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Case study of a high efficiency home

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Case study of a high efficiency home

by

David Aaron Hamilton

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:

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Ames, Iowa

2006

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ABSTRACT

The PowerHouse home in Newton, IA was designed and built with energy efficiency in mind. The main technology being studied is ZeroNet's "super envelope" design, which incorporates expanded polystyrene bonded with a fiber-reinforced concrete coating on each side. The highly insulated walls and roof of the PowerHouse should reduce heating and cooling energy consumption by up to 50% throughout the year while the sophisticated HVAC equipment will improve air quality and human comfort by reducing pollutants inside the residence.

Research Goals

- Evaluate building envelope performance with regards to design heating and cooling loads
- Estimate the annual performance using a commercially available computer program simulation and compare it to actual performance
- Simulate the annual performance of a traditionally build home and compare it to the PowerHouse
- Monitor and analyze end-use electrical consumption for various HVAC and domestic equipment and appliances
- Evaluate the performance of the home as a whole using sub-metered data to calculate a performance index
- Compare the PowerHouse home's annual energy performance index with various other homes and government indexes
- Find ways of improving the performance of the installed mechanical systems

The design heating and cooling loads were calculated to be 31,659 Btu/hr and 24,828 Btu/hr, respectively. These design loads were calculated using the ASHRAE approved method outlined in the 2005 Fundamentals Handbook (ASHRAE, 2005).

The simulated annual energy consumption of the HVAC equipment was 18,217 kWh. The home actually consumed 19,167 kWh, so the simulation was fairly accurate. The annual energy consumption of a 2x6 built home of the same design was estimated to be 25,899 kWh. The 2x6 home uses 42% more energy for heating and cooling than the PowerHouse. This extra energy use equates to over \$575 per year of extra utility bills. Considering a modest 2% fuel inflation rate, over a ten year period the ZeroNet design would save over \$6,300. The higher U-value of the exterior walls and roof and the increased infiltration rate are the main factors contributing to the extra energy use.

In 2005, the PowerHouse consumed a total of 35,480 kWh of electricity. This corresponds to an energy intensity of 28.8 kBtu/ft². According to the Energy Information Administration (EIA, 2004), in 2001 the average energy intensity of a single-family detached home in the Midwest was 49 kBtu/ft² (EIA, 2004). Thus, the PowerHouse home represents a 41% improvement in energy intensity than the average.

Detailed monitoring conducted from January, 2005 thru December 2005 showed that there are several steps that could be taken to lower the annual energy consumption of the Powerhouse home. The domestic hot water system has large standby losses due to a recirculation system that keeps hot water at all the taps in the home. While the home was unoccupied and no hot water was being used, the domestic water heater consumed over 500 kWh per month. A clean air system integrated into the air handling unit relies on the fan running at low speed 100% of the time, even when there are no loads, to circulate air and carry away heat from the ultraviolet bulb fixture.

Overall the PowerHouse was performing as expected. The detailed monitoring showed that there were still ways to greatly reduce the overall energy use. Utilizing a geothermal system's higher coefficient of performance, the HVAC cost could be cut by over 60%. The domestic hot water load would also be supplemented by a de-superheater included with most heat pumps. The PowerHouse was already performing better than average, so applying these upgrades would make it all that much better.

NOMENCLATURE

Btu	=	British thermal unit
A	=	Area, ft ²
EPS	=	Expanded polystyrene
U	=	Thermal transmittance, Btu/hr*ft ² *°F
R	=	Thermal resistance, hr*ft ² *°F/Btu
q _{opq}	=	Opaque surface cooling load, Btu/h
CF _{opq}	=	Surface cooling factor, Btu/hr*ft ²
U	=	Construction U factor, Btu/hr*ft ² *°F
OF _t	=	Opaque-surface cooling factor
OF _b	=	Opaque-surface cooling factor
OF _r	=	Opaque-surface cooling factor
DR	=	Cooling daily range, °F
q _{fen}	=	Fenestration cooling load, Btu/hr
CF _{fen}	=	Surface cooling factor, Btu/hr*ft ²
PXI	=	Peak exterior irradiance, including shading modifications, Btu/hr*ft ²
SHGC	=	Fenestration rated NFRC solar heat gain coefficient, unitless
IAC	=	Interior shading attenuation coefficient
FF _s	=	Fenestration solar load factor
PXI	=	Peak exterior irradiance, Btu/hr*ft ²
E _t	=	Peak total irradiance, Btu/hr*ft ²
T _x	=	Transmission of exterior attachment (insect screen = 0.6)
q _{ig,s}	=	Sensible cooling load from internal gains, Btu/hr
q _{ig,l}	=	Latent cooling load from internal gains, Btu/hr
A _{cf}	=	Conditioned floor area of building, ft ²
N _{oc}	=	Number of occupants
Q _i	=	Infiltration airflow rate, cfm
A _L	=	Building effective leakage area, C _D =1, in ²
IDF	=	Infiltration driving force, cfm/in ²

A_{es}	=	Building exposed surface area, ft ²
A_{ul}	=	Unit leakage area, in ² /ft ²
I_0	=	Coefficient, Cooling = 343, Heating = 698
I_1	=	Coefficient, Cooling = 0.88, Heating = .81
I_2	=	Coefficient, Cooling = 0.28, Heating = .53
H	=	Building average stack height, 9 ft
$A_{L,flue}$	=	Flue effective leakage area, in ²
q_s	=	Sensible heat transfer rate, Btu/hr
q_l	=	Latent heat transfer rate, Btu/hr
q_t	=	Total heat transfer rate, Btu/hr
C_s	=	Air sensible heat factor, Btu/hr*°F*cfm (1.1 at sea level)
C_t	=	Air total heat factor, Btu/hr*cfm per Btu/lb enthalpy (4.5 at sea level)
Δh	=	Air enthalpy difference, Btu/lb
Δt	=	Temperature difference, °F
q	=	Heat loss, Btu/hr
HF	=	Heating Factor, Btu/ft ²
t_{in}	=	Below-grade space air temperature, °F
t_{gr}	=	Design ground surface temperature, °F
\bar{t}_{gr}	=	Mean ground temperature, °F
A	=	Ground surface temperature amplitude, °F
$U_{avg,bw}$	=	Average U-factor for wall region, Btu/hr*ft ² *°F
$U_{avg,bf}$	=	Average U-factor for basement floor, Btu/hr*ft ² *°F
k_{soil}	=	Soil thermal conductivity, 0.8 Btu/hr*ft*°F
R_{other}	=	Total resistance of wall assembly, h*ft ² *°F/Btu
z_1, z_2	=	Depth of top and bottom of wall, ft
z_f	=	Floor depth below grade, ft
w_b	=	Basement width (shortest dimension), ft
COP	=	Coefficient of performance, unitless

CHAPTER 1 - INTRODUCTION

Overview of Residential Heating, Ventilation, and Air-Conditioning

On average, heating and cooling a residential home accounts for up to 48 % of the annual energy bill (Energy Star, 2001). The other 52 % of the energy bill is for hot water, lighting, appliances, and miscellaneous plug loads. Reducing the amount of energy needed to heat and cool a residential home can have several positive economic and environmental impacts.

There are two main approaches to decrease heating and cooling costs in residential homes. The first method is to increase the insulation of the home which would decrease the actual amount of heat needed to maintain the indoor temperature during heating months. This extra insulation would also keep the heat out of the home in the summer months. The second way to decrease heating and cooling costs is to utilize equipment that can heat and cool more efficiently. A combination of increased insulation and higher efficiency equipment will yield the most energy savings throughout the year.

The main barrier that stops heat from moving into or out of the home is the envelope. Consisting of the exterior walls, windows, doors, roof, and foundation, the envelope is the most critical component that keeps the heat where it is needed. The heating and cooling system can produce heat very efficiently, but without the means to keep the heat in the home, the overall system will still use more energy.

Background of PowerHouse Home

The PowerHouse Home is a single family, detached home located in Newton, Iowa. The home has five bedrooms and 4200 square feet of conditioned floor area. The primary design of the home and thermal envelope was done by ZeroNet of Johnston, IA. ZeroNet's primary objective is to provide innovative design and construction solutions for an enhanced living and working environment. The design of the "super envelope"

and HVAC systems in the home should reduce utility bills and enhance the living environment by improving indoor air quality.

The construction of the PowerHouse home was completed at the end of August 2004. The home opened to the public early in September 2004. Utility bills have been collected since the opening in September 2004, but the commissioning of the data acquisition system wasn't complete until the middle of December 2004. For the ease of calculations, January 1st, 2005 was the official first day of analysis for this report. The house remained unoccupied, except for the occasional tour and showcase, until it was sold in late August 2005 to a single occupant. September 1st, 2005 was the first observed day of occupancy for the home. A timeline of the history of the home can be found in Figure 1.1.

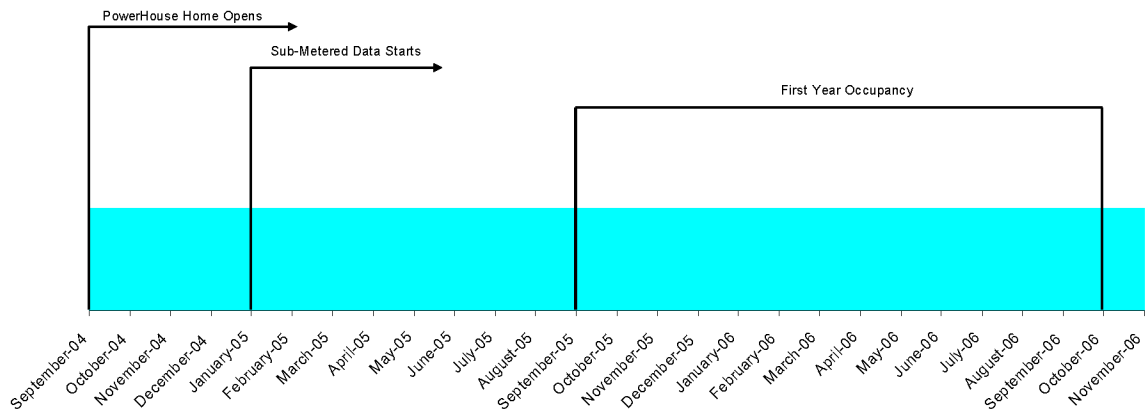


Figure 1.1: Timeline history of the PowerHouse home

The PowerHouse has two levels. The upper level floor is at the grade height except for the rear of the home where the walkout basement is at grade level. The floor plan for the upper and lower levels can be seen in Figures 1.2 and 1.3, respectively.

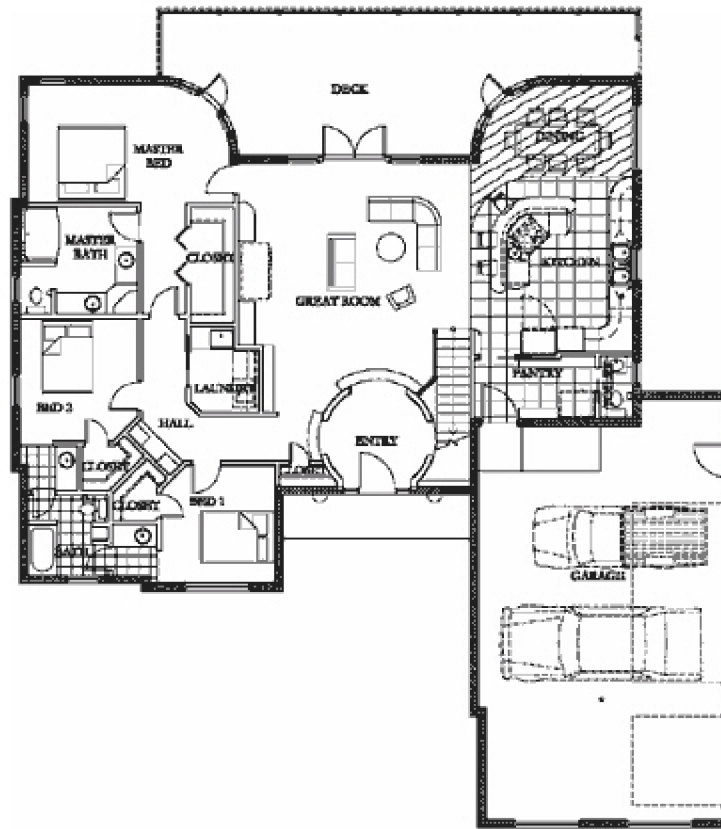


Figure 1.2: Floor plan of upper level

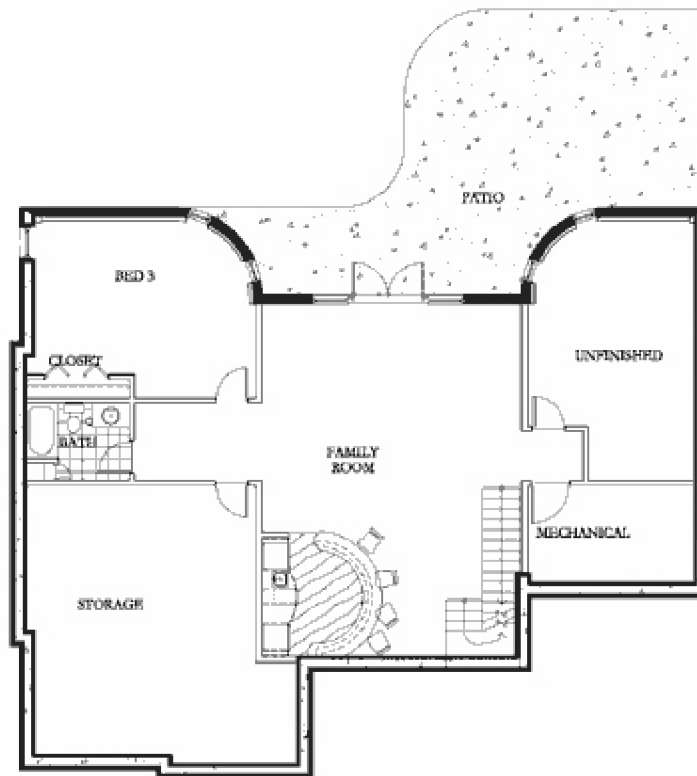


Figure 1.3: Floor plan of lower level

Overview of Case Study

This case study evaluated the performance of the PowerHouse home, focusing on the energy use dominated by the HVAC equipment. An ASHRAE approved method of calculating the design heating and cooling load was performed on the home. This hand calculation was verified with an estimate of the design loads created with energy estimating software. The design loads predicted by TRACE 700 were compared with the hand calculated loads. These estimates agreed so it can be assumed that both methods were applied correctly and the results can be trusted.

A major advantage of using TRACE 700 is the ability for it to simulate the performance of the home over an entire year. The annual energy use simulations done by TRACE 700 were compared with actual sub-metered data from the house. A simulation of a home

constructed with 2x6 framing was also presented so a comparison may be made regarding the energy savings associated with the high efficiency envelope design.

Sub-metered data recorded over a 12 month period was analyzed to understand the flow of energy in the house and to identify the problems and losses that occur in residential homes. The sub-metered data from the home was used to calculate a performance index that was compared to other residential homes and government indexes. This comparison was used to estimate the increased efficiency of the PowerHouse. Thus, several ways to improve the performance of residential energy systems will be documented.

CHAPTER 2 - POWERHOUSE HOME DESCRIPTION

The PowerHouse Home was not constructed with typical construction techniques or mechanical equipment. The following section will outline the major differences between the PowerHouse home and other traditionally constructed homes of the same size.

Building Envelope

The main technology being studied at the PowerHouse home is ZeroNet's high efficiency envelope design, which incorporates expanded polystyrene (EPS) bonded with a glass fiber reinforced concrete coating on each side. The EPS layer is the main thermal barrier in this design. The concrete coating protects the EPS from damage and also provides the necessary strength to combat the outdoor conditions. These panels take the place of the traditional 2×6 constructed wall sections which use exterior sheathing as a weather barrier and fiberglass insulation as the thermal barrier. The simplified design of the ZeroNet system leads to easier construction and thus reducing the labor involved in constructing a new home.

Wood framed walls utilizing 2×6 construction and R-19 insulation have an R-Value of 15.6. The eight inch EPS wall panels of the PowerHouse have an R-Value of 40. The twelve inch roof sections have an R-Value of 60. These R-Values are for the EPS layer only. The concrete coating on each side is thin enough that it may be ignored because of the low R-Value of concrete in general. A cross section of the wall section can be seen in Figure 2.1.

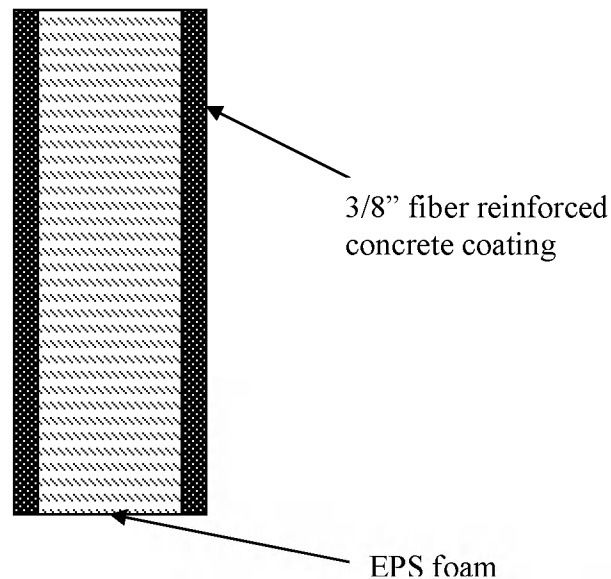


Figure 2.1: Cross section of Zero-Net wall and roof

Mechanical Systems

Cooling

Cooling is accomplished at the PowerHouse Home by a high efficiency Lennox split system. The supply fan utilizes a variable speed motor which switches among several speeds depending on the cooling load. An ultraviolet light contained in the air handling unit (Model: Lennox AM61V) helps to clean the air by killing bacteria and other organisms. This feature requires the supply fan to run on low speed 100% of the time, unless there is a call for cooling which increases the fan speed according to the load.

The condensing unit (Model: Lennox HSXA19-036) uses a two stage compressor to increase efficiency. During the majority of the cooling season, only the 1st stage of the compressor is used. This increases the efficiency by stopping the short cycling that occurs in oversized systems operating at low loads and helps to control the moisture in the air when there isn't a large demand for cooling. During design day conditions the

second stage is activated to handle the extra load that isn't seen for the majority of the cooling season.

Heating

Heating is accomplished by a hydronic radiant floor system. The heating water is produced by an electric boiler (Lennox HE212 82PC) and distributed to the zones through cross-linked polyethylene (PEX) tubing by a system of pumps and valves. The radiant floor system has 9 temperature controlled zones throughout the house, including the garage, which can all be kept at different temperatures. This feature allows the garage to be kept at a lower temperature than the rest of the residence, but still above the cold outdoor temperature.

The radiant floor heating system is generally more efficient than a forced air heating system. A forced air system increases the convective coefficient on the surface of the walls and windows because of the moving air. This will make the heat move faster out of the walls to the outdoors thus increasing the heating energy needed to maintain the indoor air temperature. The radiant floor system heats the surfaces of everything in the home by radiant heat transfer, which doesn't involve physically moving the air with the heat in it as a forced air system does. This concept leads the radiant floor heating system to be more efficient.

The heating and cooling systems work somewhat independently of each other so special care must be taken to ensure that they do not run at the same time. The thermostat settings do not let the systems run at the same time, but they don't stop the systems from alternating running time, especially when in 'auto' mode. Data collected from the monitoring equipment has shown that during some transitional season months both systems will alternate running throughout the day.

The domestic water is heated by a separate electric boiler (Lennox HE212 50PC). There is also hot water recirculation system that maintains hot water at all the taps of the home. The system is programmed to run at specific times during the day, especially during the morning and evening when the home will most likely be occupied.

Lighting Systems

A dimming system is installed at the PowerHouse home to automatically adjust the light levels depending on time of day and occupancy. At the time of construction, the Lutron dimming system could only dim regular light bulbs. Some of the lights at the PowerHouse are compact fluorescent type bulbs that use a lower wattage, but these lights cannot be dimmed. The original goal was to use all low wattage, compact fluorescent lights, but the Lutron system didn't support fluorescent bulbs. The new dimming systems on the market with updated circuitry can utilize fluorescent bulbs. In the future this system will be used to greatly reduce the electricity needed to illuminate homes.

The Lutron system also controls the blinds on many of the windows within the main living areas. The blinds can be set on a daily schedule or manually opened and closed when needed. This system can be utilized to minimize solar heat gain in the summer, and maximize the heat gain during the winter. It is also a luxury feature to be able to open and close all the blinds in the room with a single switch.

All of these systems in use at the PowerHouse were designed to work together to maximize efficiency and comfort while still providing for a luxurious style of living.

CHAPTER 3 - HEATING AND COOLING ENERGY ANALYSIS

The design heating and cooling loads were calculated using ASHRAE approved techniques found in chapter 29 of the 2005 Fundamentals Handbook (ASHRAE, 2005). The procedure is called the Residential Load Factor (RLF) method and is a simplified process that uses load factors derived from thousands of cooling load results across the U.S. These results are from a computerized program called ResHB that was used to analyze many buildings in several different climate zones (ASHRAE, 2005). The advantage of using the RLF method is that it can be easily applied to many residences in a simple spreadsheet format.

The following sections detail the steps involved with using the RLF method to estimate design cooling and heating loads. The indoor design temperature for cooling and heating is 71 °F and 70°F, respectively. This is the set-point of the thermostat at the PowerHouse so using it will be consistent with the actual operation of the HVAC equipment. The outdoor air design temperature is 90.3 °F for cooling and -2.9 °F for heating.

Design Cooling Loads

This method of calculating the design cooling load takes into account the sensible heat gain from several components of the home. First the heat gain from the opaque surfaces of the home was calculated. Next, the heat gain due to transparent fenestrations was calculated. Then, the sensible and latent heat loads due to occupancy and infiltration were found.

Heat Gain through Opaque Surfaces

The cooling load for each surface was found by first calculating a cooling factor (CF) for that surface, and then multiplying by the area of the surface. The cooling factor takes into account the temperature difference across the surface and also the solar gains

incident on the surface. The following equations show how the sensible heat gains for the opaque surfaces were calculated:

$$q_{opq} = A \times CF_{opq} \quad (3.1)$$

$$CF_{opq} = U \times (OF_t \times \Delta t + OF_b + OF_r \times DR) \quad (3.2)$$

where

$$\begin{aligned} q_{opq} &= \text{opaque surface cooling load, Btu/hr} \\ A &= \text{net surface area, ft}^2 \\ CF_{opq} &= \text{surface cooling factor, Btu/hr*ft}^2 \\ U &= \text{construction U factor, Btu/hr*ft}^2\text{*}^\circ\text{F} \\ \Delta t &= \text{cooling design temperature difference, } 19.3 \text{ }^\circ\text{F} \\ OF_t, OF_b, OF_r &= \text{opaque-surface cooling factors} \\ DR &= \text{cooling daily range, }^\circ\text{F} \end{aligned}$$

The OF factors found in equation 3.2 represent construction specific characteristics that capture buffering effects (OF_t), incident solar gains (OF_b), and heat storage effects (OF_r). The actual values used for this home can be seen in Table 3.1.

Table 3.1: Opaque surface cooling factor coefficients

Surface Type	OF_t	OF_b	OF_r
Ceiling/roof assembly	1	$70.2\alpha_{\text{roof}} - 12.2$	-0.42
Wall or door with solar exposure	1	14.2	-0.34
Shaded wall or door	1	0	-0.34

The roof solar absorptance (α_{roof}) is 0.80. This value is read from a table and corresponds to the medium colored tiles on the roof (ASHRAE, 2005). Table 3.2 below details the coefficients used to calculate CF_{opq} .

Table 3.2: Opaque cooling factor calculation

Surface	Area ft ²	U Btu/hr*ft ² *°F	Oft	Ofb	Ofr	CFopq Btu/hr*ft ²
Ceiling	3,369	0.017	1	43.96	-0.42	0.921
Exterior Wall	1,672	0.025	1	14.2	-0.34	0.681
Garage Wall	198	0.025	1	0	-0.34	0.326
Front Door	45	0.300	1	0	-0.34	3.923
Bedroom Door	24.5	0.300	1	14.2	-0.34	8.183
Door to Garage	24.5	0.300	1	0	-0.34	3.923

Heat Gain through Transparent Fenestration Surfaces

Transparent fenestration surfaces are calculated very much the same way as opaque surfaces, except for a slightly more complicated CF equation.

$$q_{fen} = A \times CF_{fen} \quad (3.3)$$

$$CF_{fen} = U \times (\Delta t - 0.49DR) + PXI \times SHGC \times IAC \times FF_s \quad (3.4)$$

where

- q_{fen} = fenestration cooling load, Btu/hr
- A = fenestration area (including frame), ft²
- CF_{fen} = surface cooling factor, Btu/hr*ft²
- U = fenestration NFRC heating U-Factor, Btu/hr*ft²*°F
- Δt = cooling design temperature difference, 19.3 °F
- PXI = peak exterior irradiance, including shading modifications, Btu/hr*ft²
- $SHGC$ = fenestration rated NFRC solar heat gain coefficient,
- IAC = interior shading attenuation coefficient
- FF_s = fenestration solar load factor

The transparent fenestrations at the PowerHouse do not have significant shading so the cooling load contributions of the windows correlates well with the peak hour irradiance

incident on the fenestration exterior (ASHRAE, 2005). The following equation is used to calculate the PXI:

$$PXI = T_x \times E_t \quad (3.5)$$

where

$$\begin{aligned} PXI &= \text{peak exterior irradiance, Btu/hr*ft}^2 \\ E_t &= \text{peak total irradiance, Btu/hr*ft}^2 \\ T_x &= \text{Transmission of exterior attachment (insect screen = 0.6)} \end{aligned}$$

The IAC is specific to the type of interior shade being used. The automatic shading devices installed at the PowerHouse correspond to an IAC value of 0.71 (ASHRAE, 2005). The fenestration solar load factor (FF_s) takes into account the exposure of the fenestration. Windows facing the south or west will typically have the highest solar gain in the afternoon, which is when the design cooling load will occur. Table 3.3 shows the calculated CF_{fen} values for each fenestration surface.

Table 3.3: Transparent surface cooling factors

Exposure	Area ft ²	U Btu/hr*ft ² *°F	T _x	PXI Btu/hr*ft ²	SHGC	IAC	FFs	CF _{fen} Btu/hr*ft ²
South	29.9	0.300	1.0	153	0.4	0.71	0.45	22.65
South	29.9	0.300	1.0	153	0.4	0.71	0.45	22.65
South	22.2	0.300	1.0	153	0.4	0.71	0.45	22.65
East	22.6	0.300	0.6	157	0.4	0.71	0.17	10.66
East	40.9	0.300	0.6	157	0.4	0.71	0.17	10.66
North	17.4	0.300	0.6	36	0.4	0.71	0.17	4.84
North	18.7	0.300	1.0	60	0.4	0.71	0.17	6.00
North	37.7	0.300	1.0	60	0.4	0.71	0.17	6.00
West	29.9	0.300	1.0	261	0.4	0.71	0.48	38.68
West	29.9	0.300	1.0	261	0.4	0.71	0.48	38.68
West	138.7	0.300	0.6	157	0.4	0.71	0.48	24.45
West Door	37.0	0.300	1.0	261	0.4	0.71	0.48	38.68
West LL	22.6	0.300	1.0	261	0.4	0.71	0.48	38.68
West LL	29.9	0.300	1.0	261	0.4	0.71	0.48	38.68
West LL	109.2	0.300	0.6	157	0.4	0.71	0.48	24.45

The last step to finish the transmission and solar heat gain calculation was to multiply the cooling factor of each surface by the area of that corresponding surface. Table 3.4 illustrates the total heat gain through the exterior walls and fenestrations due to the design temperature difference and solar rays incident on the surfaces.

Table 3.4: Total transmission and solar heat gain

Surface	Design Cooling Load Btu/hr
Exterior Walls and Doors	4,804
Windows	14,799

Internal Load Heat Gain

The internal loads were calculated using the ASHRAE approved equations derived from Building America load profiles (ASHRAE, 2005). There are two equations used to estimate the internal loads, one is for the sensible heat and the other is for latent heat. The latent heat equation takes into account the factors that lead to latent heat gain (cooking, showers, breathing).

$$q_{ig,s} = 464 + 0.7A_{cf} + 75N_{oc} \quad (3.6)$$

$$q_{ig,l} = 68 + 0.07A_{cf} + 41N_{oc} \quad (3.7)$$

where

- $q_{ig,s}$ = sensible cooling load from internal gains, Btu/hr
- $q_{ig,l}$ = latent cooling load from internal gains, Btu/hr
- A_{cf} = conditioned floor area of building, ft²
- N_{oc} = number of occupants

There is 4200 ft² of conditioned floor area at the residence and an assumed occupancy of 4 for the internal gain calculation. Using equations (3.6) and (3.7) the sensible and latent heat gains are 3432 Btu/hr and 480 Btu/hr, respectively.

Infiltration Heat Gain

The PowerHouse home is not of typical construction so care must be taken when evaluating the infiltration. Typically homes of this type of construction are naturally airtight so the ASHRAE method would not be applicable. There are a few factors associated with this home that allow the ASHRAE method to be used. First, there is an economizer installed in the air handling unit which does allow some infiltration through leaks in the damper. Secondly, there are an above average number of windows in this residence which contribute to infiltration. These factors should allow the ASHRAE method of using an assumed average leakage per unit of building surface area to be acceptable. The following equations are used to estimate the leakage into the home.

$$Q_i = A_L \times IDF \quad (3.8)$$

$$A_L = A_{es} \times A_{ul} \quad (3.9)$$

where

$$\begin{aligned} Q_i &= \text{infiltration airflow rate, cfm} \\ A_L &= \text{building effective leakage area, assuming discharge} \\ &\quad \text{coefficient } C_D=1, \text{ in}^2 \\ IDF &= \text{infiltration driving force, cfm/in}^2 \\ A_{es} &= \text{building exposed surface area, ft}^2 \\ A_{ul} &= \text{unit leakage area, in}^2/\text{ft}^2 \end{aligned}$$

To solve the infiltration equations, the exposed building area was determined. This includes all exterior walls and roofs that are exposed to outdoor air. The PowerHouse

home has 5511 ft² of exposed surface area. The unit leakage area (A_{ul}) is determined by the quality of construction of the home. As described earlier, the PowerHouse home's construction technique leads to very little infiltration. This would be considered a "tight" construction so a value of 0.01 in²/ft² would be appropriate. The infiltration driving force (IDF) is what drives the outdoor air into the residence. The following relationship has been derived for design conditions.

$$IDF = \frac{I_0 + H \times |\Delta t| \times [I_1 + I_2 (A_{L,flue} / A_L)]}{1000} \quad (3.10)$$

where

$$\begin{aligned} I_0 &= \text{coefficient, Cooling} = 343, \text{ Heating} = 698 \\ I_1 &= \text{coefficient, Cooling} = 0.88, \text{ Heating} = 0.81 \\ I_2 &= \text{coefficient, Cooling} = 0.28, \text{ Heating} = 0.53 \\ H &= \text{building average stack height, 9 ft} \\ A_{L,flue} &= \text{flue effective leakage area, in}^2 \end{aligned}$$

The PowerHouse home is all electric so there are no flues to account for. The average stack height is the distance between the floor and ceiling, which is 9 ft for the residence being studied. The following table shows the infiltration rate at the cooling design condition.

Table 3.5: Infiltration rate for cooling design day

Infiltration	A_{es} ft ²	A_{ul} in ² /ft ²	IDF cfm/in ²	Q_{inf} cfm
Cooling Design	4,271	0.01	0.5	22.3

Once the infiltration rate was calculated, the sensible and latent heat carried in by the air on a volumetric basis were determined using the following equations.

$$q_s = C_s \times Q_{\text{inf}} \times \Delta t \quad (3.11)$$

$$q_t = C_t \times Q_{\text{inf}} \times \Delta h \quad (3.12)$$

$$q_t = q_s + q_l \quad (3.13)$$

where

- q_s = sensible heat transfer rate, Btu/hr
- q_l = latent heat transfer rate, Btu/hr
- q_t = total heat transfer rate, Btu/hr
- C_s = air sensible heat factor, Btu/hr*°F*cfm (1.1 at sea level)
- C_t = air total heat factor, Btu/hr*cfm per Btu/lb enthalpy (4.5 at sea level)
- Δh = air enthalpy difference, Btu/lb
- Δt = air temperature difference, °F

The heat factors are given at sea level but can be used for elevations up to 1,000 ft.

Using psychrometric charts, the enthalpy difference (Δh) between the indoor air (71°F, 45% RH, 20 Btu/lb) and outdoor air (90°F, 40% RH, 35 Btu/lb) is 15 Btu/lb. This corresponds to a total infiltration heat gain of 1,503 Btu/hr.

Design Heat Gain Summary

Every heat gain portion needed to complete the design cooling load calculation has been presented. The contribution of each source of heat gain to the total design cooling load can be seen in Table 3.6. The total design cooling load was calculated to be 24,828 Btu/hr (2.1 tons).

Table 3.6: Summary of design cooling loads

Heat Gain	Opaque Surfaces	Windows	Internal Gains	Infiltration	Total
	Btu/hr				
Sensible	4,804	14,799	3,242	473	23,318
Latent	0	0	480	1,030	1,510
Total	4,804	14,799	3,722	1503	24,828

Design Heating Load

The calculation of the design heating load is similar to the cooling load except for a few small differences that make it simpler. First, since the design heat loss will most likely occur at night, there will be no solar contribution. This makes it a basic $Q=UA\Delta t$ relationship. Second, the internal gains are ignored to make sure the heating equipment will be sized large enough. This section calculates the opaque and fenestration surface design heat loss for the residence, with special attention being paid to the below-grade wall sections and basement floor. The heat loss due to infiltration was also calculated and included into the design heat loss value.

Opaque and Transparent Surface Heat Loss

All above grade surfaces that are exposed to outdoor conditions will be treated like a simple one dimensional heat conduction problem. The area of each surface was multiplied by its corresponding heating load factor to come up with that surface's heat loss.

$$q = A \times HF \quad (3.14)$$

$$HF = U \times \Delta t \quad (3.15)$$

where

- q = heat loss, Btu/hr
 A = area of surface, ft²
 U = U-value of surface, Btu/hr*ft²*°F
 Δt = heating design temperature difference, 72.9 °F

Tables 3.7 and 3.8 show the opaque and fenestration surfaces and the associated heat loss associated with them.

Table 3.7: Heat loss for opaque surfaces

Opaque Surfaces	Area ft ²	U-Value Btu/h*ft ² *°F	HF Btu/hr*ft ²	q Btu/hr
Ceiling	3,369	0.017	1.22	4,101
Exterior Wall	1,672	0.025	1.82	3,046
Basement Wall	1,494	0.025	1.00	1,494
Garage Wall	198	0.025	0.50	99
Front Door	45	0.300	21.87	984
Bedroom Door	25	0.300	21.87	536
Door to Garage	25	0.300	6.00	147

Table 3.8: Heat loss for fenestration surfaces

Fenestration Exposure	Area ft ²	U-Value Btu/h*ft ² *°F	HF Btu/hr*ft ²	q Btu/hr
South	29.9	0.300	21.9	655
South	29.9	0.300	21.9	655
South	22.2	0.300	21.9	487
East	22.6	0.300	21.9	495
East	40.9	0.300	21.9	895
North	17.3	0.300	21.9	380
North	18.7	0.300	21.9	409
North	37.7	0.300	21.9	824
West	29.9	0.300	21.9	655
West	29.9	0.300	21.9	655
West	138.7	0.300	21.9	3,033
West Door	37.0	0.300	21.9	809
West Lower	22.6	0.300	21.9	495
West Lower	29.9	0.300	21.9	655
West Lower	109.2	0.300	21.9	2,387

Below-Grade Surface Heat Loss

Special attention must be paid to the below-grade basement wall and floor because of the different heat flow paths encountered in the ground. Figure 3.1 shows the circular isotherms that were accounted for when estimating heat loss for the below-grade surfaces.

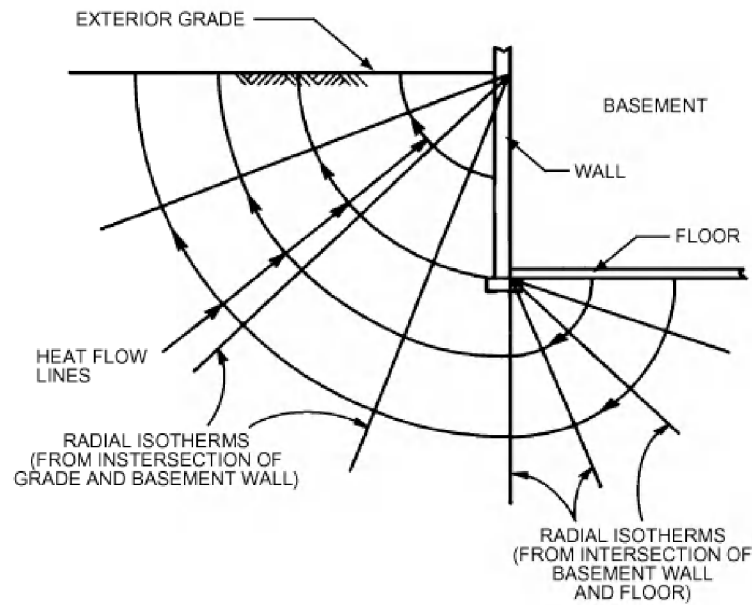


Figure 3.1: Heat flow from below-grade surfaces
Source: ASHRAE, 2005

The following method is an acceptable way to estimate the steady-state heat loss of the below-grade walls and floor. The same method of calculating a heating factor (HF) and multiplying it by the area of the surface was still used, but the calculation of the U-value was modified to account for the radial isotherms and the effect of soil heat capacity. The following equations demonstrate how the below-grade surface heat loss was calculated.

$$HF = U_{avg} (t_{in} - t_{gr}) \quad (3.16)$$

$$t_{gr} = \bar{t}_{gr} - A \quad (3.17)$$

where

$$\begin{aligned} U_{avg} &= \text{average U-factor for below grade surface, Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F} \\ t_{in} &= \text{below-grade space air temperature, }^\circ\text{F} \\ t_{gr} &= \text{design ground surface temperature, }^\circ\text{F} \\ \bar{t}_{gr} &= \text{mean ground temperature, }^\circ\text{F} \\ A &= \text{ground surface temperature amplitude, }^\circ\text{F} \end{aligned}$$

The ground temperature was calculated because the effect of soil heat capacity makes it different from the outdoor temperature. The mean ground temperature is estimated as the average air temperature for the design month. At this site in Newton, IA, the average outdoor air temperature was calculated to be 34.4 °F. This was calculated from data taken at the site for the month of January in 2005. The ground surface temperature fluctuates about an annual mean value. For this geographic location the ground surface temperature amplitude (A) is about 23 °F. Applying equation (3.17) will give a design ground surface temperature of 11.4 °F.

The average U-value for the below-grade structures need to be calculated, taking into account the radial heat flow paths discussed previously. The following equations were used to calculate the average U-Value for the basement walls and floor.

$$U_{avg,bw} = \frac{2k_{soil}}{\pi(z_2 - z_1)} \times \left[\ln\left(z_2 + \frac{2k_{soil}R_{other}}{\pi}\right) - \ln\left(z_1 + \frac{2k_{soil}R_{other}}{\pi}\right) \right] \quad (3.18)$$

$$U_{avg,bf} = \frac{2k_{soil}}{\pi w_b} \times \left[\ln\left(\frac{w_b}{2} + \frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right) - \ln\left(\frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right) \right] \quad (3.19)$$

where

- $U_{avg,bw}$ = average U-factor for wall region, Btu/hr* ft^2 *°F
 $U_{avg,bf}$ = average U-factor for basement floor, Btu/hr* ft^2 *°F
 k_{soil} = soil thermal conductivity, 0.8 Btu/hr* ft *°F
 R_{other} = total resistance of wall assembly, h* ft^2 *°F/Btu
 z_1, z_2 = depth of top and bottom of wall, ft
 z_f = floor depth below grade, ft
 w_b = basement width (shortest dimension), ft

The calculated U-values and heat loss for the below-grade surfaces can be found in Table 3.9.

Table 3.9: Calculated heat loss for below-grade surfaces

Surface	Area ft^2	R_{other} hr* ft^2 *°F/Btu	U_{avg} Btu/hr* ft^2 *°F	HF Btu/hr* ft^2	q Btu/hr
Basement Walls	1,494	24.6	0.031	1.80	2,687
Floor	2,200	10.9	0.016	0.94	2,057

Infiltration Heat Loss

Infiltration was calculated the same as it was before except that the larger IDF value, caused by the increased wind speed (15 mph vs. 7.5 mph for cooling), cause a greater infiltration rate. Because the cold outdoor has less moisture than the indoor air, only the sensible heat loss will be calculated. Applying equation (3.11) with a temperature difference of 72.9 °F and an infiltration rate given in Table 3.10, the infiltration heat loss was calculated to be 4514 Btu/hr.

Table 3.10: Winter infiltration rate

Infiltration	A_{es} ft^2	A_{ul} in^2/ft^2	IDF cfm/ in^2	Q_{inf} cfm
Heating Design	4,271	0.01	1.23	52.5

Design Heat Loss Summary

As discussed previously, internal gains are not included in the design heat loss calculation. The total design heat loss was calculated to be 31,659 Btu/hr. A summary of the heat losses associated with the different surfaces can be found in Table 3.11.

Table 3.11: Design heat loss summary

Heat Loss	Opaque Surfaces	Windows	Below-grade	Infiltration	Total
	Btu/hr				
Sensible	8,913	13,488	4,744	4,514	31,659

CHAPTER 4 - TRACE 700 ANALYSIS

The energy estimating software TRACE 700 was used to verify the heating and cooling load calculation method used in the previous chapter. This software was also used to estimate the annual energy consumption of the PowerHouse home. The annual energy consumption was then compared to actual sub-metered data available from the energy monitoring equipment installed at the residence.

To compare the energy use of the PowerHouse to a 2×6 constructed home of the same size, the physical parameters of the home were copied and the U-values of the wall and roof were changed to reflect a 2×6 wood framed house. The annual simulation was run for this new home and the results were compared. The results of the simulations are presented in this chapter.

Design Heating and Cooling Load Analysis

The TRACE 700 model of the home consists mainly of the exterior surfaces that constitute the building envelope. The details of the windows (% wall area, U-factor, SHGC) are also input so the solar load could be analyzed for the design cooling calculations. The exposure of the walls and windows was also specified for the model.

The heating design calculation performed by the program uses the same logic as the hand calculation. The solar gains and internal loads were not included when the design heating load was calculated.

The same values for indoor and outdoor design temperatures were used so comparing the TRACE estimation with the hand calculation will be accurate. A comparison of the TRACE results and ASHRAE hand calculation method can be found in Table 4.1. These values contain both the sensible and latent loads.

Table 4.1: Comparison of ASHRAE and TRACE design loads

Heat Gain	Opaque Surfaces	Windows	Internal Gains	Infiltration	Total
	Btu/hr				
ASHRAE	4,804	14,799	3,722	1,503	24,828
TRACE	7,322	13,571	3,607	1,135	25,635
Heat Loss					
ASHRAE	13,657	13,488	0	4,514	31,659
TRACE	13,447	12,142	0	4,594	30,183

The results of the TRACE 700 simulation show that either method of calculating the design heating and cooling load will yield acceptable results. Although the heat gain through the opaque surfaces differs by over 30%, the total load only differs by 3%. The total heat loss differs by 4.7%.

Annual Energy Use Simulation

The annual energy use of the PowerHouse home was simulated using the same model used for the design load calculations. A Typical Meteorological Year (TMY2) weather file was used to predict the outdoor conditions for the simulation. A TMY2 file contains 12 months of hourly weather data (temperature, solar levels, wind speed, etc) for a specific location. The data in the file represents the typical weather a city would experience in a year, so extreme weather conditions do not generally show up. The TMY2 file used for this simulation is for Des Moines, IA, which is the closest major city to Newton, IA (<30 miles distance).

The energy use of the HVAC equipment is the most useful information for heating and cooling analysis so these were the primary focus of the energy simulations. After modeling the HVAC system in TRACE, the annual simulation was performed. The annual energy use predictions of the Heating Water Boiler (HWB), air-conditioning condensing unit (ACCU), and supply fan (SF) can be found in Table 4.2 along with the actual usage from the sub-metered data.

Table 4.2: Annual energy use summary

Source	Heating Water Boiler kWh	Condensing Unit kWh	Supply Fan kWh	Annual Total kWh
TRACE 700	12,966	1,880	3,371	18,217
Actual Data	14,181	1,762	3,224	19,167

The actual data recorded at the PowerHouse home confirm the TRACE simulation. The total annual energy use discrepancy is under 6%. This is a good correlation considering the weather data used for the simulation is typical weather and not specific to the time period of the monitored data.

Energy Savings vs. Typical Wood Framed Construction

It is useful to compare the performance of the PowerHouse home's unique envelope design to the standard energy efficient 2x6 wood framed construction. To perform this analysis, changes were made to the parameters relating to U-factors for the roof and exterior wall assemblies and the infiltration rate. The wood framed home was expected to have more leakage because it is not a sealed-shell type construction. The U-values for the EPS panel system and the wood framed construction can be found in Table 4.3.

Table 4.3: U-Values for EPS and 2x4 assemblies

Construction	U-value Btu/hr*ft ² *°F
EPS Roof	0.017
EPS Wall	0.025
2x6 Roof	.029
2x6 Wall	.064

The TRACE simulation for the wood framed home reveals that it will use 42% more electricity than the PowerHouse home. The breakdown of energy use can be found in Table 4.4.

Table 4.4: Summary of annual energy use for PH and 2×6 home

Home	Heating Water Boiler kWh	Condensing Unit kWh	Supply Fan kWh	Annual Total kWh
PowerHouse	12,966	1,880	3,371	18,217
Traditional	19,101	2,198	4,600	25,899

Over a period of 10 years, the cumulative extra utility costs can add up. Assuming an inflation rate of 2% for electricity, after 10 years of operation it will cost \$6,309 more to heat and cool the 2×6 built home. The yearly operating costs can be found in Table 4.5.

Table 4.5: Extra operating cost of traditional 2x6 design

Year	Electricity rate \$/kWh	Extra Operating Cost	Cumulative
1	0.075	\$576.15	\$576
2	0.077	\$587.67	\$1,164
3	0.078	\$599.43	\$1,763
4	0.080	\$611.41	\$2,375
5	0.081	\$623.64	\$2,998
6	0.083	\$636.12	\$3,634
7	0.084	\$648.84	\$4,283
8	0.086	\$661.82	\$4,945
9	0.088	\$675.05	\$5,620
10	0.090	\$688.55	\$6,309

CHAPTER 5 - MONITORED DATA ANALYSIS

The PowerHouse home is monitored with a Johnson Controls Metasys system. This system has the ability to output control signals, but the HVAC systems installed at this home are controlled by their own integrated circuits. Most residential systems don't have the flexibility of direct digital control (DDC). The Metasys DDC equipment is used solely for its input and data storage capabilities.

Data Acquisition System

There are six types of sensors that are read by the data acquisition system (DAS). Temperature sensors are located throughout the residence measuring room air temperatures, radiant floor water supply and return temperatures, air handling unit return, entering and leaving air temperatures, and the outdoor air temperature. Relative humidity sensors are also located throughout the home to measure the amount of moisture inside and outside of the home. A CO₂ sensor located in the return air duct monitors the carbon dioxide levels and runs a heat recovery ventilator unit (HRV) when the levels get too high. Current transducers are wired into the power distribution panels to measure the energy use of several key HVAC and domestic components. There are also 4 power meters that monitor the main distribution boxes (total consumption, HVAC consumption, lighting consumption, appliance consumption, and plug loads). These 4 end uses represent 100% of the electrical usage of the house. A schematic of the electrical system and the related monitoring equipment can be seen in Figure 5.1.

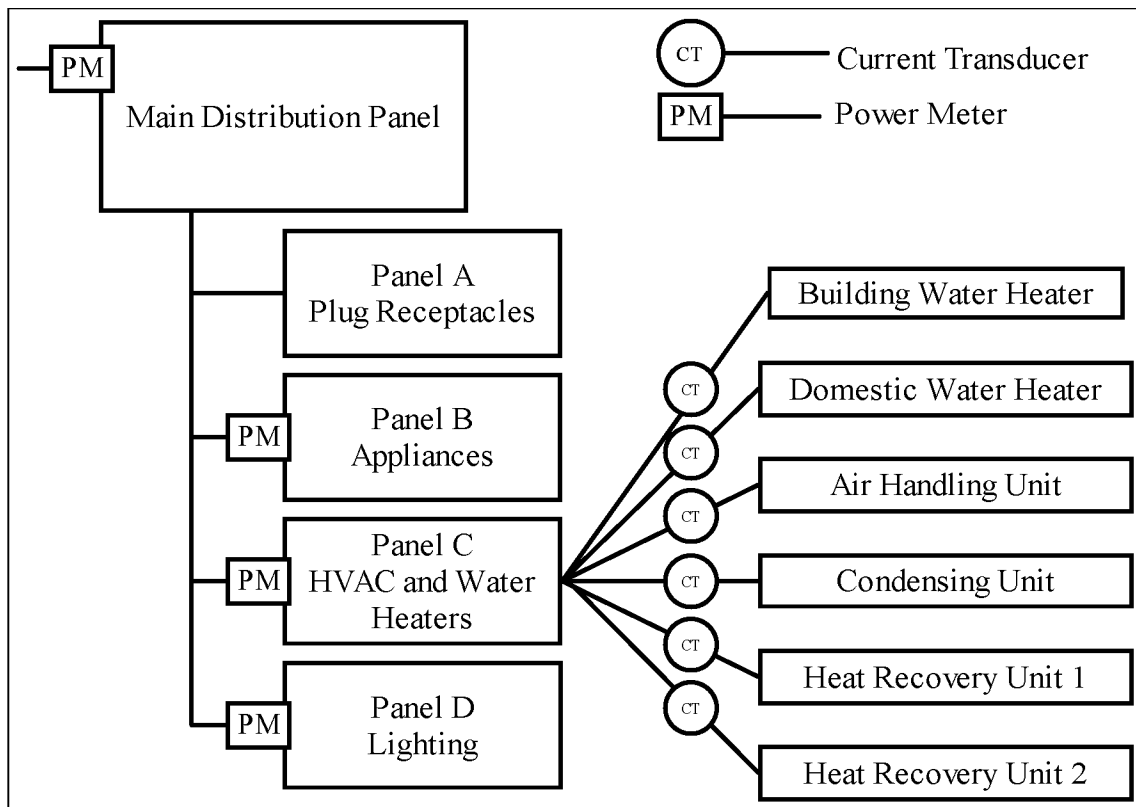


Figure 5.1: Electrical monitoring schematic

All of the sensors throughout the house are wired to the digital controllers that take the output signal of the sensor and translate it to a real value. For example, the digital controllers read the resistance of the temperature sensors and use a calibrated equation to determine the temperature. The digital controllers are linked together through the N2 Bus. The N2 Bus is the pipeline for all the data and signals transferring to and from the many digital controllers. The main digital controllers are the two DX-9100s. These controllers only have a certain number of available inputs so expansions modules (XT) must be installed. The PowerHouse has two expansion modules to allow for more sensors to be installed and monitored. All of the controllers report to the Network Automation Engine (NAE) through the N2 Bus. The NAE stores data short-term and communicates with the computer via a network connection. The NAE also allows access to real time system data through any internet connection that can connect to the network. This allows for remote monitoring and data retrieval. The basic lay-out of the Metasys

system at the PowerHouse can be seen in Figure 5.2. All of the sensors are not shown, but the basic architecture of the system can be easily identified.

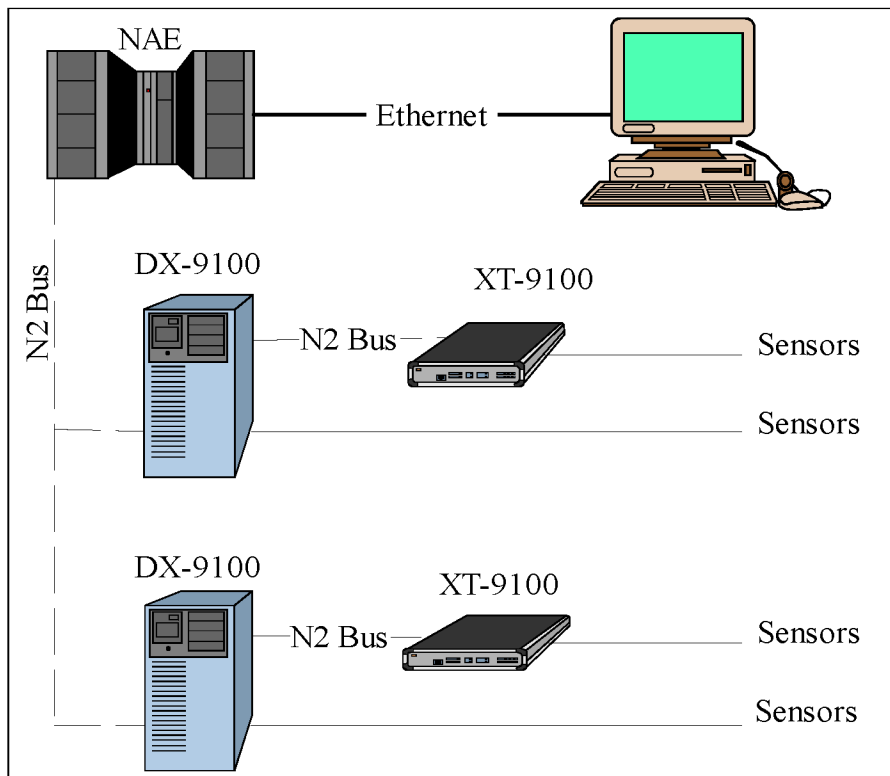


Figure 5.2: Metasys DAS architecture

Data Retrieval and Analysis

Once the data has been transferred to the personal computer by the NAE it can be retrieved. A shared network folder allows retrieval from any remote location. Once the data is retrieved it can be processed and analyzed. The system is configured to take data readings from each sensor every 5 min. The data files that are generated by the DAS system need to be formatted so the data can be plotted and/or analyzed in chronological order. A program written in the Perl language was created to sort the data and put it into a comma-separated column format in chronological order. Each column in the file represents an input to the data-acquisition system. Once the Perl script is run on the data,

it can be imported into a program like Excel or MATLAB to do further analysis. Because of the large amounts of data, MATLAB was the main program used to analyze the data.

The power meters attached to the main distribution panels output a cumulative running total of the electricity going to the different panels. Simple subtraction was used to find the monthly energy use for each box. A special analysis had to be performed to find the energy use of the various HVAC components because the power meters used to record the main power were too expensive to use on the HVAC equipment. It was more economically feasible to install current transducers to monitor the energy use of the boilers, air handling unit, condensing unit, and HRV units. The transducers only measure the current going to the unit, so the voltage and power factor had to be used to calculate the actual energy usage. Each data sample represents 5 min of operation so the following equation represents how much electricity was consumed in that 5 min time period.

$$KWHR_{5\min} = PF \times I \times V \left[\frac{5\min}{60 \frac{\min}{hr} \times 1000 \frac{W}{KW}} \right] \quad (5.1)$$

where

$$\begin{aligned} KWHR_{5\min} &= \text{electricity consumed in 5 min interval, kWh} \\ PF &= \text{power factor of unit} \\ I &= \text{current, A} \\ V &= \text{voltage, V} \end{aligned}$$

The power factor and voltage was found by analyzing data recorded by the main power meters. This calculation procedure was verified by comparing its output to that of the cumulative power meter attached to the HVAC panel and the difference was found to be less than 3%.

Monitored Energy Use

The monthly electrical consumption of the main distribution panels at the PowerHouse can be found in Table 5.1.

Table 5.1: Main component consumption breakdown

Month	Yr	Total	HVAC	Appliance	Lighting	Outlets
		kWh				
Jan	05	5,674	4,197	591	120	766
Feb	05	3,667	2,567	531	120	449
Mar	05	3,639	2,404	592	120	523
Apr	05	1,610	698	563	120	229
May	05	1,726	812	578	141	195
June	05	1,812	893	583	45	291
July	05	2,004	889	597	108	411
Aug	05	2,034	896	616	266	256
Sept	05	2,289	885	857	174	373
Oct	05	2,210	691	957	139	423
Nov	05	3,271	1,522	1,012	169	568
Dec	05	5,544	3,395	1,203	137	810
Total		35,480	19,848	8,679	1,660	5,294

The energy consumption of the HVAC equipment can be found in Table 5.2. Even though the domestic water heater is under the appliance category, it is shown in this table because it is a main source of energy consumption.

Table 5.2: Monthly breakdown of HVAC metered equipment

Month	Yr	HWB	AHU	ACCU	HRV-1	HRV-2	DWH
		kWh					
Jan	05	3,830	328	28	38	1	536
Feb	05	2,317	249	20	1	1	476
Mar	05	2,101	291	28	11	1	537
Apr	05	462	234	15	1	1	508
May	05	329	249	140	94	1	524
June	05	286	263	343	1	1	530
July	05	250	294	342	1	2	538
Aug	05	66	276	431	1	122	549

Table 5.2 (Cont.)

Month	Yr	HWB	AHU	ACCU	HRV-1	HRV-2	DWH
		kWh					
Sept	05	145	254	363	1	16	775
Oct	05	204	222	91	1	11	864
Nov	05	1,171	229	24	1	2	918
Dec	05	3,020	335	28	1	8	1,107
Total		14,181	3,224	1,762	154	164	7,860

The PowerHouse was un-occupied from January thru August, but the domestic water heater was still consuming over 500 kWh/month. This is due to a hot water recirculation system installed at the home that keeps hot water at all the taps consistently throughout the day. A typical electric water heater producing 65 gallons of hot water per day will only use about 400 kWh/month so it can be concluded that the recirculation system is very inefficient.

The heat recovery ventilators installed at the home also contribute to the energy consumption. A detailed analysis cannot be performed because the units were not instrumentated. In the un-occupied period it can be noticed that they were left on for a significant part of two months. They are wired to run with the bathroom and kitchen exhaust fans so it can be assumed somebody accidentally left a bathroom light on when they left the home.

Figure 5.3 below is a pie chart showing the end-use distribution for all metered equipment. It can be seen that the heating water boiler consumes the largest percentage of energy over a year. The domestic water heater consumes the second most. The heating of water for HVAC and domestic use accounts for 61.4% of the annual energy consumption.

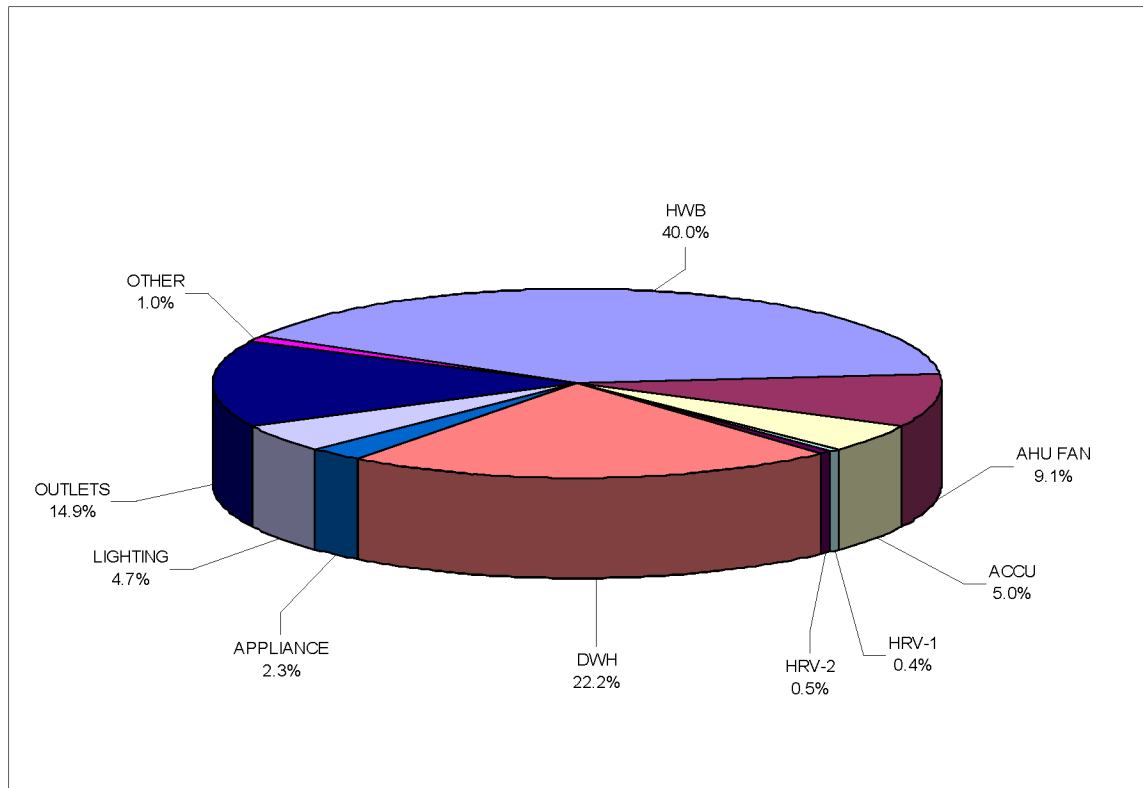


Figure 5.3: End-use distribution at the PowerHouse Home

Energy Performance Index

Calculating a performance index was important because it was used for comparing the PowerHouse with other residences. The main index that will be used in this report is the Energy Utilization Index (EUI). This index has many different names in the industry (Energy Intensity, Energy Use Intensity, Energy Consumption Intensity, etc), but they all refer to the same index. The EIA defines energy intensity (EUI) as site energy consumption per square foot of total floor space. To calculate the EUI, the total energy consumed in 12 consecutive months is divided by the square footage of the home. Larger homes have more wall area that lose heat, so dividing by the square footage normalizes the index so larger homes will not be penalized for using more energy. In 2005, the EUI of the PowerHouse was 28.8 kBtu/ft².

The EIA conducts surveys of residential homes every 3 years to collect information about different types of homes and their energy use characteristics. This study will help to compare the performance of the PowerHouse with other residences in the same climate region. Figure 5.3 below shows how the PowerHouse's EUI compares to the homes included in the EIA consumption survey. The data shown below is for single-family homes in the Midwest built after 1980 that are at least 1000 ft². To further narrow down the comparison, well-insulated and all electric homes that fit the criteria are shown in Figure 5.4.

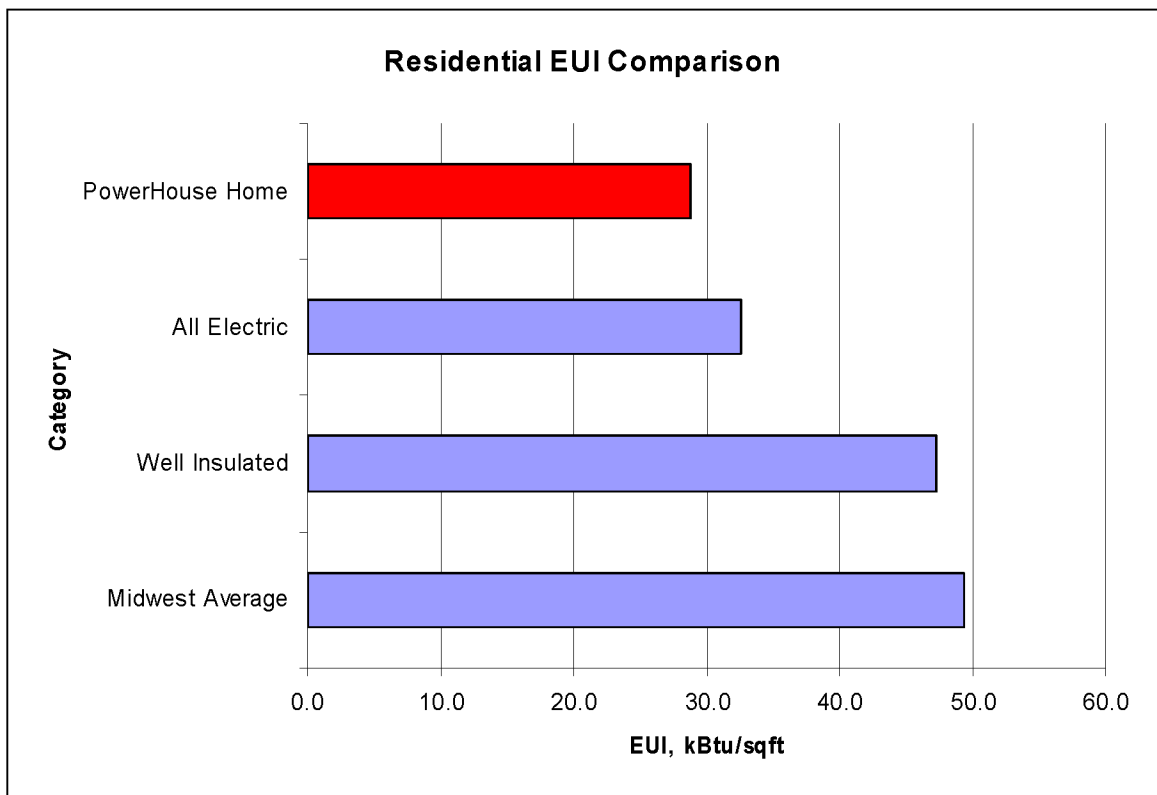


Figure 5.4: Residential EUI comparison from RECS

Data from a study of Iowa homes utilizing geothermal heat pumps (Foster, 2005) was also used for comparison. The twenty homes in the study showed an average EUI of 29.2 kBtu/ft². This comparison also shows how well the PowerHouse is performing. The homes in this study are all utilizing the higher COP of the heat pump equipment while the PowerHouse is heating with a COP of 1.

To further see where the energy is going in the home, it is worthwhile to account for all the end-uses of the energy. Figure 5.5 shows the average distribution of energy in a typical home. Figure 5.6 shows how energy is proportioned at the PowerHouse. It can be seen that the HVAC equipment at the PowerHouse consumes more of a percentage of total energy than a typical home. The fact that the house was unoccupied for the majority of the year would account for this. When the house became occupied, more appliance and plug loads appeared.

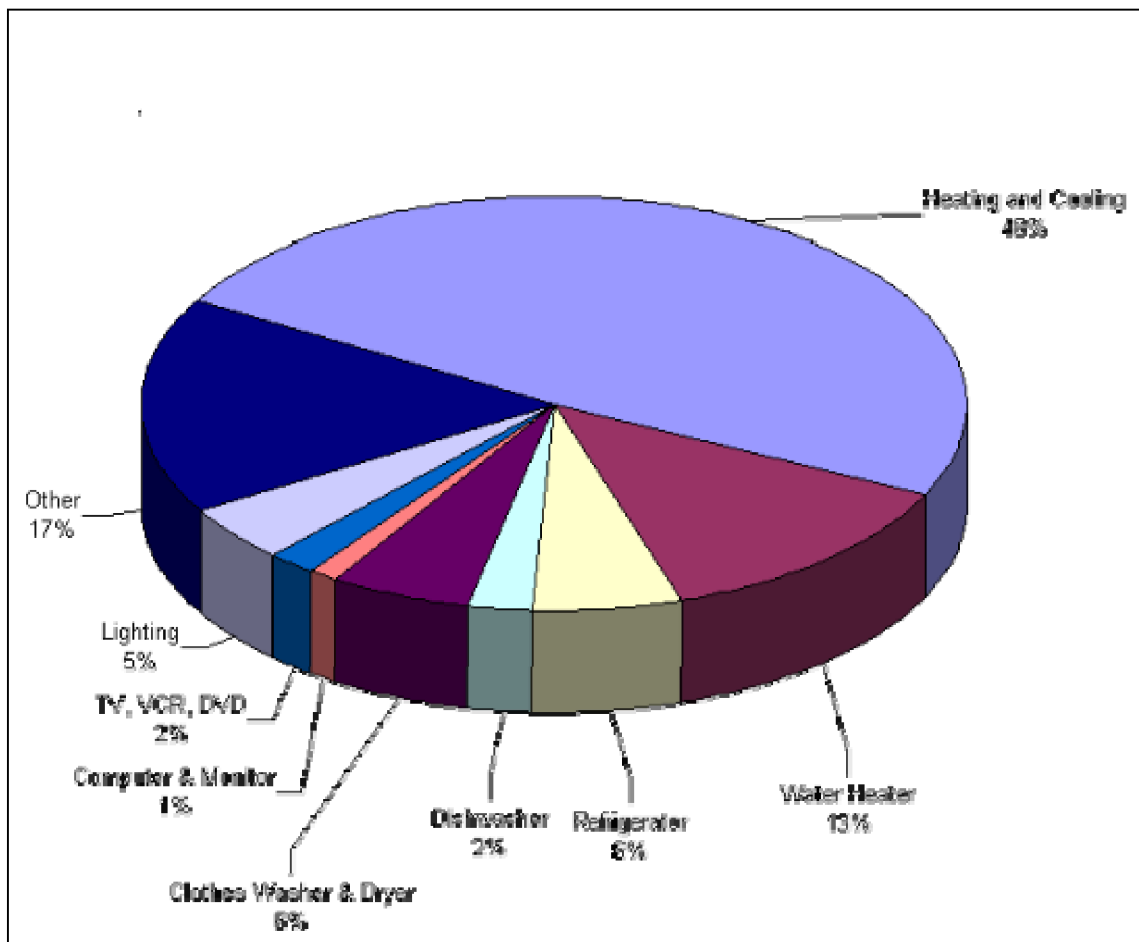


Figure 5.5: Energy distribution of a typical US home
Source: Energy Star, 2001

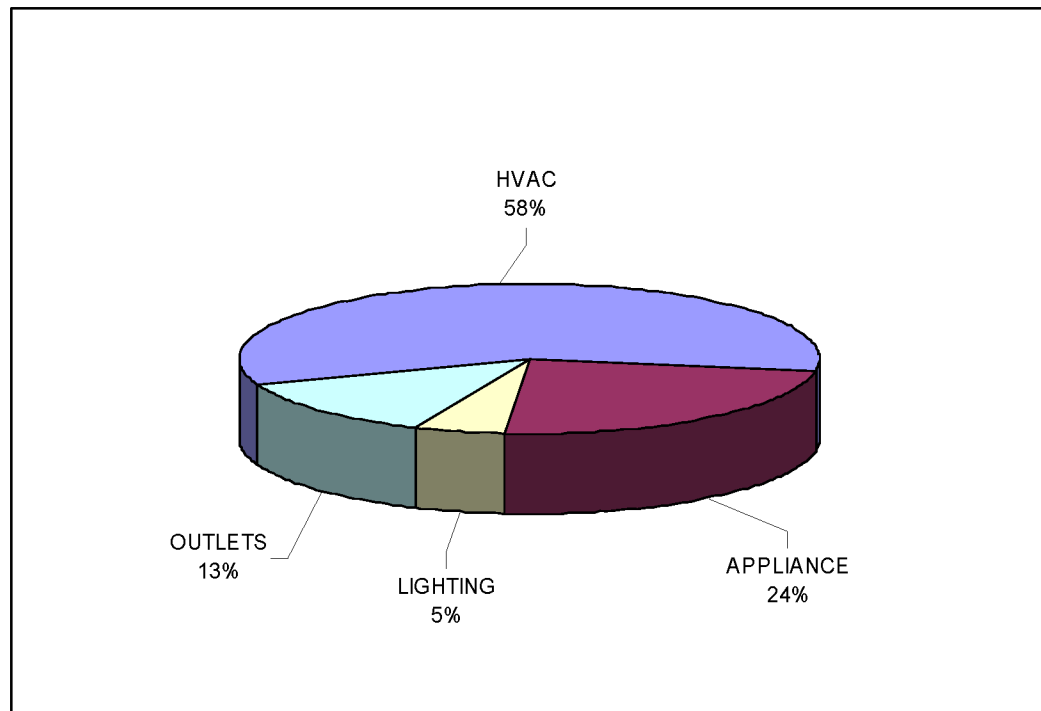


Figure 5.6: Energy distribution for the PowerHouse Home

CHAPTER 6 - DISCUSSION AND RESULTS

The design heating and cooling load results from the hand calculation and the TRACE 700 simulation correlate well with each other. The ASHRAE method of calculating heating and cooling loads was developed by performing thousands of computer simulated trials on various buildings at different geographical locations. Even though TRACE 700 wasn't the simulation tool that was used, it predicted the design heating and cooling load just as well as the hand calculation. The correlations used to estimate the loads work just as well as a computer program, but can be done on paper if needed.

The annual energy simulations done by TRACE 700 matched the actual energy use with only a 6% difference. If the actual weather data for 2005 was used in the simulation it probably would have been closer. The construction of a weather file from actual recorded data was beyond the scope of this project considering the typical weather worked so well.

Comparing the annual energy use of the PowerHouse and a wood-framed home showed that significant money could be saved on utility bills if a high efficiency envelope was used. Also, the initial cost of the HVAC equipment would be lower because it wouldn't have to be as large. An economic analysis of the cost of the more efficient envelope design would reveal if the extra initial cost of the envelope would be worth the investment in the long run.

Analyzing the end-use breakdown of the energy consumption reveals a large amount of energy going to the domestic water heater while the home was unoccupied. A re-circulation system that was installed for convenience was the main culprit of that inefficiency. The system was turned off in March 2006 and a detailed analysis shows the stand-by losses dropped from 17.5 KWHR/day to 12 KWHR/day. This results in a savings of 170 KWHR/month. For the un-occupied months there still exists a 330 KWHR loss. The only explanation for this is conduction and convection from the tank and outlet pipe.

Another source of inefficiency is the supply fan operating 100% of the time. The fan operates on low speed all the time because of the ultraviolet air cleaning system. The fan must remove the heat generated by the light, and it must be circulating air to be effective. A better control strategy would be to cycle the fan and light with occupancy. This would conserve energy while still controlling the indoor air quality. The low infiltration rate of this home supports the idea that the clean air system shouldn't have to run constantly. Even though these large power drains existed, the house still performs better than other well-insulated homes.

CHAPTER 7 - CONCLUSIONS

The simulations developed in earlier sections show that the PowerHouse home is truly energy efficient. Although there is still a lot of room for improvement, research on this design should continue. An economic analysis of the extra cost associated with the EPS envelope would reveal the potential of the cost savings.

Currently the home is performing very well compared to the Midwest averages researched by the Energy Information Administration. The average for a single family detached home in the Midwest was 49 kBtu/ft² (EIA, 2004). In 2005 the PowerHouse had a recorded energy intensity of only

The majority of the energy use goes to heat the home in the winter. One way to make this home more efficient would be to install a geothermal heat pump system. Currently the home is producing heat with an electric boiler that only has a coefficient of performance of 1. This means that for every 1 kilowatt of electricity input to the boiler, 1 kilowatt (3412 BTU) of useful heat is supplied. Geothermal heat pumps have an average C.O.P. of greater than 3 which means for every kilowatt of electricity input to the heat pump, over 10,000 BTU of useful heat is supplied (USDOE, 1999). Most geothermal systems can also heat domestic water, which will lower the load supplied by the domestic water heater which also has a C.O.P. of 1. Although the cost of installation and equipment is high, the utility savings over the life of the system outweighs the initial cost.

The cost of the PowerHouse's envelope system is still under evaluation so a detailed economic analysis cannot be performed. Once the actual cost of the PowerHouse is determined, it can be compared with the cost of a traditionally built 2×6 house and a full analysis can be done. The saving associated with lower utility bills at the PowerHouse can be used to determine the payback period of the extra initial cost. This will be the next step in the analysis of this high efficiency home.

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APPENDIX A: PERL PROGRAM

The following program is used to make a data file that can be easily imported into excel or MATLAB. The original data acquisition file contains information that isn't necessary for the data reduction. For example, each data point contains a line that tells if the sensor is working properly and in the correct range. This information is not needed for the analysis because visual inspection will identify points that do not lie in the correct range.

```
#!/usr/bin/env perl

# Strict perl syntax
use strict;

# Parsing dates to sort the fields by date, so we need this.
use Date::Parse;

# Declare global variables. These are perl hash tables.
our (%field_names, %data);

# Main program unit, reads input, sends data to output routine.
sub main {
    my ($instring) = @_;

    # The next section opens input files based on a search string.
    # The format of the string is very simple. It just matches the files
    # in the directory with the string. This makes creating a full data
    # file for one day easy. It would also be fairly easy to create a
    # single data file for the full data collection.

    # Open current working directory
    opendir(DIR, ".") or die ("Cannot read from this directory");

    # Create array of files to work with
    my @files = ();

    # Find matching files in the current directory and add them to the array
    my($fn);
    while ($fn = readdir(DIR)) {
        if ($fn =~ m/([^\.\.])/ && $fn =~ m/$instring/i) {
            push @files, $fn;
        }
    }

    # Now read those files and add the contents of them all to a large
```

```

# array. No format validation is being done here, so be careful
my @values = ();
foreach $fn (@files) {
    next if (-d $fn); # skip subdirectories
    open(FILE,$fn) or die ("Error opening file $fn");
    my $getridoffirstline = 0; # The first line has headers we don't need
    while(<FILE>) {
        $getridoffirstline++;
        chop;
        if ($getridoffirstline > 1) {
            # Add contents of all matching input files to the array @values
            push(@values,$_);
        }
    }
    close(FILE)
}

# Initialize some variables
my $numlines = 0;
my $data_points = 0;
my $datapoint;
foreach $datapoint (@values) {
    $numlines++;
    # Clean up
    chop($datapoint);

    # Split csv into fields
    my($time,$desc,$datum,$unit) = split (/./, $datapoint);

    # Ignore the first line, then start forming a data table based on
    # the rest of the lines in the file.
    if ($numlines > 1) {
        # Set keys. The time field includes both date and time, we might
        # want to do something about that later.
        #
        # The structure of [data] is keyed by time and the description
        # of the field. This will be used to construct the output format,
        # which has one long line of data for each time, with column
        # headings for each different text field.
        $data{$time}{$desc} = $datum;

        # Increment number of datapoints processed if there was actually data
        if ($datum ne "") {
            $data_points++;
        }
    }
}

```

```

        # Increment number of fields used if we find a new one.
        $field_names{$desc}++;
    }
}
# Call the data printing routine
print_data();
}

sub print_data {
    my $file = $ARGV[1];
    my @ordered_field_names = ();
    my $out_line = "";

    # Create the output file and print first field header
    open(OUTFILE, ">$file") or die("Error: could not write to $file\n");
    print OUTFILE "Date / Time,";

    # Sort field names and prepare header output line
    foreach my $field_name (sort(keys %field_names)) {
        $out_line .= $field_name.',';
        push @ordered_field_names, $field_name;
    }
    # Write headers to output file
    print OUTFILE substr($out_line, 0, -1)."\n";

    # The data is keyed by date/time. Extract those date/time fields
    # and sort them in the natural order
    my @dates = keys %data;
    my @sorted_dates = sort { str2time($a) <=> str2time($b) } @dates;

    # Now that the dates are sorted, create each output line
    # The format is: date/time, field1, field2, field3, ... fieldn
    foreach my $the_date (@sorted_dates) {
        $out_line = $the_date.',';
        my $out_num_times++; # Line number counter
        # Loop through every field name
        for (my $i = 0; $i < @ordered_field_names; $i++) {
            my $out_data_points++ if ($data{$the_date}{$ordered_field_names[$i]} ne ""); #
Data point counter
            # Output line in CSV format.
            $out_line .= $data{$the_date}{$ordered_field_names[$i]}.',';
        }
        # Print the data line to the output file
        print OUTFILE substr($out_line,0,-1)."\n";
    }
}

```

```
    }  
    close(OUTFILE);  
}
```

```
# If input and output are specified on the command line, call the main  
# routine. Otherwise, print program usage to the screen  
if($ARGV[0],$ARGV[1]) {  
    main($ARGV[0]);  
} else {  
    print "PowerHouse data converter/sorter\n\n";  
    print "Usage: perl phconv.pl input_string output_file\n";  
    print "Example: convert data for July 26, 2005 into a more usable format\n";  
    print "\t> perl phconv.pl 050726 050726.csv\n";  
}
```


APPENDIX B: MATLAB PROGRAMS

The following code is used to add the data from the Perl generated file (filename.phs) to the MATLAB workspace:

```
clear all;
clc;
file = 'may06.phs';
[DateString A_AMPS AB_VOLT AC_VOLT AHU_DAT AHU_EAT AHU_RAT
AMPS AN_VOLT APPLIANCE_METER ATTIC_RH ATTIC_T AVG_DEMD
B_AMPS BC_VOLT BN_VOLT BSMT_T C_AMPS CN_VOLT CONSUMPTION
CU1_AMP DEMAND DEMD_A DEMD_B DEMD_C ER1_AMP ER2_AMP
FC1_AMP GARAGE_TEMP GREAT_TEMP HRUEAEAT HRUEALAT
HRUOALAT HVAC_METER HWR_TEMP HWS_TEMP IWHRAD_AMPS
IWHDOM_AMPS KITCH_TEMP LIGHTING_METER MAX_DEMD
MIN_DEMD OA_HUMD OA_TEMP PF_A PF_B PF_C PWR_FACT REA_PWR
RM_CO2 RM_HUMD RM_TEMP SKIN_TEMP SLEEP_TEMP VOLT_L_L
VOLT_L_N kVA] = textread(file,'%s %f %f %f %f %f %f %f %f %f %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f
%f','headerlines',1,'delimiter',';');

Date = datenum(DateString);

% Makes 1 the first day of the Month. 12:00 AM is the first entry
Date = Date-(Date(1)-1);
```

The following MATLAB code calculates the monthly energy consumption from the recorded data:

```
close all;
clear all;
clc;

load 'maydata.mat';
adj = 1.0;

IWH1_kWHr = adj*.99*(5/60/1000)*(IWHRAD_AMPS)*AB_VOLT;
IWH2_kWHr = adj*.99*(5/60/1000)*(IWHDOM_AMPS)*AB_VOLT;
FC1_kWHr = adj*.85*(5/60/1000)*(FC1_AMP)*AN_VOLT;
CU1_kWHr = adj*.95*(5/60/1000)*(CU1_AMP)*AB_VOLT;
ER1_kWHr = adj*.90*(5/60/1000)*(ER1_AMP)*BN_VOLT;
ER2_kWHr = adj*.90*(5/60/1000)*(ER2_AMP)*BN_VOLT;

SUM_HVAC_PANEL = (IWH1_kWHr + IWH2_kWHr + FC1_kWHr + CU1_kWHr
+ ER1_kWHr + ER2_kWHr);
HVAC = IWH1_kWHr+FC1_kWHr+CU1_kWHr+ER1_kWHr+ER2_kWHr;
SUM_A_B = (5/60/1000)*((A_AMPS.*PF_A)*AN_VOLT +
(B_AMPS.*PF_B)*BN_VOLT);

consump_meter = CONSUMPTION(length(CONSUMPTION))-
CONSUMPTION(1);

% HVAC meter resets every Sunday. This loop reads when the HVAC meter goes to
% zero and adds the maxes up.
j=1;
n=1;
hvac(1) = HVAC_METER(1);
while j< length(HVAC_METER)
    if HVAC_METER(j+1)-HVAC_METER(j)<0
        n = n+1;
        hvac(n) = HVAC_METER(j);
    end
    j=j+1;
end
n = n+1;
hvac(n) = HVAC_METER(length(HVAC_METER));

hvactotal = 0;
k = length(hvac);
```

```

while k>0
    if k == 1
        hvactotal = hvactotal-hvac(k);
    else
        hvactotal = hvactotal+hvac(k);
    end
    k=k-1;
end

appl_meter = (APPLIANCE_METER(length(APPLIANCE_METER))-
APPLIANCE_METER(1));

light_meter = LIGHTING_METER(length(LIGHTING_METER))-
LIGHTING_METER(1);

HVAC = hvactotal-IWH2_kWHr;
appliance = appl_meter + IWH2_kWHr;

fid = 1; % fid = 1 for screen or for file use fid = fopen('filename.txt', 'w');

fprintf(fid, file);
fprintf(fid, '\n\n IWH1 = %4.1f kWhr \n', IWH1_kWHr);
fprintf(fid, ' IWH2 = %4.1f kWhr \n', IWH2_kWHr);
fprintf(fid, ' FCU1 = %4.1f kWhr \n', FC1_kWHr);
fprintf(fid, ' CU1 = %4.1f kWhr \n', CU1_kWHr);
fprintf(fid, ' ER1 = %4.1f kWhr \n', ER1_kWHr);
fprintf(fid, ' ER2 = %4.1f kWhr \n', ER2_kWHr);
fprintf(fid, ' HVAC_PANEL = %4.1f kWhr \n\n', SUM_HVAC_PANEL);

fprintf(fid, ' HVAC_METER = %4.1f kWhr \n', hvactotal);
fprintf(fid, ' APPLIANCE METER = %4.1f kWhr \n', appl_meter);
fprintf(fid, ' LIGHTING METER = %4.1f kWhr \n\n', light_meter);

fprintf(fid, ' HVAC = %4.1f kWhr \n', HVAC);
fprintf(fid, ' APPL = %4.1f kWhr \n', appliance);
fprintf(fid, ' LIGHT = %4.1f kWhr \n\n', light_meter);

fprintf(fid, ' TOTAL_PANEL = %4.1f kWhr \n', SUM_A_B);
fprintf(fid, ' TOTAL_METER = %4.1f kWhr \n\n', consump_meter);

plot(...
    Date,OA_TEMP,...
    'Color',[0 0 1],...
    'LineStyle','none',...

```

```
'Marker','',...  
'DisplayName','OA_TEMP');
```