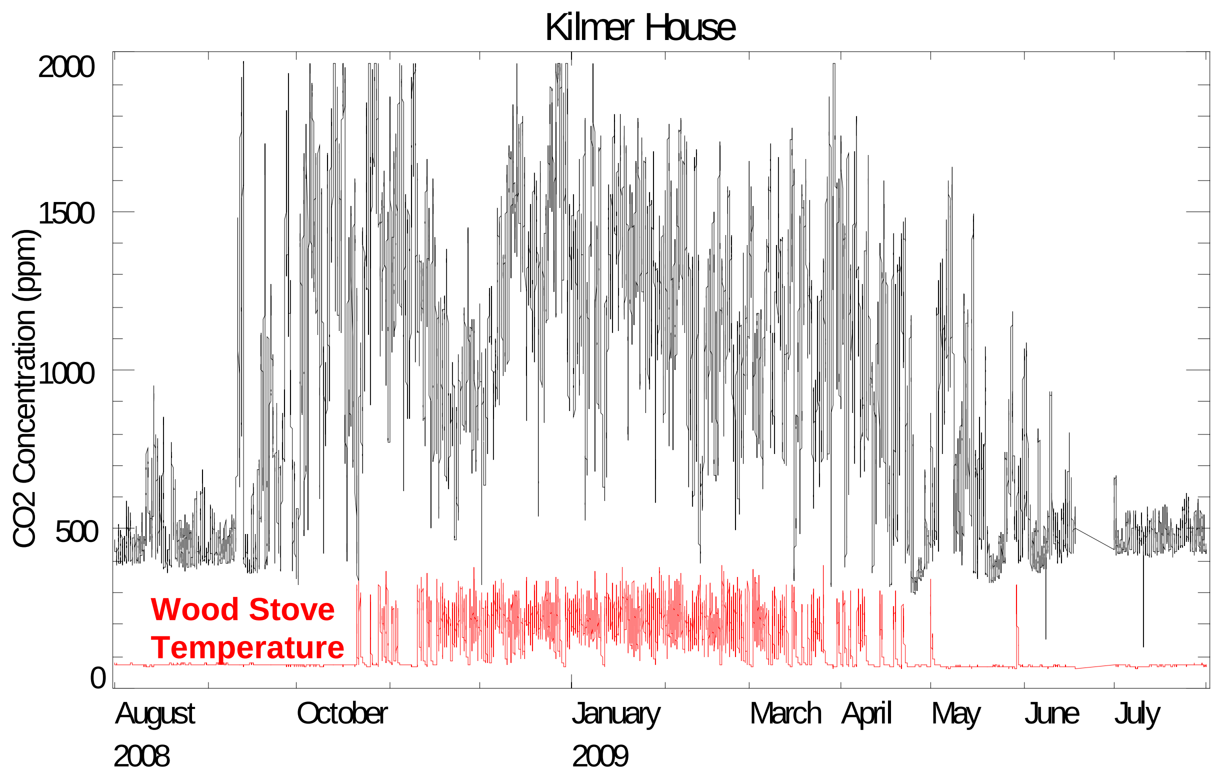


Figure 30. CO_2 Levels Compared to Wood Stove Operation During First 12 Months of Operation

Performance Profiles for Winter and Summer Periods

Figure 31 shows the daily temperature excursions for January 16, 2009 a cold day when the low reached -9ºF. The indoor temperature ranged from 62ºF to 66ºF. The temperature into the slab was 2ºF higher because of the added fan heat. The temperature difference through the slab indicates that heat is continuously added to the floor mass and released at the floor surface.

Typical operating patterns for a summer period are shown in Figure 32.

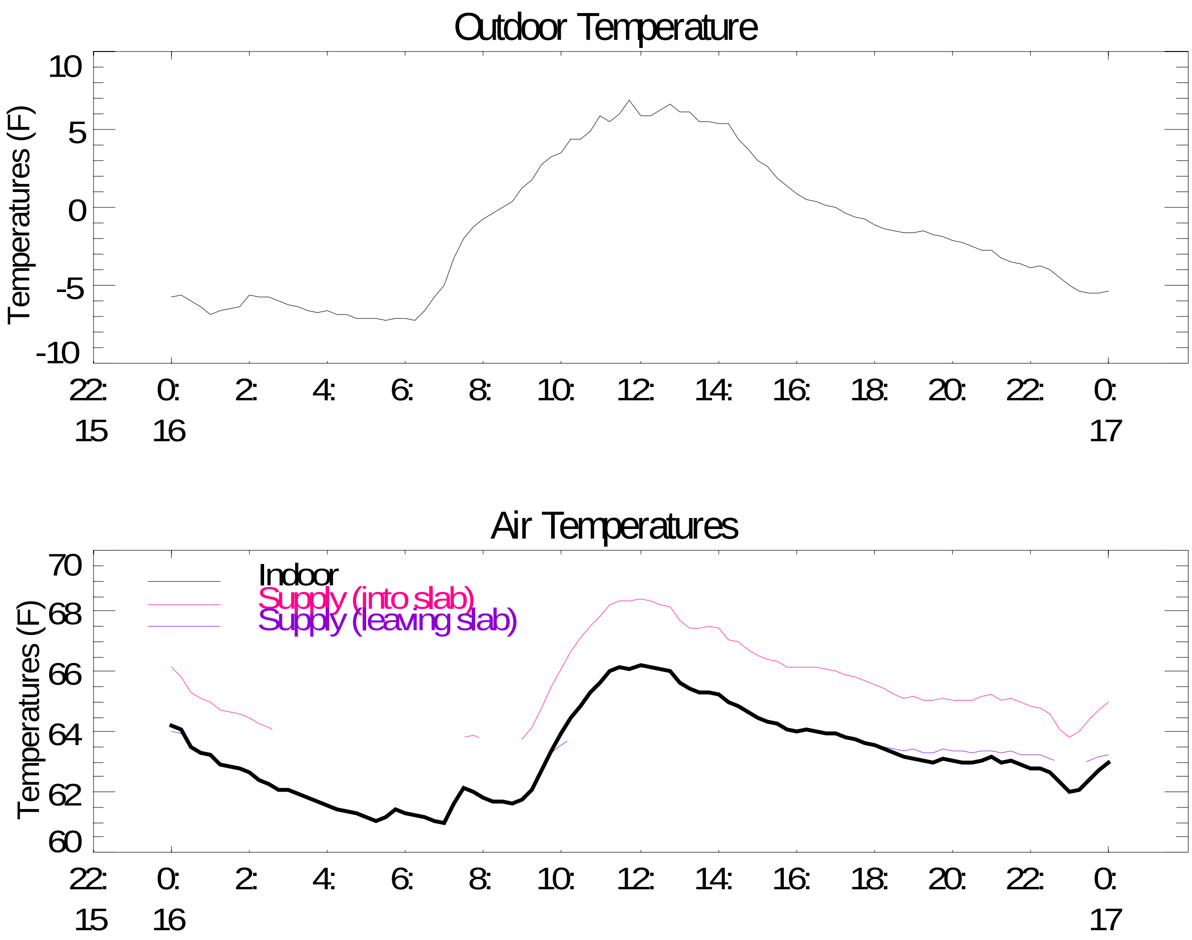


Figure 31. Performance for a Cold Winter Day (January 16, 2009)

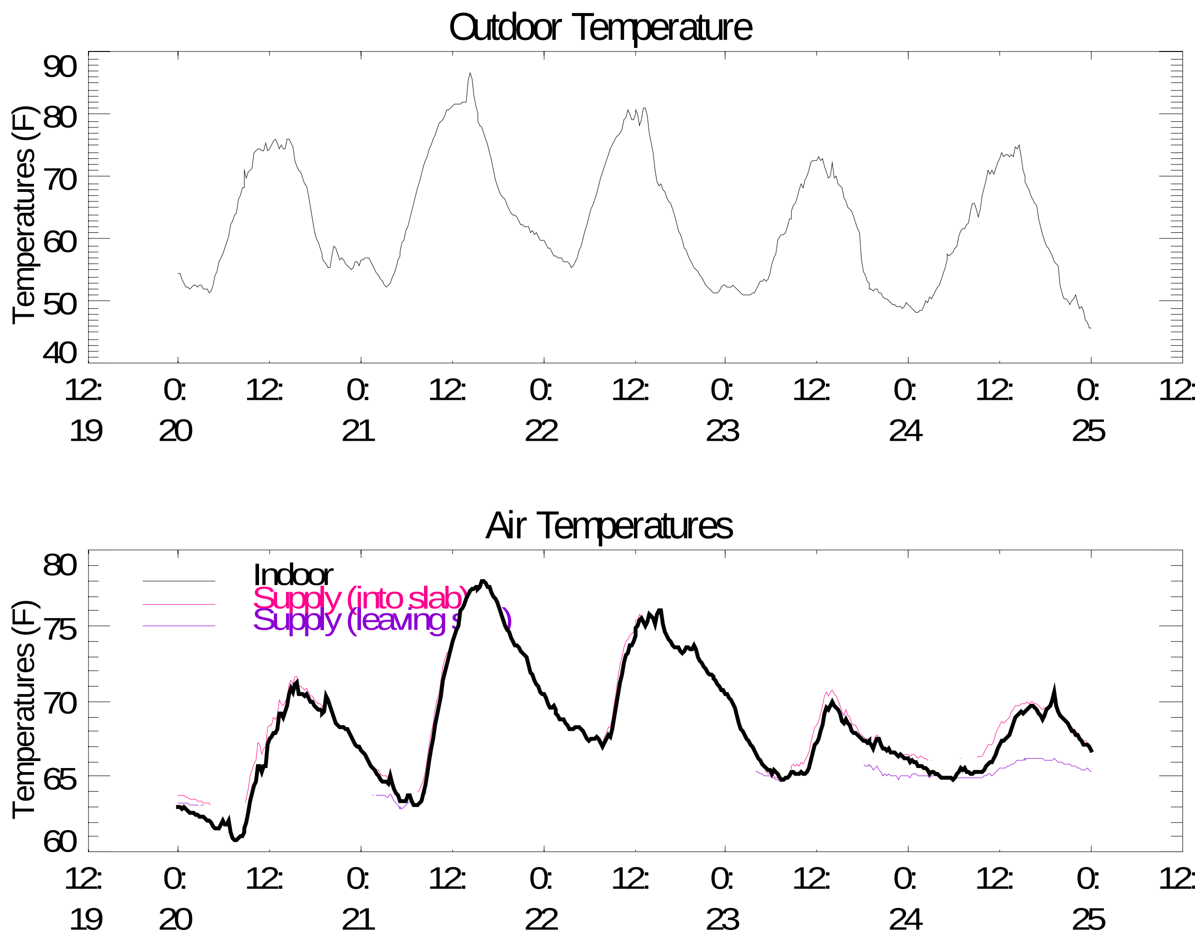


Figure 32. Performance for a Warm Summer Period (May 20-24, 2009)

Impact of Airflow through the Slab

The house includes a fan in a vertical plenum that pulls air from the top of the house and blows it through ducts buried in the concrete slab. Figure 33 and Figure 34 show the temperature difference as air passes through the ductwork in the floor slab. Generally the temperature difference is positive, indicating that the floor slab is absorbing heat, temporarily storing it, and then later releasing that heat back to the space via convection from the floor surface (with some convection occasionally back into the air duct, as indicated by the negative temperature difference). The airflow through ducts in the slab serves to closely-couple that thermal mass with the zone air and keep zones temperatures consistent over the day.

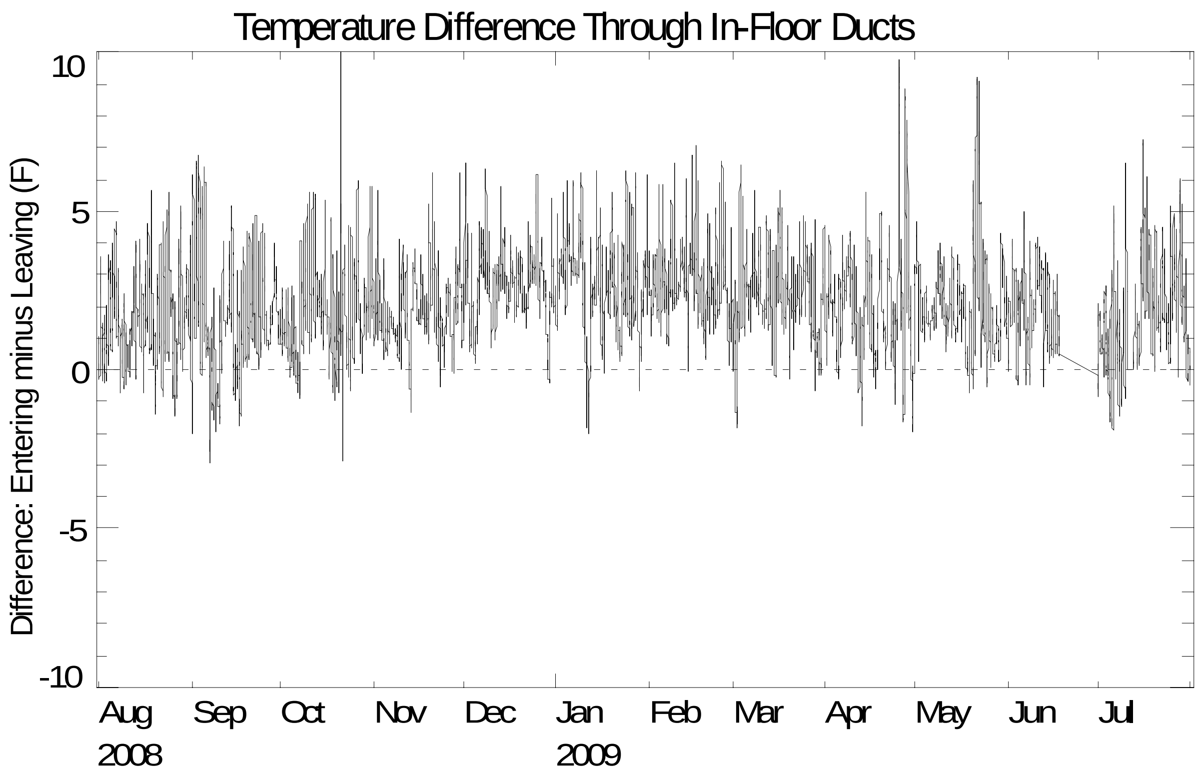


Figure 33. Temperature Difference (Drop) Through the Slab During First 12 Months

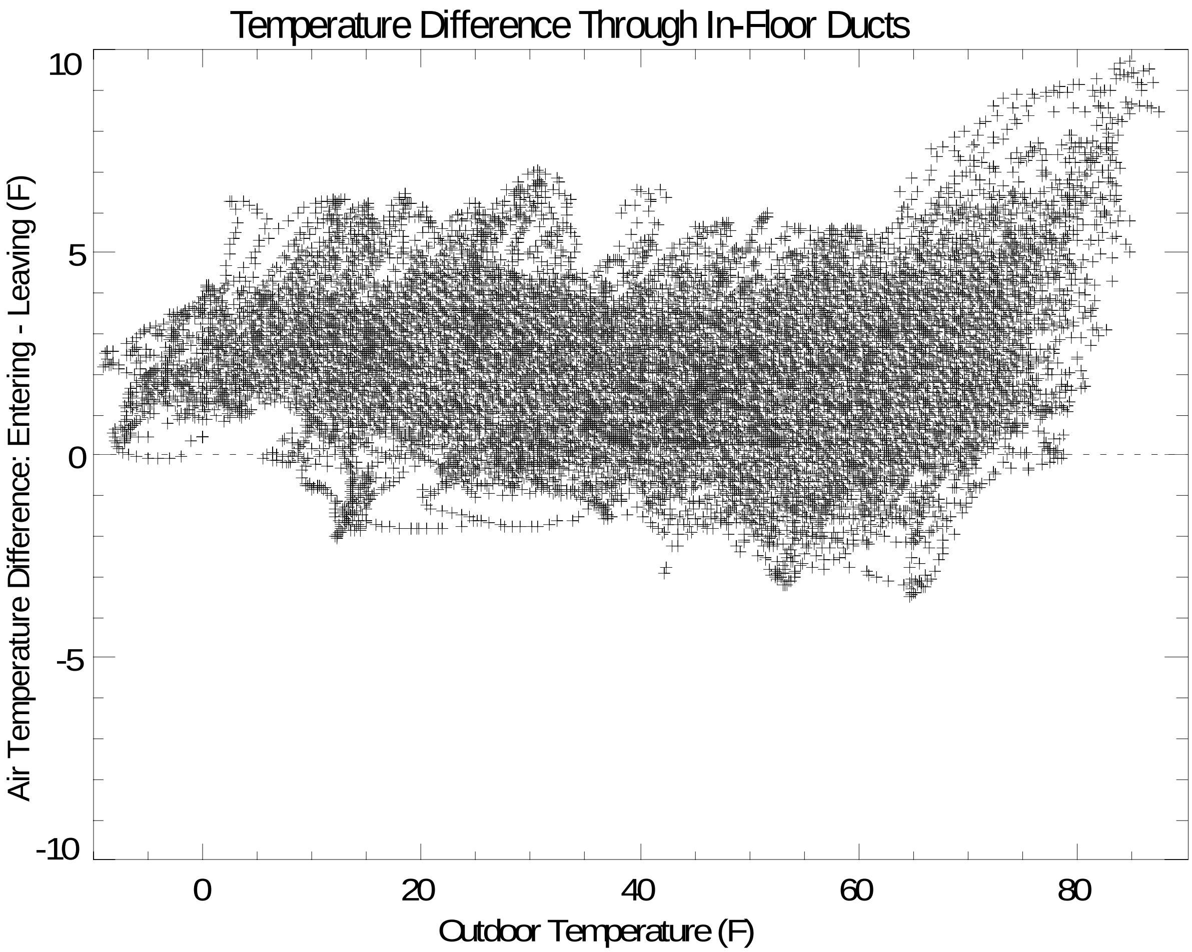


Figure 34. Slab Temperature Difference Compared to Outdoor Temperature

In October a new fan controller was added to the supply fan at Kilmer. The motor was changed to be a DC motor with a speed controller. The controller varies the speed in response to the space temperature at the top of the fan shaft, the outdoor temperature, and the slab temperature. The algorithm reportedly speeds up as the space temperature get farther from the slab temperature.

Figure 35 shows that supply air temperature into the slab increased from 1-2ºF above indoor conditions to 5-6ºF above indoor conditions. This implies that the fan power stayed about the same but the airflow was reduced. As a result, the temperature rise across the fan increased considerably.

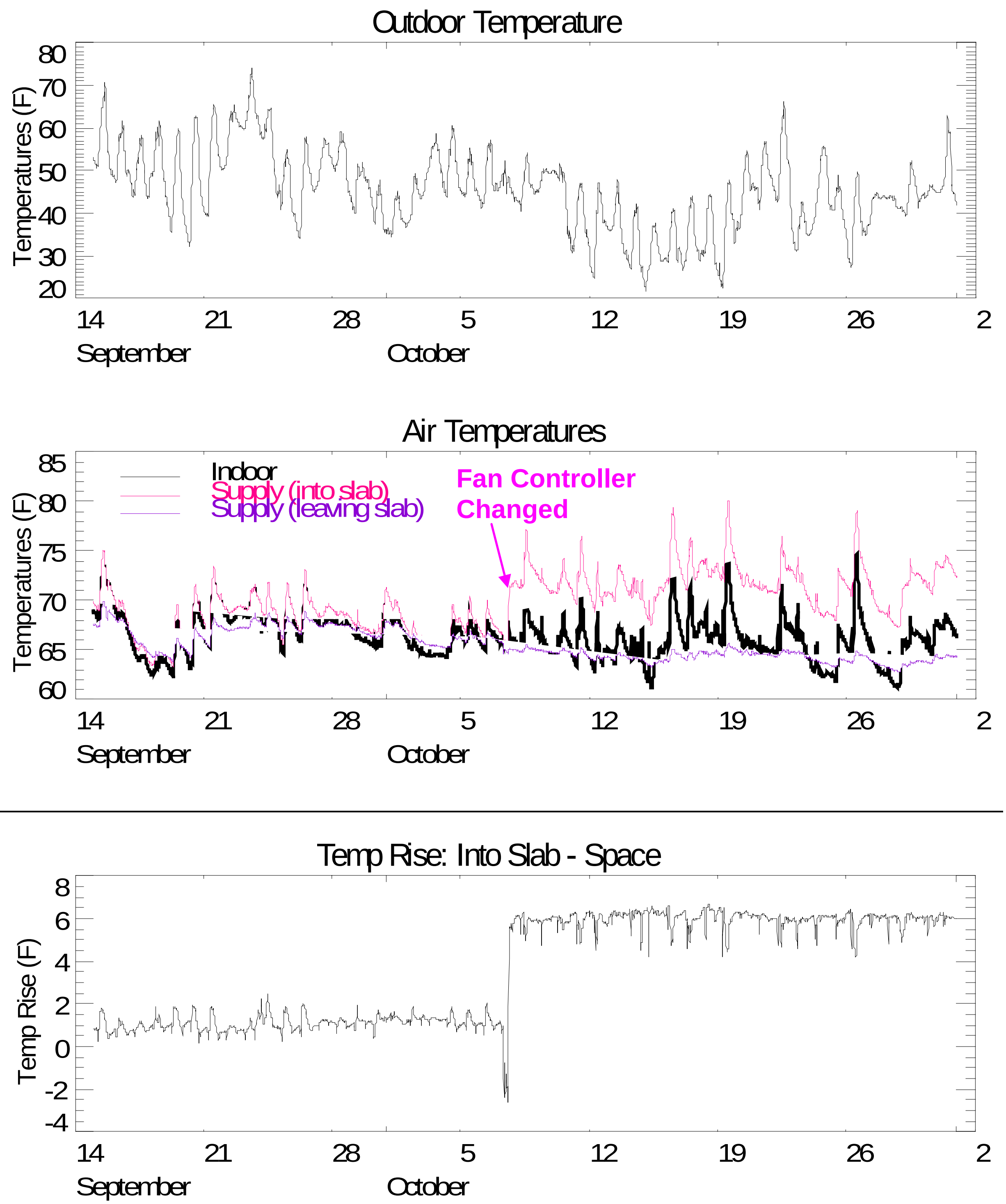


Figure 35. Change in Supply Air Temperature with New Fan Controller on October 7, 2009

Space Humidity Trends

The temperature and humidity of the space was measured at the top of the plenum. Figure 36 shows the temperature and humidity trends across the first 12-months of monitoring. The plenum fan ran continuously for this period.

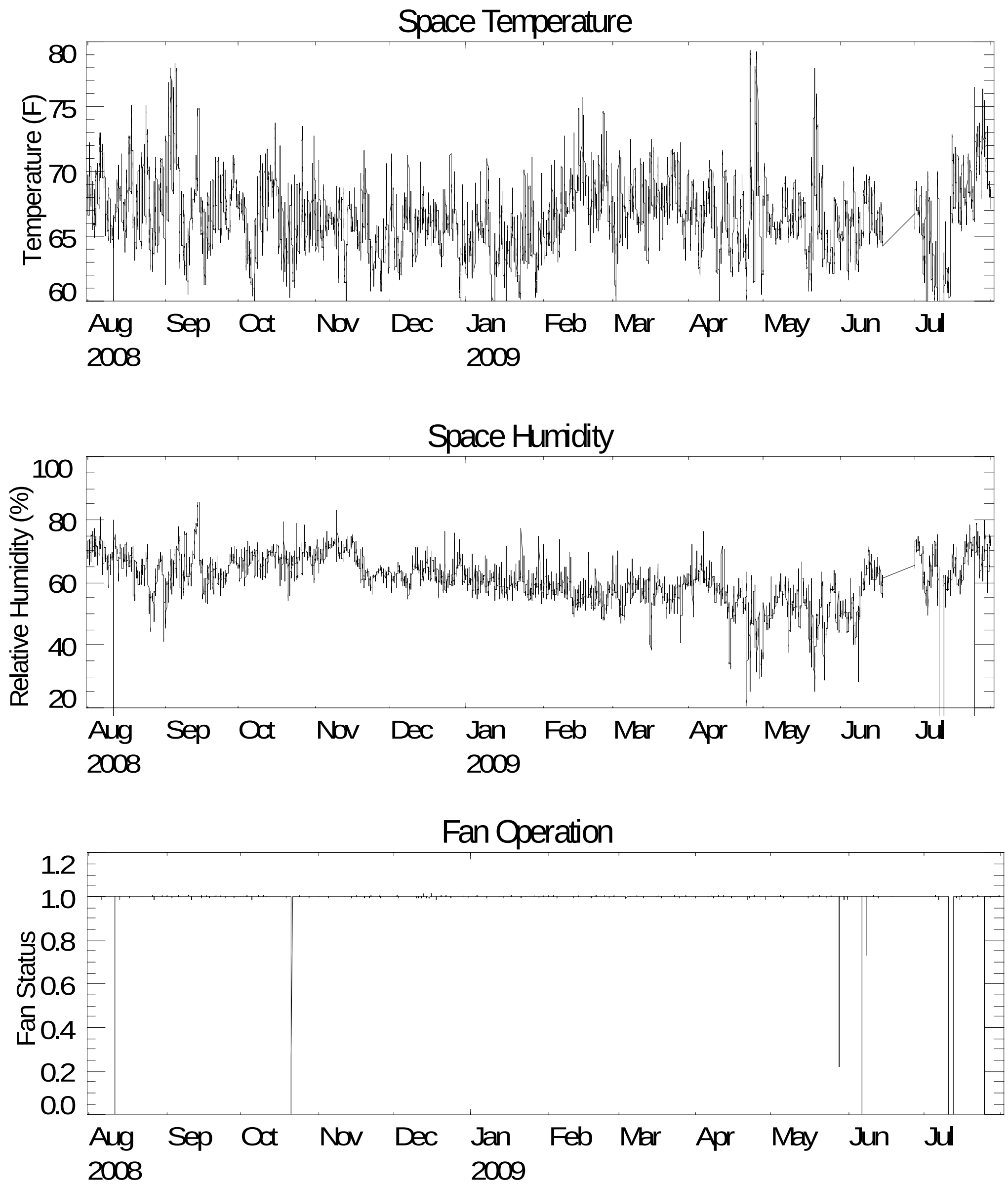


Figure 36. Variation in Space Temperature and Humidity for First 12 Months

The data show that space humidity levels remained high in the winter period. This trend confirms that the house is very tight and that no ventilation is provided. Internally generated moisture from people, showers, and cooking without ventilation leads to higher indoor humidity levels.

Figure 37 shows the trend of daily average indoor humidity ratio verses the daily average outdoor humidity ratio. The outdoor humidity data comes from Albany airport which is more than 30 miles to the south and at an elevation 1000 ft lower than the house (and is therefore likely a more humid location). In spite of this difference, the data basically show the expected trends: 1) indoor humidity approximately follows the outdoor humidity in the summer because the windows are open and, 2) the indoor humidity is much higher than the outdoor humidity in the winter, because the house closed up and internal moisture generation pushes space humidity levels into the range of 50-70 gr/lb. The winter time humidity of 55 gr/lb corresponds to 50-60% RH at 65-70°F.

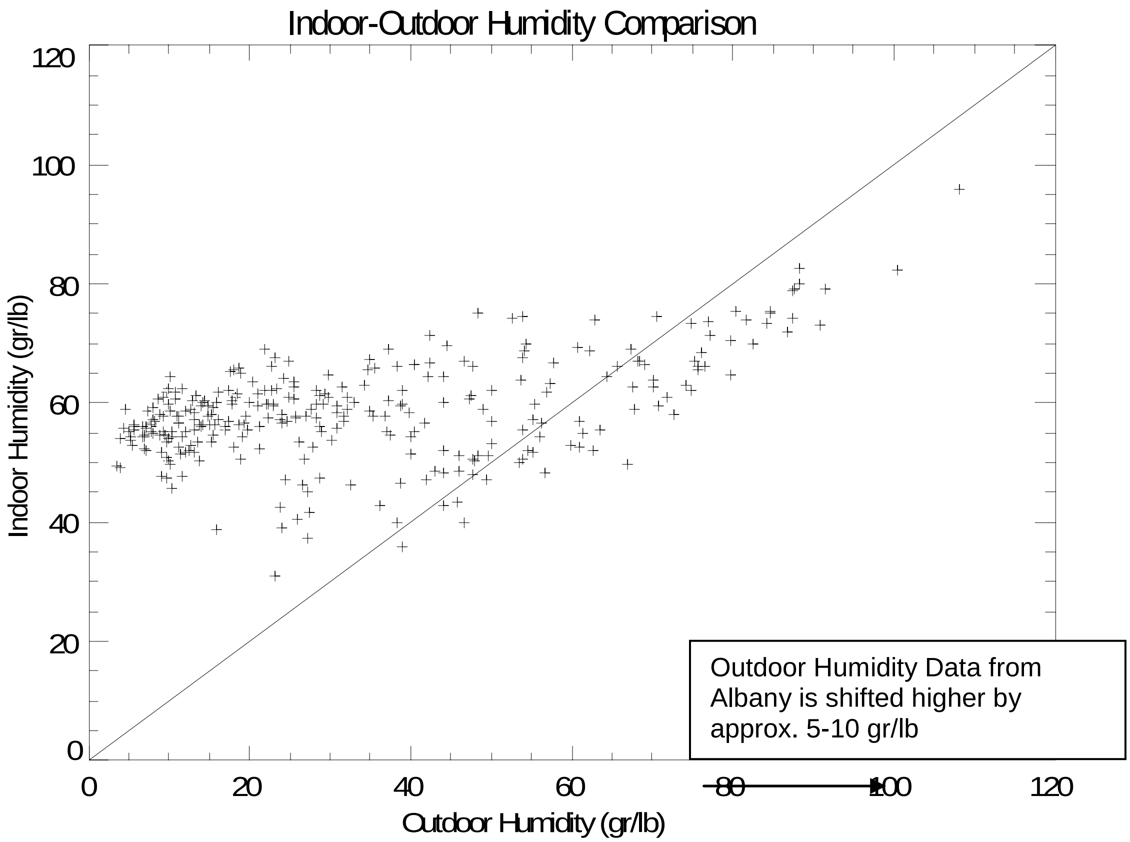


Figure 37. Indoor-Outdoor Humidity Comparison (August 2008 to July 2009)

Door Openings and Carbon Dioxide Levels

It was postulated that ventilation in the house would be naturally provided by door openings. To test this assumption, a sensor was installed to measure when the main of the house was open or closed. The data was used to determine a count of door openings and also record the amount of time the main door was closed (and open). Figure 38 has shade plots showing the frequency of door openings as well as the amount of time the door was open. The plots show consistent patterns when occupants left for work or school at 5 am and 8 am each day. The door was sometimes left open for long periods of time in the summer as expected. Otherwise the door was typically closed in the winter period.

Figure 39 and Figure 40 compare the carbon dioxide level for each day to the frequency and duration of door openings. If it were true that door openings did provide some degree of ventilation, we would expect that CO_2 levels be lower for days with more door openings. The plots show there is no discernible impact of door activity on CO_2 level.

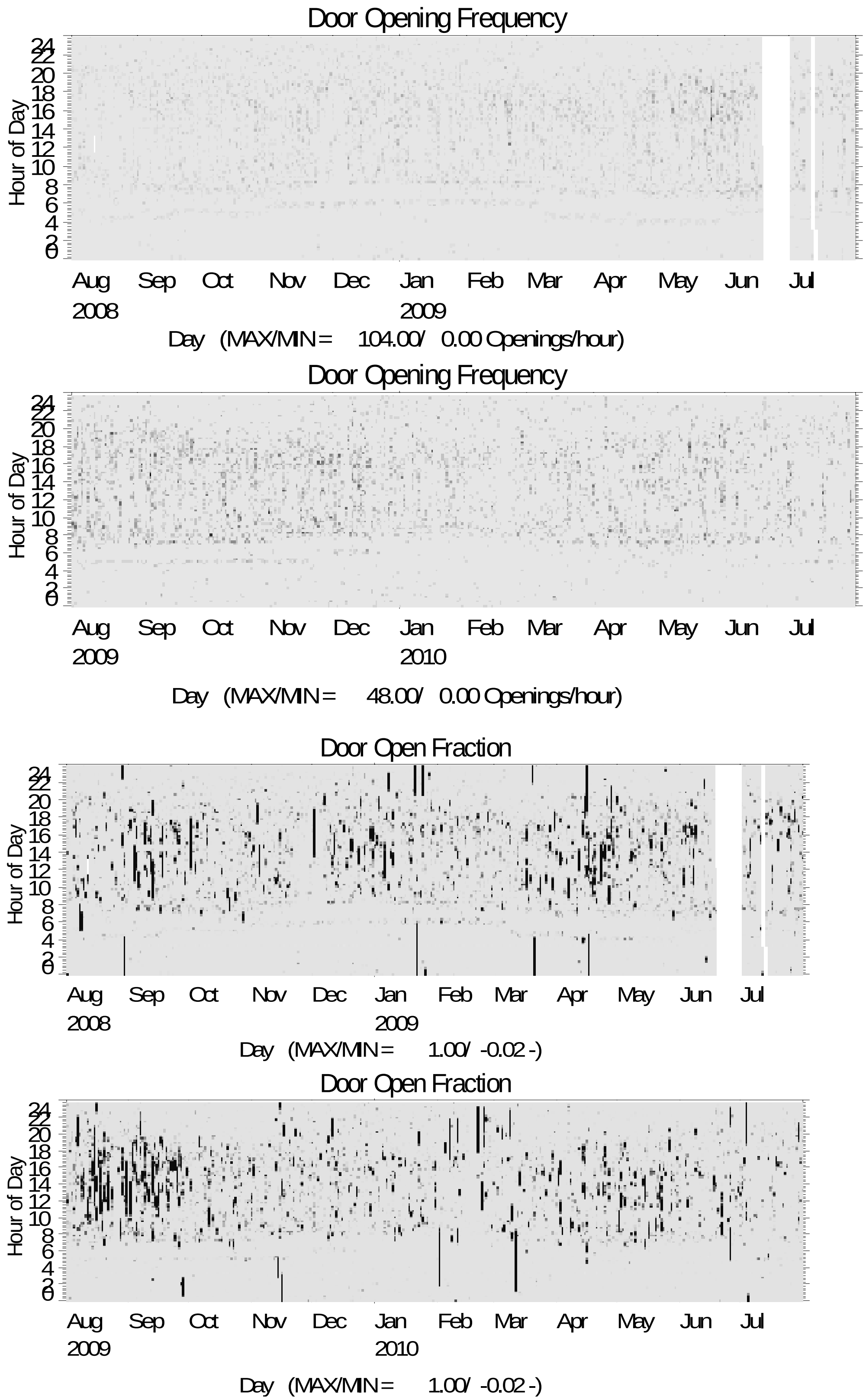


Figure 38. Shade Plots of Door Opening Frequency and Opening Duration

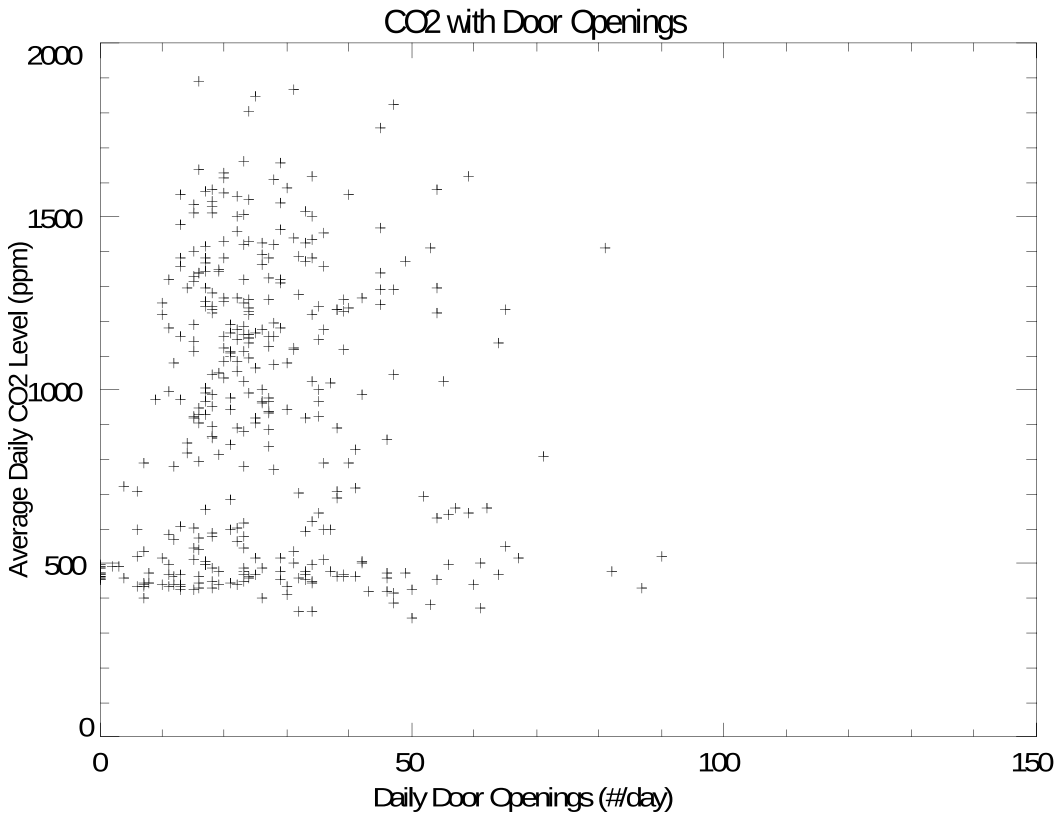


Figure 39. Daily Carbon Dioxide Level with Total Door Opening Frequency

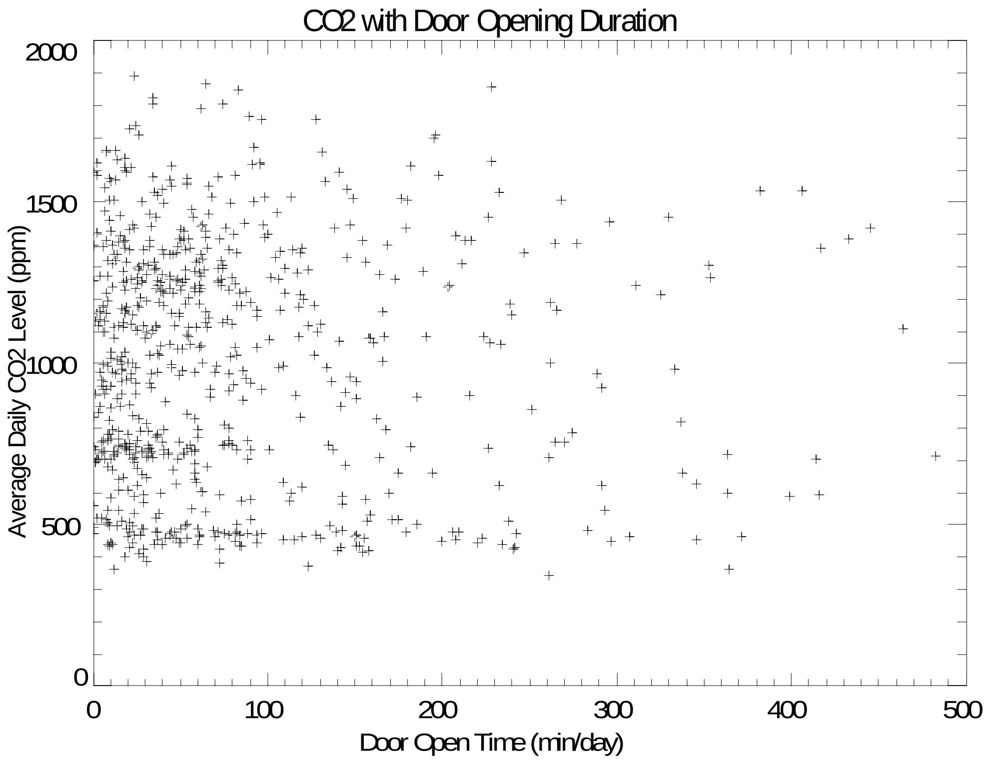


Figure 40. Daily Carbon Dioxide Level with Total Door Opening Duration

Figure 41 shows the variation of CO_2 level with outdoor temperature. CO_2 levels are not strongly dependent on outdoor temperature, except when homeowners open the windows and naturally ventilate the space in the summer months. CO_2 levels are typically 1500 ppm. If code-required ventilation were provided, maximum CO_2 levels near 1,000-1,100 ppm would be expected.

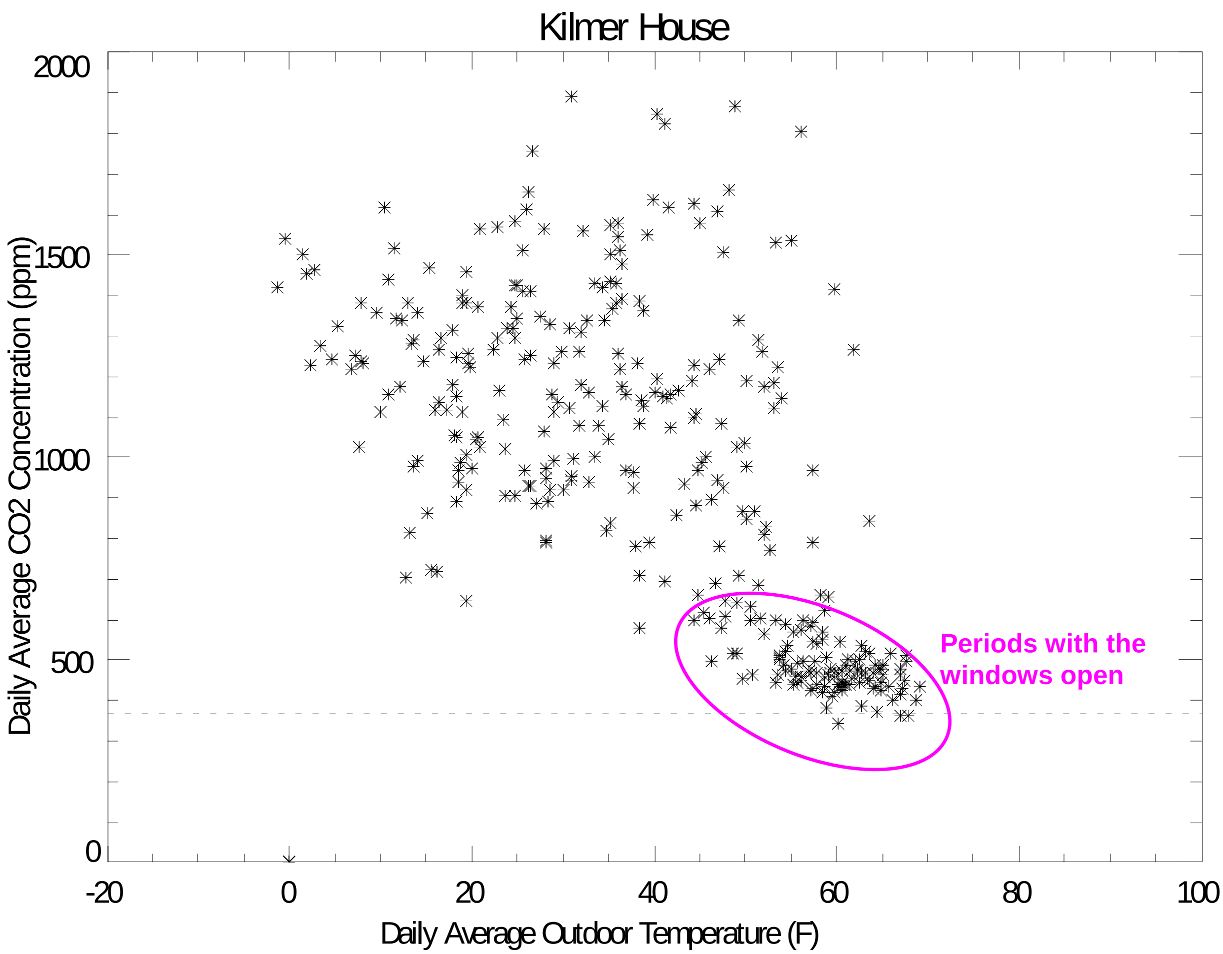


Figure 41. Variation of CO_2 Concentration with Outdoor Temperature

SUMMARY COST COMPARISONS

The two houses are both highly efficient homes. The electric use in the two houses is compared in Figure 42. The "other" loads in the home, excluding heating, cooling and water heating were very similar in the two homes. Hot water loads were much smaller in the Hyspot house (15 gallons/day) which had two adults that worked outside the home. The Kilmer House had a family of four, so hot water loads were much larger (40-50 gallons/day). The water heating loads at Kilmer had an annual cost of $537, which was larger than water heating, space heating and space cooling loads combined at the Hyspot House. Heating at the Kilmer House was provided by a woodstove.

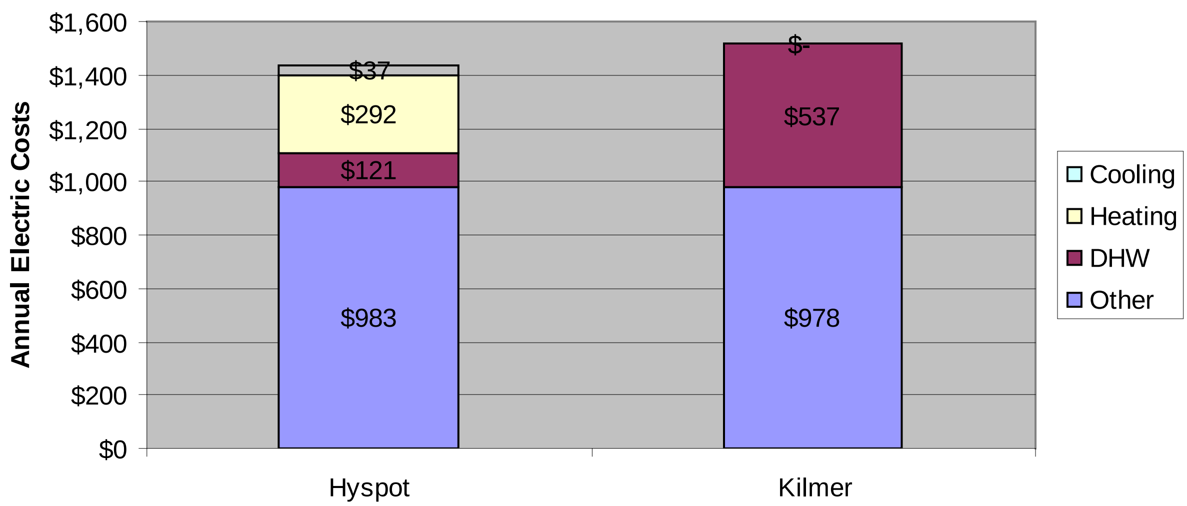


Figure 42. Comparing Electric Costs at Hyspot and Kilmer

CONCLUSIONS AND RECOMMENDATIONS

The two houses are both highly efficient homes that are very air tight and have low energy consumption for space conditioning.

High CO_2, Humidity and Ventilation

However, both houses showed high levels of indoor humidity in the winter as well as high CO_2 levels (over 1,500 ppm) when the windows were closed. Both these issues occur because no ventilation was provided in the homes.

The calculations in the appendix of commercial ventilation standard (ASHRAE 62.1) show that if the nominal amount of ventilation is provided in a building – i.e., about 15 cfm per person – then the indoor concentration of CO_2 from human activity should be about 1,000 ppm. While CO_2 is not pollutant in and of itself, the ASHRAE standards state that CO_2 can be used as a surrogate for the bioeffluents, pollutants, and smells associated with human occupancy. The measured CO_2 levels in both these houses confirms that insufficient amounts of fresh air were provided by natural infiltration.

One research question addressed by this monitoring effort is whether door openings were sufficient to provide fresh air into the home. The number and duration of door openings was measured along with the CO_2 levels. The daily average long-term data did NOT show any discernable correlation between door activity and CO_2 levels. This finding indicates that door openings alone are not sufficient to introduce the necessary fresh air into the space.

The measured space humidity in the wintertime was typically 50-60% RH in both houses. This is much higher than the value of 40% RH generally regarded as optimal for human health and comfort in the winter. Even though the large moisture storage capacity associated with wood interior finishes in this house tended to moderate the impact of humidity swings, high humidity at least has the potential to cause problems. In both houses, the occupants reported (or we observed) that some condensation and mold had occurred around the edge of windows, near exterior doors (Figure 5), or on other cold surfaces in the winter. Mechanical ventilation would introduce drier air in the winter, which would lower space humidity levels and reduce the risk of condensation and nuisance mold formation.

The residential ventilation standard (ASHRAE 62.2) requires the following ventilation rate be provided as mechanical ventilation:

Vent cfm	=	0.01 x floor area	+	7.5 x (number of bedrooms + 1)
	=	0.01 x 1,584	+	7.5 x (3 + 1)
	=	47 cfm		

<u>Thermal Mass and Plenum Airflow</u>

A key aspect of the house design is the continuous air motion: pulling air down a vertical plenum from the top of the house and forcing it through ductwork buried in the concrete slab on the first floor. The data shows that heat is typically added to the slab in the winter and released through floor. The heat gains to the floor were on the order of 5,000 Btu/h. This approach most certainly tends to eliminate temperature stratification in the house due to solar gains and keeps the main zone well mixed. However it appears to have little impact on the overall energy use of the house, except that the constant fan operation results in about 200 to 300 Watts of heat added to the house. This fan operation equates to an additional consumption of 2,000-3,000 kWh per year. Only about half to a third of this heat goes towards meeting the space heating load in the winter (for 3000-4000 hours per year).

<u>Cooling Operation with Constant Fan Operation and In-Floor Ducts</u>

The Hyspot house used a water source heat pump to provide cooling. The cold supply air from the heat pump is blown into in-floor ducts. The cold, nearly-saturated air (typically 48-55ºF) transfers heat into the slab and may result in condensation inside the in-floor ductwork. Because of the continuously operating fan, it is likely that any moisture that forms in the ductwork evaporates during the compressor off cycle. However, at some conditions the ducts may be wetted for long periods of time and some long-term mold formation is possible.

To compound the problem, constant fan operation means that the cooling coil itself evaporates moisture on coil fins back into the space during the compressor off-cycle and the overall moisture removal capacity of the air conditioner is reduced. The measured data (in Figure 18) confirms that space humidity levels were much higher when the heat pump supply fan operated continuously in the summer. The result was very little moisture removal and indoor humidity levels that approached ambient conditions.

Recommendations

Ventilation. We strongly recommend that the AAE home design include mechanical ventilation. One option would be to bring a ventilation air duct into the vertical plenum, either through the roof above the plenum or through a small duct running through a 1st or 2nd floor wall. Approximately 50 cfm is needed, so a 4 to 6 in diameter duct would be sufficient. Flow could be induced by the supply fan, or even better, the exhaust fan in the bathroom could operate continuously to slightly depressurize the house and draw in air.

Variable Flow Supply Fan. A variable speed fan was installed at Kilmer in October 2009. The speed of this DC Motor was controlled based on the temperature difference between the slab and the top of plenum. The motor is not a high efficiency Brushless Permanent Magnet (BPM) motor or Electronically Commutated Motor (ECM) – based on the high temperature rise we observed across the fan motor (Figure 35) and the measured power use (100 Watts at 30 hz).

We recommend using a BPM/ECM motor that is controlled based on the stratification from the top of the house to the first floor thermostat location. A simple two-speed controller, such as those used on a furnace or air handler, could be used with a low cost differential thermostat. Low speed would be used most of the time. High speed would be activated when the stratification exceeds a differential setpoint (e.g., 2-4ºF) using an off-the-shelf differential controller. Instead of the field-erected fan system and coil in the plenum, a conventional, down-flow air handler unit (AHU) with electric resistance heat with an efficient ECM fan could be used.

Reduce Underslab Ductwork / Smaller Plenum. The size of the 30 x 30 inch vertical plenum and the amount of ductwork in slab would seem to add significant cost to the house. We believe that the benefits of destratification could still be adequately provided with smaller plenum shaft and about half as much duct work in the slab.

Ductless Heat Pumps. Some manufacturers of ductless heat pumps now offer greatly improved performance (i.e., high capacity and high efficiency) at lower outdoor temperatures. One example is the Mitsubishi “Hyper-heat” units. A ductless unit in the main living area would be very well suited to this house. The circulation with the plenum fan would serve to distribute heating and cooling throughout the house. Cooling could be provided without the risk of condensation in the slab ductwork.

APPENDIX A: BLOWER DOOR TEST RESULTS

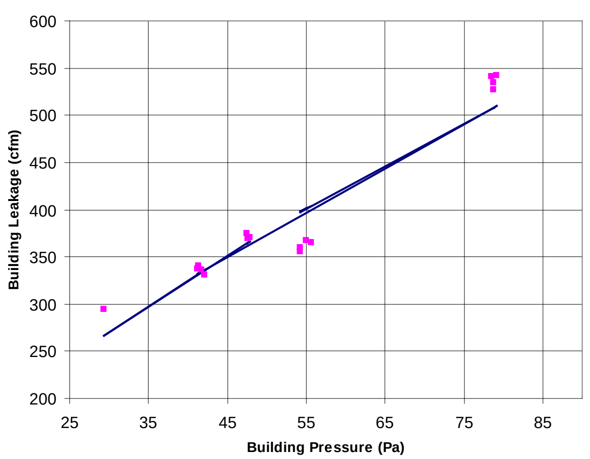
Blower Door Test – Hyspot

A blower door test was conducted on the Hyspot house during the July 17, 2007 site visit. The blower door fits in a doorframe and has a fan that is used to depressurize the space to a nominal 50 Pa. The blower door also allows the pressure-flow relationship for the house to be determined and the equivalent leakage area (ELA) of the leakage paths to be calculated.

The floor area for the building is 1,584 ft^2. The envelope surface area is 3,056 ft^2, excluding the slab. The volume of the house was 14,761 ft^3.

The house was depressurized to determine air change rate at 50 Pa (ACH_{50}) and the equivalent leakage (ELA). The measured ACH_{50} was 1.38 and the ELA was 0.55 in^2 per 100 ft^2 of surface area. The ACH_{50} for an EnergyStar home must be less than 5 and the ELA for tight house is usually less than 2.5 in^2 per 100 ft^2. The data shows the house has approximately 5-10 times less infiltration than a typical well built home.

Figure A-1 shows the pressure – flow data in both a regular and logarithmic form. The exponent, n, in the equation listed below is 0.657, which also implies the home is tight.



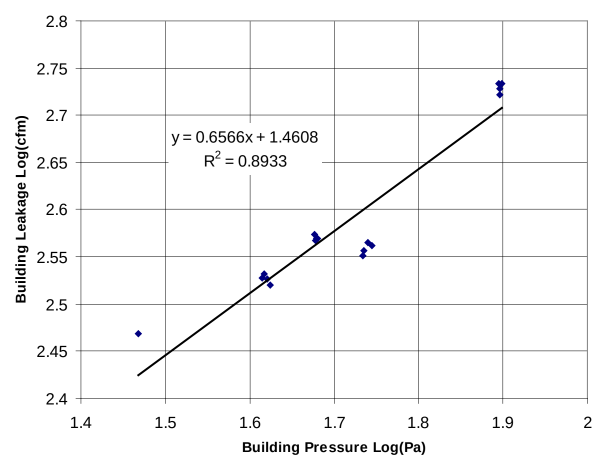


Figure A-43. Variation of House Leakage with Pressure: cfm = $K(\Delta P)^n$

Table A-1. Blower Door Test Results - Hyspot

Building Geometry

Floor Area:	1,584	ft^2
Total Volume:	14,761	ft^3
Envelope Area:	3,056	ft^2

Test Results:

Flow Coefficient (K)	28.9	1,584 sq ft, floor area
Exponent (n)	0.657	
Leakage area (LBL ELA @ 4 Pa)	20.3 sq in	0.67 ELA / 100 sq ft
Airflow @ 50 Pa	377.0 cfm	1.53 ACH @ 50

Test Data:

Nominal Building Pressure (Pa)	Nominal Flow (cfm)	Ring
55.6	365	B
55.0	367	B
54.3	360	B
54.2	356	B
78.8	527	B
78.8	535	B
79.2	542	B
78.5	541	B
41.2	337	B
41.4	340	B
41.7	336	B
42.1	331	B
29.4	294	B
47.6	369	B
47.8	371	B
47.5	375	B
47.9	371	B

The bathroom exhaust fans were both blocked for the house pressurization test described above. To test the impact of bathroom exhaust fans, the blower door was shut off and the bathroom fans were turned on individually. The activation of each fan should produce a change in the pressure within the house. For both fans no change in building was detected. A piece of bathroom tissue was also held up to the fan and there was not sufficient suction to hold the tissue. These results imply the bathroom fans do not vent to outdoors.

Blower Door Test - Kilmer

A blower door test was conducted on the Kilmer house during the May 27, 2008 site visit. The blower door fits in a doorframe (South Door) and has a fan that is used to pressurize the space to a nominal 50 Pa. The blower door also allows the pressure-flow relationship for the house to be determined and the equivalent leakage area (ELA) of the leakage paths to be calculated.

The floor area for the main building is 1,584 ft^2. The envelope surface area is 3,056 ft^2, excluding the slab. The volume of the main house was 14,761 ft^3. The 3-Seasons room was 12 ft x 24 ft (288 ft^2) which increased the volume to 17,641 ft^3 and the surface area to 3,584 ft^2.

The test was conducted on the entire house (including the 3-Season room) because of several penetrations through the kitchen wall. The woodstove was still warm so we did the test by pressurizing the house (so we would not back draft the stove).

The house was pressurized to determine air change rate at 50 Pa (ACH_{50}) and the equivalent leakage area (ELA). The measured ACH_{50} was 1.7 and the ELA was 0.95 in^2 per 100 ft^2 of surface area. The ACH_{50} for an EnergyStar home must be less than 5 and the ELA for tight house is usually less than 2.5 in^2 per 100 ft^2. The data shows the house has approximately 3 times less infiltration than a typical well built home.

Figure A-2 shows the pressure – flow data in both a regular and logarithmic form. The exponent, n, in the equation listed below is 0.629, which also implies the leakage paths are “long” and approach laminar flow.

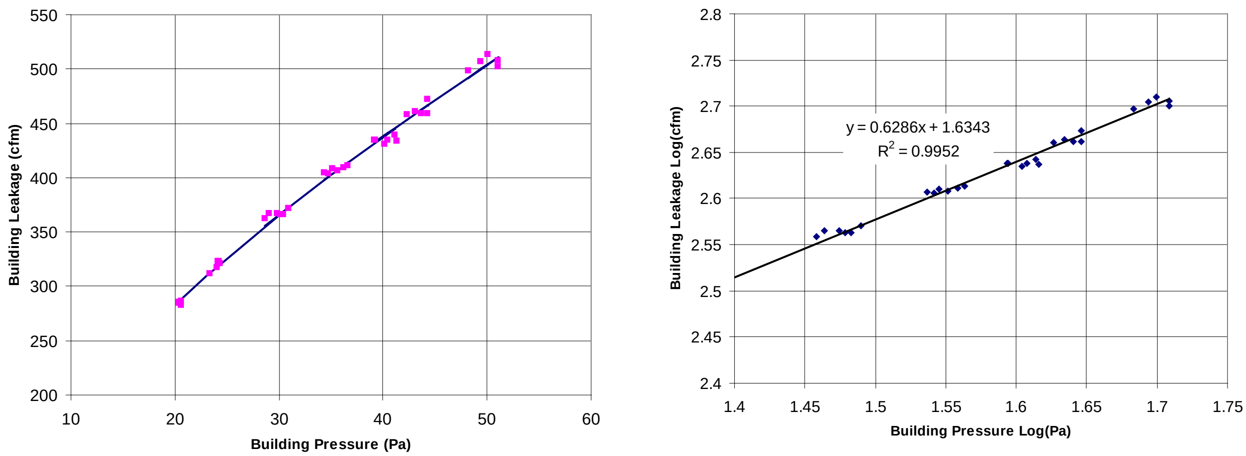


Figure A-2. Variation of House Leakage with Pressure: $cfm = K(\Delta P)^n$

Table A-2. Blower Door Test Results - Kilmer

Building Geometry

Floor Area:	1,584	ft^2
Total Volume:	17,641	ft^3
Envelope Area:	3,584	ft^2

Test Results:

Flow Coefficient (K)	43.1	1,584 sq ft, floor area
Exponent (n)	0.629	
Leakage area (LBL ELA @ 4 Pa)	29.2 sq in	0.81 ELA / 100 sq ft
Airflow @ 50 Pa	503.7 cfm	1.71 ACH @ 50

Test Data:

Nominal Building Pressure (Pa)	Nominal Flow (cfm)	Ring
50.1	513	B
48.2	498	B
49.4	507	B
51.1	502	B
51.1	508	B
43.1	461	B
43.7	459	B
44.3	459	B
44.3	472	B
42.3	458	B
41.3	434	B
40.2	431	B
39.2	435	B
39.3	435	B
40.5	435	B
41.1	439	B
36.2	409	B
36.6	411	B
35.6	406	B
35.1	408	B
34.4	405	B
34.8	404	B
28.7	362	B
29.1	367	B
29.8	367	B
30.1	366	B
30.4	366	B
30.9	372	B
24.2	323	B
24.1	323	B
24.3	321	B
24.0	317	B
23.4	312	B
20.6	283	B
20.4	284	B
20.6	286	B
20.4	285	B

Woodstove operating during pressurization test

Bloor Door installed in South Door

Penetrations between Kitchen and 3-Seasons Room

APPENDIX B: HYSPOT INSTALLATION SUMMARY

Installation and verification of the data logging system occurred during three trips in between May and July 2007. The majority of the data logging equipment was installed during the initial visit on May 23 and subsequent trips were required for verification of the data logging system and installation of new sensors.

A dedicated monitoring system was installed to measure power, temperatures and space conditions of the house. A Campbell Scientific CR10x was used to collect data at the site on a 15-minute interval. The CR10x has the capability of reading 12 analog and 5 digital channels. Data is collected through a modem by a dedicated phone line once a day. The project webpage[4] is then updated via automated processes that are initiated after successful data collection has occurred.

Table 1 displays the data points installed at the Hyspot House.

Table 11. Summary of Monitored Data Points

Channel Type	Logger Channel	Name	*Description*	*Eng Units*	Instrument
Pulse	P1	WT	Total House Power	kWh/kW	Ohio Semitronics WL40R - 053
Pulse	P2	WDHW	Domestic Water Heater Power	kWh/kW	Ohio Semitronics WL40R - 049
Pulse	C6	SDR	Door Photo Sensor	min	Newark 89F1404/89F1401
Pulse	C6	CDR	Door Photo Sensor	count	Newark 89F1404/89F1401
Pulse	C7	WP	Well Pump Power	kWh/kW	Ohio Semitronics SWH - 2100
Pulse	C8	WHP	Heat Pump Power	kWh/kW	Ohio Semitronics SWH - 2100
Analog	A2	TCW	Water Entering Heat Pump	°F	Watlow Type T-TC
Analog	A3	TWLS	South Wall Sheathing Temperature	°F	Watlow Type T-TC
Analog	A4	TAI	Indoor Temperature	°F	Watlow Type T-TC
Analog	A5	TSE	Supply Temperature (into slab)	°F	Watlow Type T-TC
Analog	A6	TSL	Supply Temperature (from slab)	°F	Watlow Type T-TC
Analog	A7	TAO	Outdoor Temperature	°F	Watlow Type T-TC
Analog	A8	TWALL	North Wall Sheathing Temperature	°F	Watlow Type T-TC
Analog	A9	TWO	Water Leaving Heat Pump	°F	Watlow Type T-TC
Analog	A10	RHI	Indoor RH	%	Vaisala HMD60U
Analog	A11	CO2	Carbon Dioxide Concentration	ppm	Telaire Ventostat 8102

[4] http://cdhenrgy.user.openhosting.com/cdhenergy.com/adirondack/index.htm
username: adirondack
password: solar

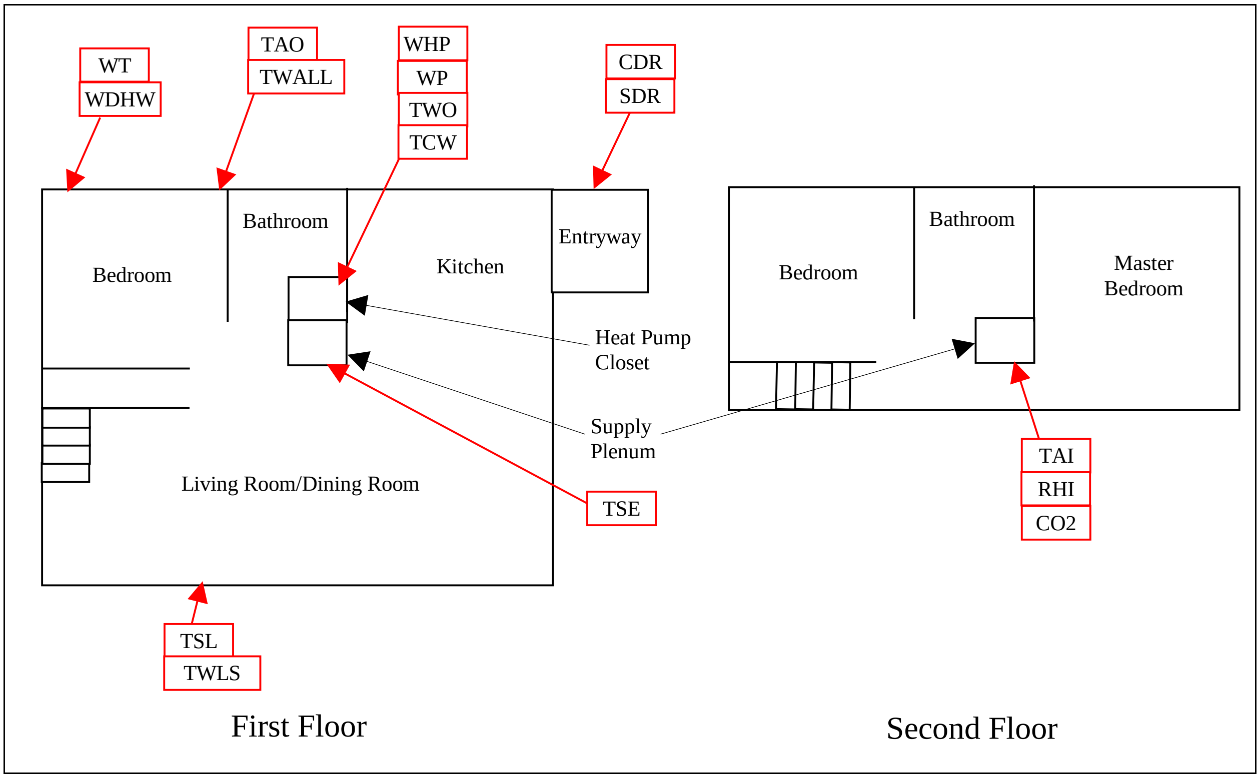


Figure 44. Sensor Locations in Hyspot House

Figure 45. CR10x Installed in Bathroom above Toilet

The following section details the installation timeline:

May 23, 2007

- All thermocouples installed
- Door Photo Sensor Installed
- 50 Amp CTs installed for Whole House Power and Domestic Water Heater Power
- RH and CO_2 sensors installed at top of Plenum
- Data Logger wired for Data Collection on installed points.

June 15, 2007

- Un-calibrated CO_2 sensor replaced with calibrated sensor.
- 100 Amp CTs installed to correct Total House Power Reading
- Heat Pump Power and Well Pump Power sensors installed and Heat Pump Power was verified.
- Supply fan power read for Heat Pump Statuses.
- Phone line connected and capability to collect data via modem was verified.
- Official data collection begins.

July 17, 2007

- Replaced CO_2 sensor with original sensor (now calibrated).
- 100 Amp CT installed to correct Domestic Water Heater Power. Measurement was verified.
- Attempted to install Heating, Cooling and Supply Fan statuses but determined it's not feasible due to unit/thermostat wiring.
- Verified/calibrated accessible thermocouples.
- Performed Blower Door Test.

Heat Pump Statuses

An attempt was made to install status sensors for heating operation, cooling operation and supply fan operation on the thermostat wiring. The unit is oriented so that the heat pump controls are not accessible, which is where all three sensors were to be located. We used the heat pump power (see Figure 3) and the heat pump entering and leaving air temperatures to assign the statuses.

Supply Fan Status

The fully-on supply fan power was measured at 340 Watts. When the heat pump power exceeds 340, the supply fan is assumed to be fully on, otherwise runtime is assumed proportional to the heat pump power.

Cooling Status

The fully-on cooling power observed in the data is 1.64 kW. When the difference between the air temperature entering the heat pump and leaving is greater than 2ºF, the heat pump is in cooling mode. When the heat pump power exceeds 1.64, it assumed to be fully on. Below 1.64, the cooling runtime fraction is assumed proportional to the fully-on cooling power minus the supply fan power.

Heating Status

The heating status is assigned similarly to the cooling status, with a fully-on heating power of 1.92 kW and the reverse of the heat pump entering and leaving air conditions.

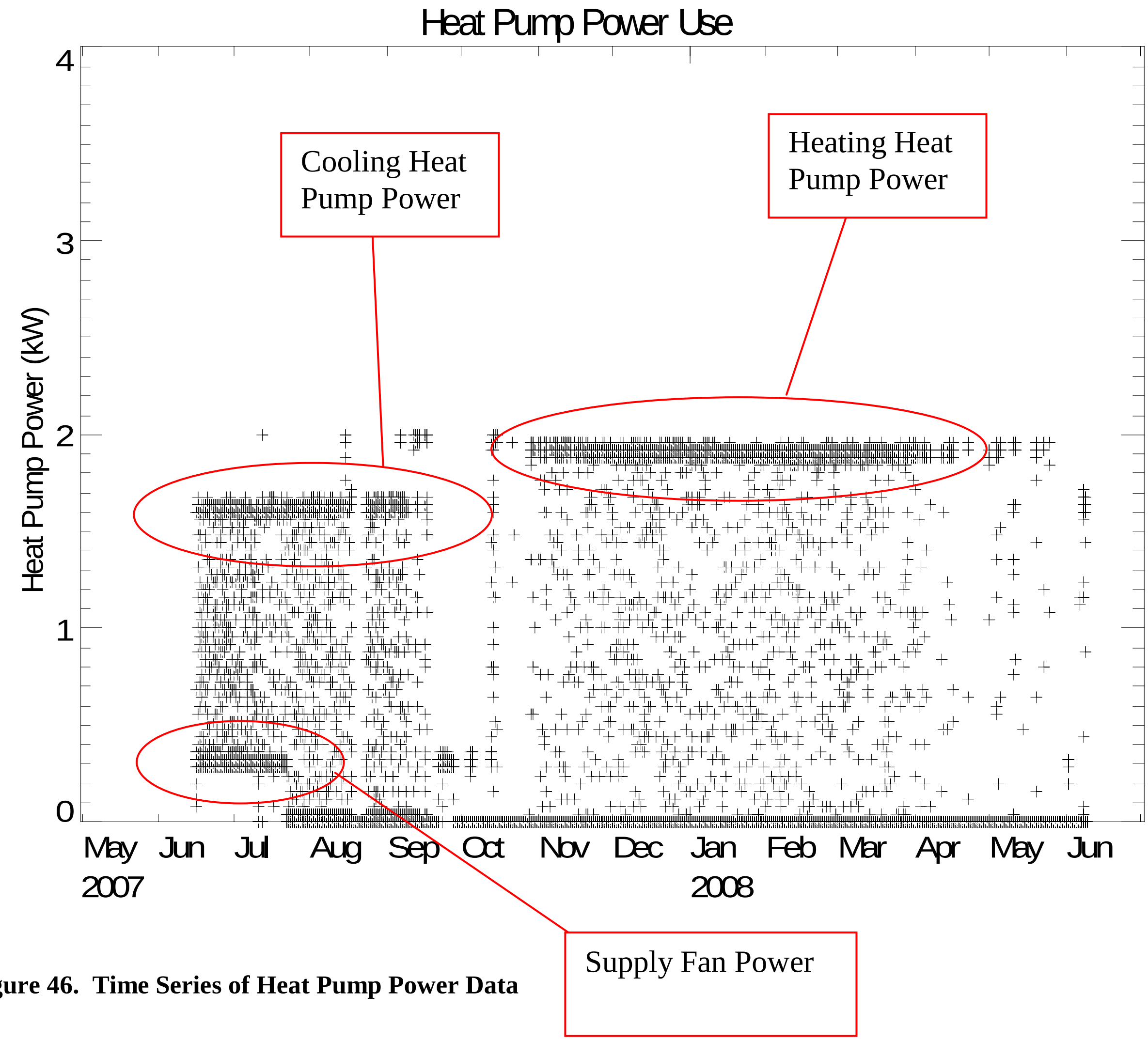


Figure 46. Time Series of Heat Pump Power Data

Verification Data

The data logger temperature sensors installed were calibrated to readings taken with a handheld thermocouple probe with a that had recently been ice water and boiling point calibrated against NIST traceable mercury thermometers.

The installed thermocouples were off by 1 to 3ºF from the handheld readings.

Table 12. Verification of Temperature Sensors

Data Point	Data Logger Reading (F)	Handheld Thermocouple Reading (F)[2]	Temperature Difference (F)	Percent Difference (%)
TAI	76.6	73.5	3.1	4.0%
TAO	78.6	77.0	1.6	2.0%
TSE[1]	52.0	66.0	-14.0	-26.9%
TSL	64.3	63.0	1.3	1.9%

Notes: [1] – An accurate Handheld Reading for TSE could not be taken because the temperature was varying too much from sample-to-sample.
[2] – Thermocouple probe readings were adjusted by adding 4°F to readings from a recent thermometer calibration.

A handheld Fluke power meter was used to confirm the power being recorded by the datalogger. The datalogger can perform a running average of the power over a given interval to be compared to instantaneous handheld readings during that interval, which should be representative.

The handheld readings were within 5% of the datalogger readings for WDHW and WHP (cooling). The WHP (fan only) reading was near the lower end of what can accurately be measured by the datalogger and fluke, so an 8% difference is acceptable. The WP could not be verified as operation was not observed during the verification readings.

Table 13. Verification of Power Readings

Data Point	Data Logger Reading (kW)	Handheld Power Reading (kW)	Power Difference (kW)	Percent Difference (%)
DHW	16.6	15.8	0.8	4.8%
WHP (cooling)	1.7	1.7	0.1	2.9%
WHP (fan only)	0.36	0.33	0.0	8.3%
WP[1]	0.0045	0.0130	0.0	-188.9%

Notes: [1] – The well pump was not running during the site visit so the power transducer could not be verified.

The Ambient temperature sensor at the house was compared to hourly data available from the Weather Underground (wunderground.com) for the Albany airport. The airport data reports at uneven intervals so all of the temperatures were match to their closest 15-minute intervals in our database for comparison. Figure 4 shows the ambient temperature sensor correlates well with the Weather Underground data.

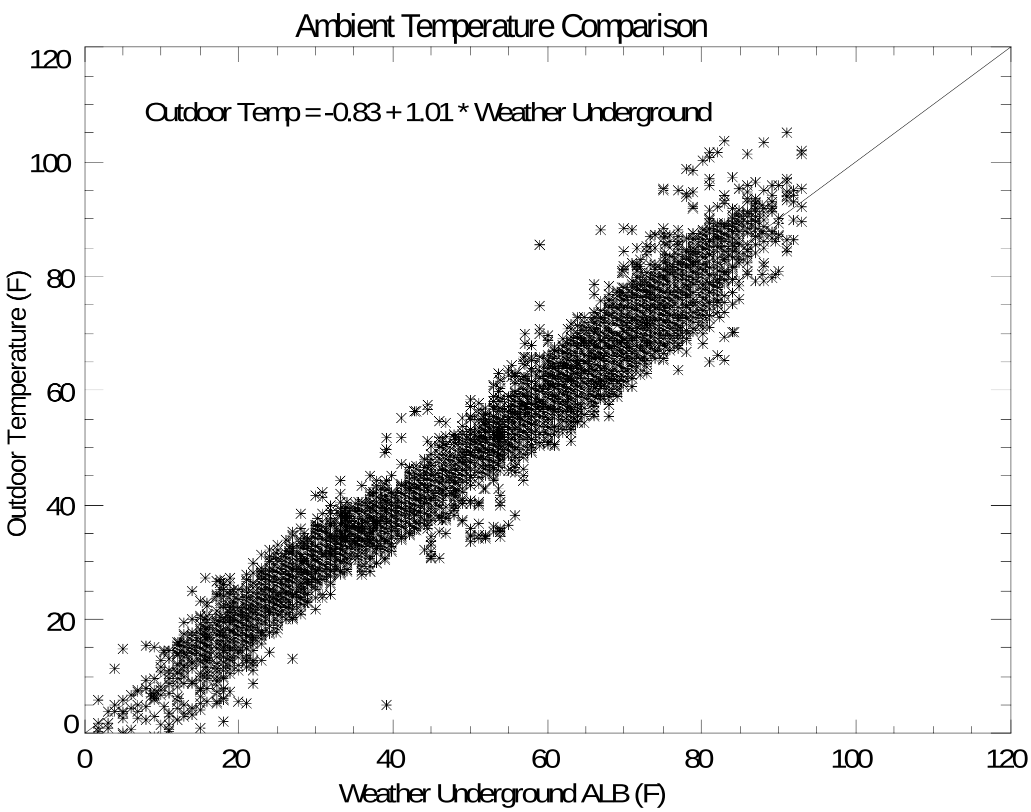


Figure 47. Ambient Temperature Comparison with Albany Airport

Figure 5 shows a shade plot of the ambient temperature. There are periods in the summer evening where the temperature jumps by about 5-10°F. This is due to direct sunlight hitting the sensor before dusk for periods of up to 2 hours. These periods represent a 10°F high-side bias in the daily temperature readings for up to 2 hours (approximately 8% of the day). At 2 hours, that would represent a daily temperature bias of 0.83°F (less than 1°F).

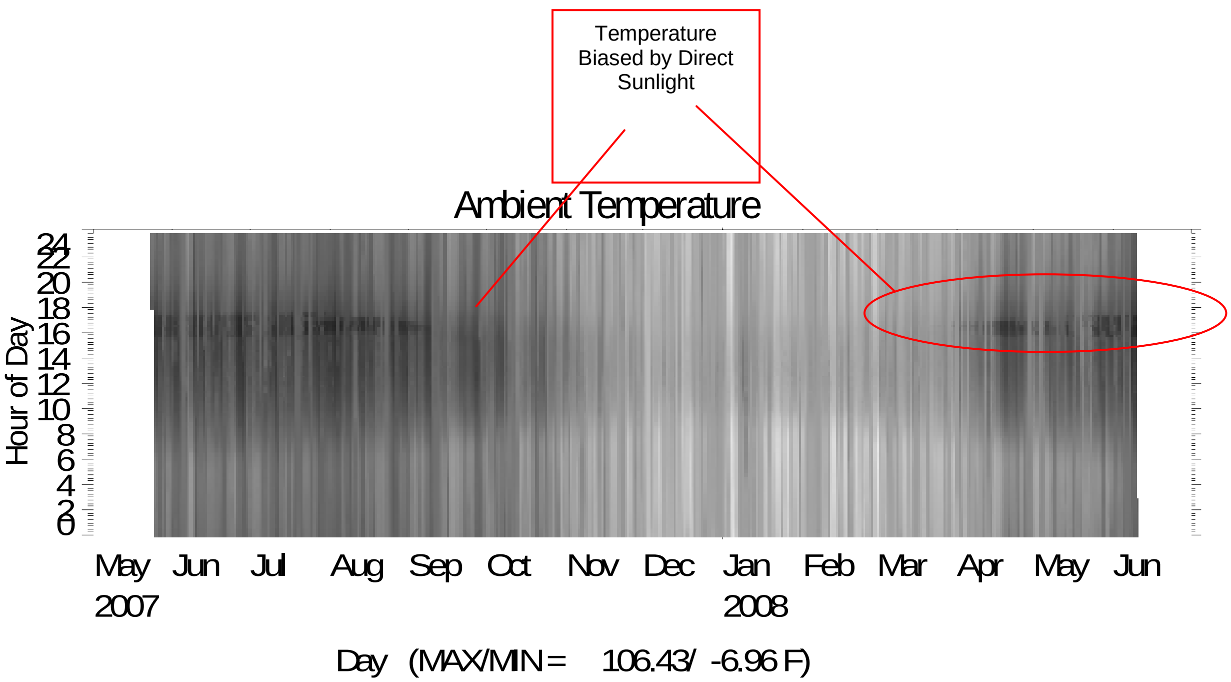
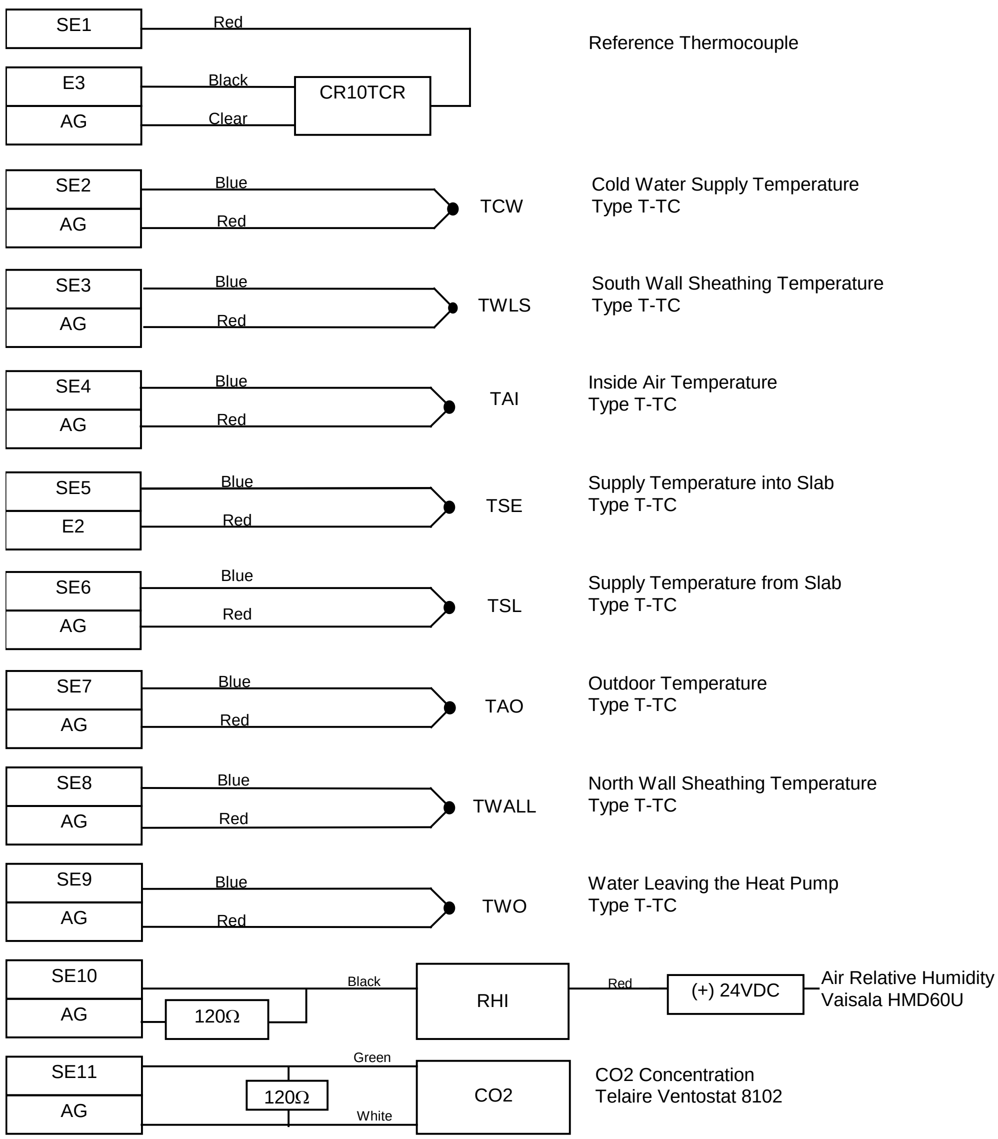
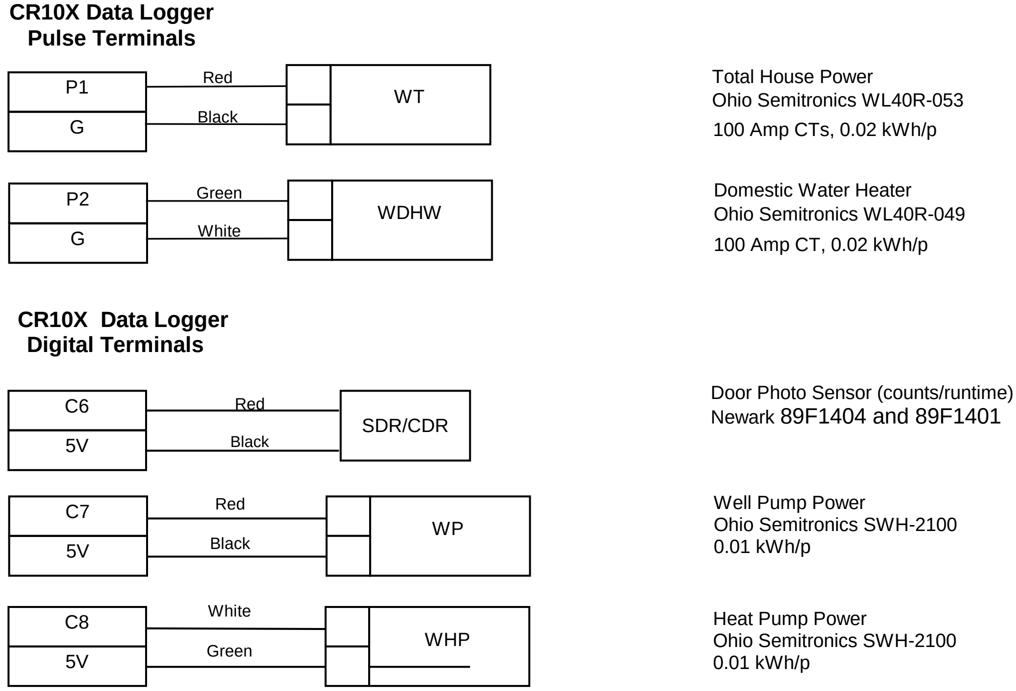


Figure 48. Hyspot House Ambient Temperature

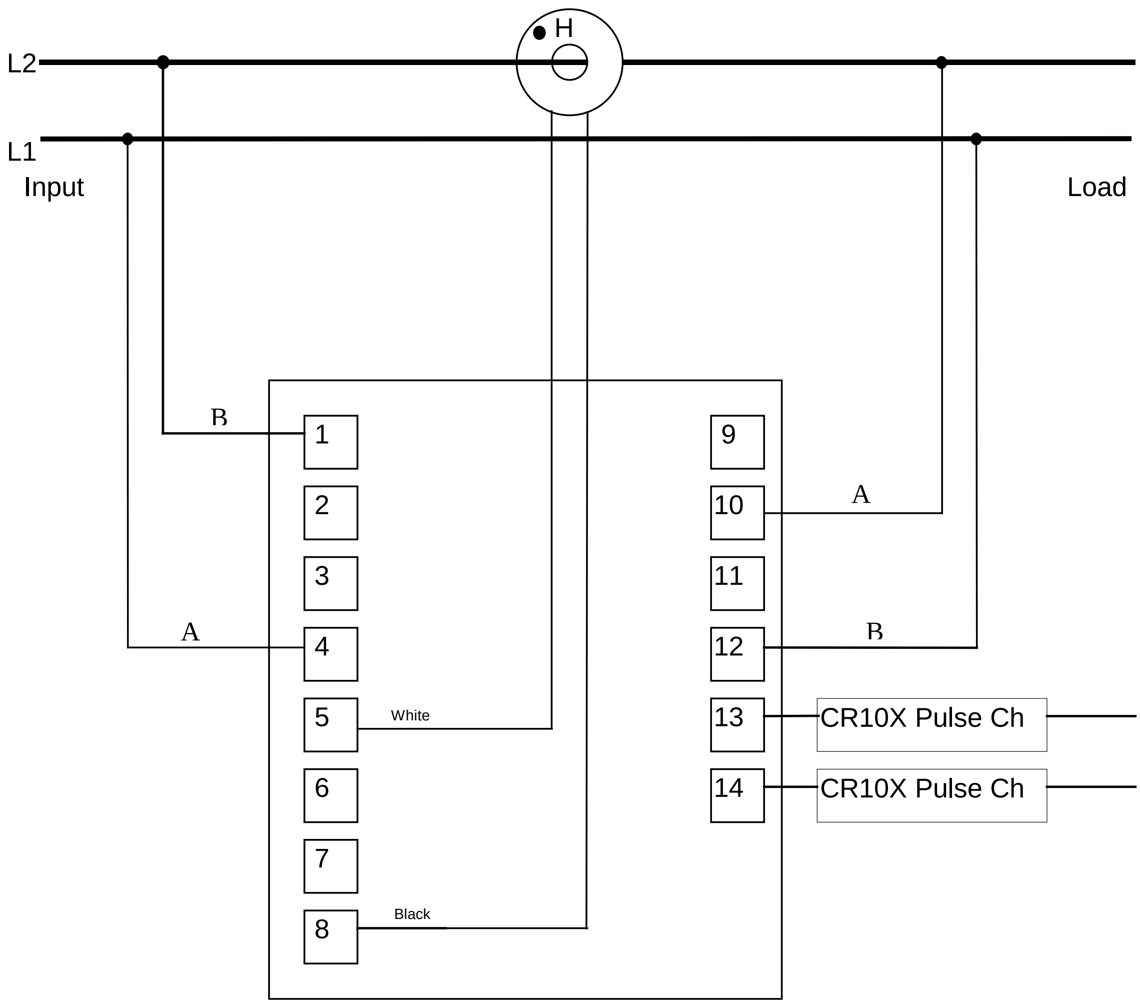
Wiring Diagrams

CR10X Data Logger
Analog Terminals

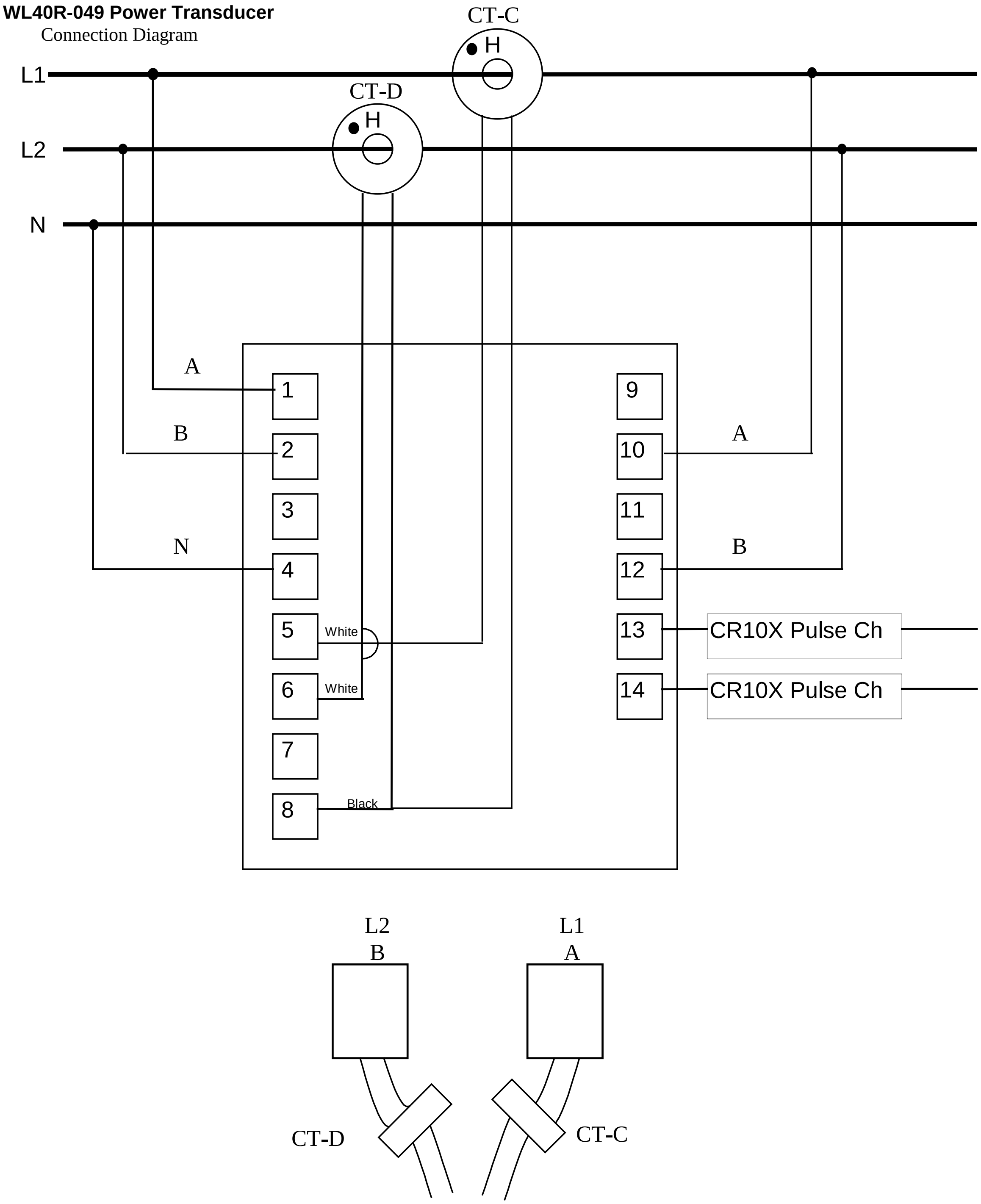



CR10X Data Logger
Pulse Terminals
P1
G
Red
Black
WT
Total House Power
Ohio Semitronics WL40R-053
100 Amp CTs, 0.02 kWh/p
P2
G
Green
White
WDHW
Domestic Water Heater
Ohio Semitronics WL40R-049
100 Amp CT, 0.02 kWh/p
CR10X Data Logger
Digital Terminals
C6
5V
Red
Black
SDR/CDR
Door Photo Sensor (counts/runtime)
Newark 89F1404 and 89F1401
C7
5V
Red
Black
WP
Well Pump Power
Ohio Semitronics SWH-2100
0.01 kWh/p
C8
5V
White
Green
WHP
Heat Pump Power
Ohio Semitronics SWH-2100
0.01 kWh/p

**WL40R-053 Power Transducer
Connection Diagram**



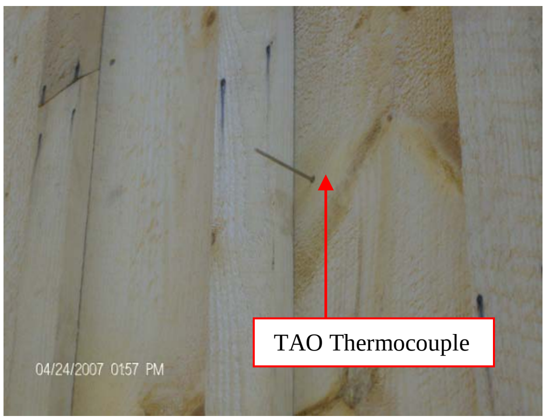
WL40R-049 Power Transducer
Connection Diagram



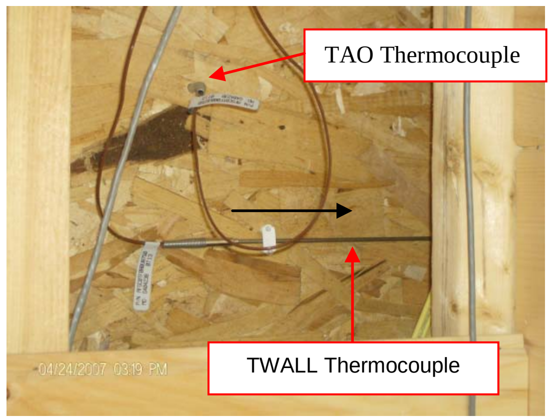
Site Photos

West and North Exterior Walls of the House

West and South Exterior Walls of the House

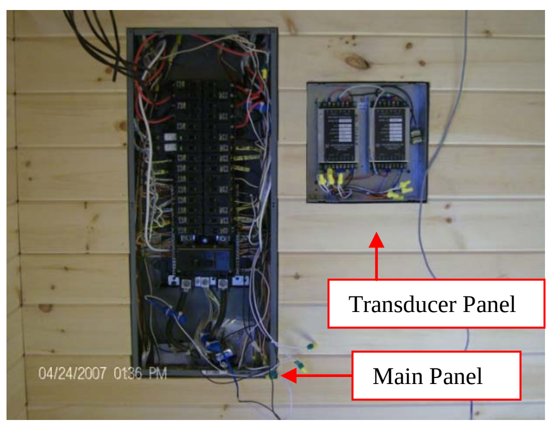


TAO at North Exterior Wall



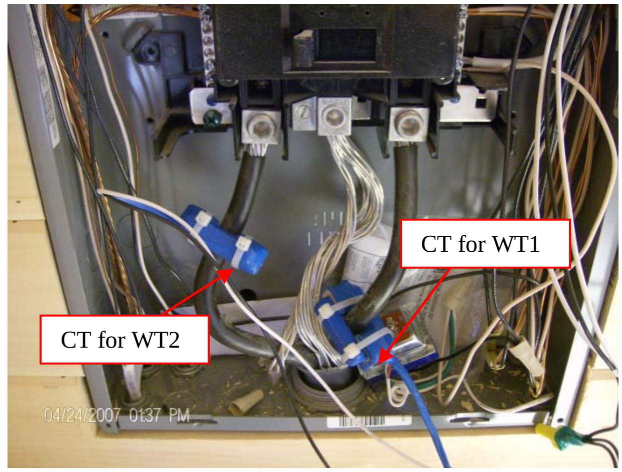
TAO and TWALL at North Interior Wall

Data Logger Panel in the Bathroom

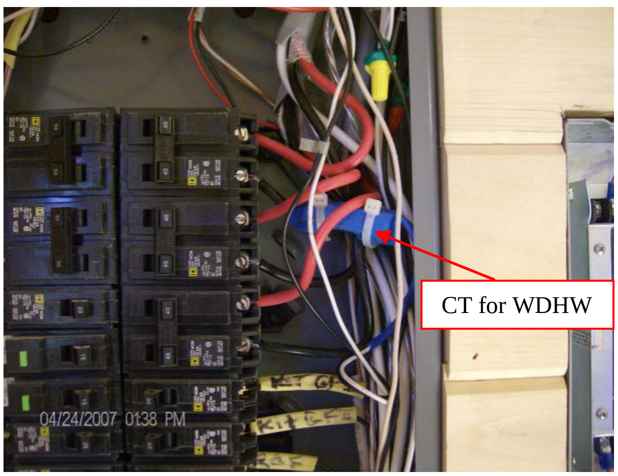


Main Panel and Transducer Panel in Northwest Room

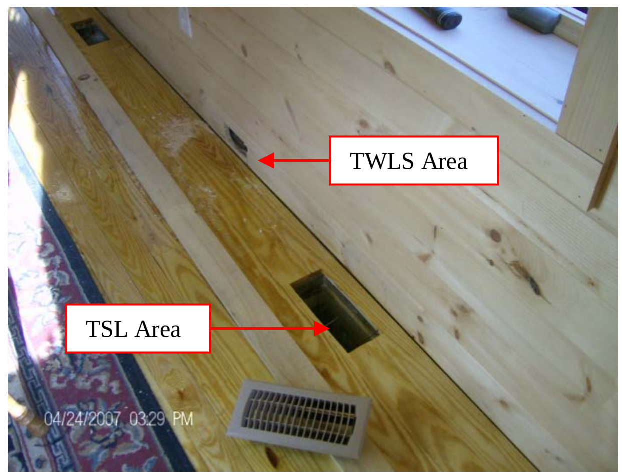
Transducer Panel in Northwest Room



CT's for WT1 and WT2 in Main Panel

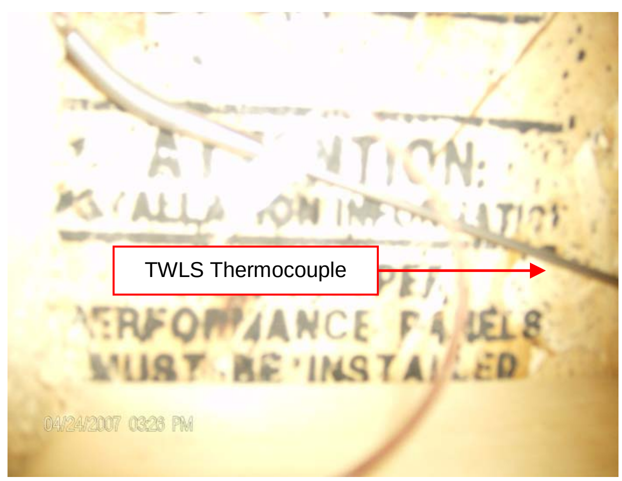


CT for WDHW in Main Panel



Locations of TSL and TWLS – South Interior Wall

TSL in Southwest Register



TWLS at the South Interior Wall

For information on other
NYSERDA reports, contact:

New York State Energy Research
and Development Authority
17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.org
www.nyserda.org

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