Logging of Performance of my Geothermal Heat Pump GeoMax2 from Heat Controller Inc

(Permanently on low power mode)

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INTRODUCTION

When building my home in NY I had no luck in finding any heating installer (with knowledge) who believed that geothermal heat pumps work in Clinton County. I know locally they have a bad reputation because of past failures due to improper installation. In the end I had to learn a lot more about heat pumps than I ever thought I needed to know so that I could install it myself with the aid of an installer willing to learn about heat pumps. Installers said things like: 'they don't work here', 'they use too much electricity and cost too much to run', 'open loop systems aren't advised', 'in forced air applications they don't heat the air enough to work', 'you will pump your well dry…they use a million gallons of water a year', 'manufactures exaggerate performance so they won't work as well as they say' etc.

Well, as a scientist-engineer I was not convinced so I decided to install one against local advice AND use my laboratory equipment to check performance as a reality check and 'science project'.

EXECUTIVE SUMMARY: My open loop heat pump went on line in Jan 2008 and has been working just fine. In my 2000 sq ft home with standard insulation the HP will use 7,970 kWh of electricity in an 8010 HDD heating year at a cost of $1,355, which is competitive with fuel oil costs at current market prices.

READ ON IF YOU WANT TO SEE THE PROOF

<u>Basics of how a GHP works.</u>

My HP draws in room air at T_{AirIn} and warms it up to a higher temperature, T_{AirOut}. The amount of heat supplied (HS) in BTU/h distributed to the house depends on the volume of air moved in (CFM = cubic feet per minute) and the amount of heat energy in the warmed air. The equation that applies to any hot air furnace (including a GHP) is:

$HS = 1.06 \times CFM \times (T_{AirOut} - T_{AirIn})$. Eq. 1

A GHP extracts some of the heat sent to the house (in HS) from well water. A BTU is defined as the amount of energy needed to change one lb of water 1 ^{o}F. One gal of water weights 8.35 lbs and if I pump at 1 GPM (gal per minute) I pump 500 lb/h (= 60 x 8.35). Hence the rate of heat extraction (HE) is given by

HE = 500 x GPM x water temperature drop OR

$HE = 500 \times GPM \times (T_{WaterIn} - T_{WaterOut})$ (Eq. 2)

The temperature of the water falls during the heating season because the GHP is extracting water from the ground.

The whole process is illustrated in Fig. 1

The ‘pumping’ part of the GHP is provided by a refrigeration compressor that pumps freon gas/liquid (or its modern equivalent) through a refrigeration cycle. At the cold end, the freon is at low temperature (about 30 to 35 ^oF) and pressure and is colder than the well water hence it can extract heat via a heat exchanger. At the warm end, the freon is under high pressure and is warmer than the room air (125 to 135 ^oF) and hence can deliver warm air to the house through a heat exchanger; another heat exchanger also heats my hot water tank, providing assistance to my hot water tank. Electricity is used to drive the compressor adding some energy to the process (= EA = energy added), and some of this electrical energy goes to heat the air and to heat my hot water tank. Below are performance data I have measured. I installed temperature sensor to measure T_{AirIn}, T_{AirOut}, $T_{WaterIn}$, $T_{WaterOut}$. I installed a water flow meter to measure GPM. The GHP measures and reports CFM to within 5% accuracy. I also have a power meters to measure EA and the energy to drive my well pump. The overall accuracy of the measurements is probably about 10% because T measurements are accurate to only ± 0.5 ^oF.

COP = coefficient of performance = HS/EA.

Overall efficiency = 100% x HS/(EA + the energy needed to run my well pump).

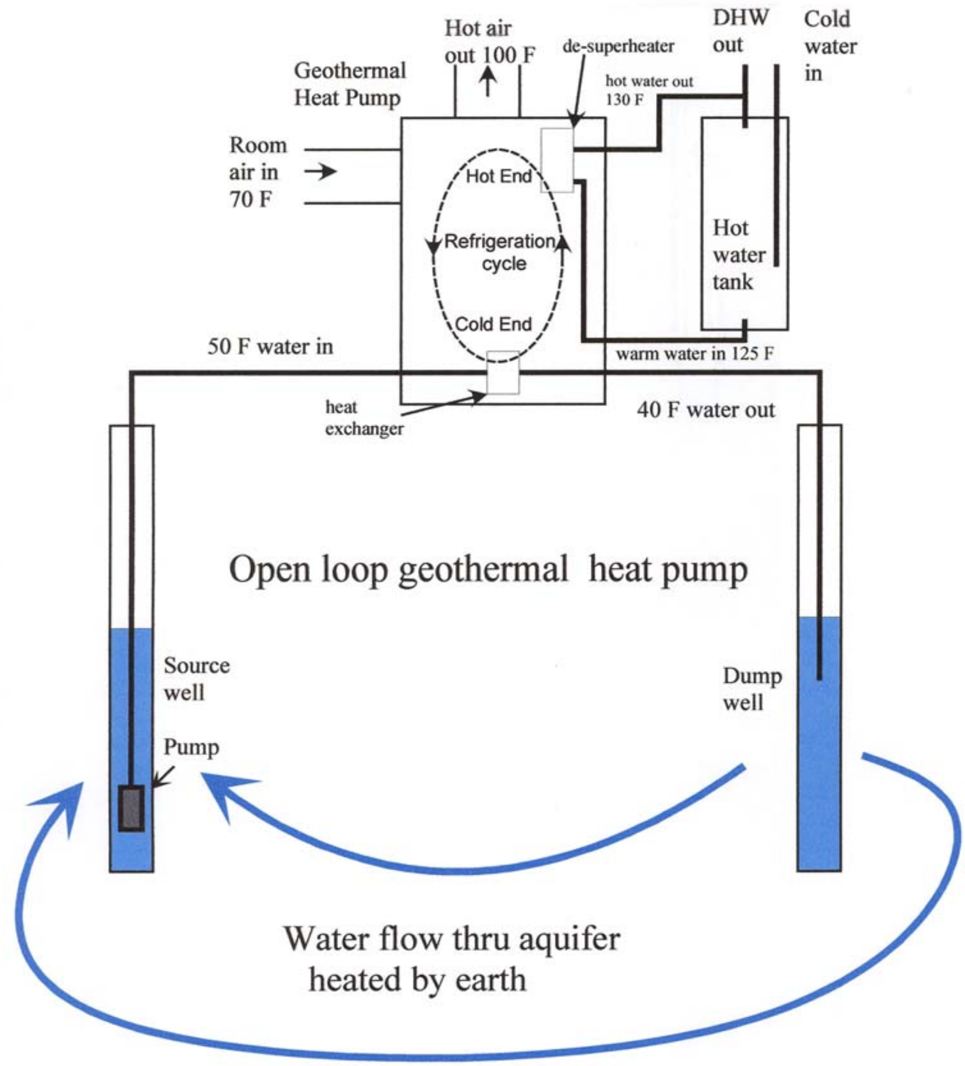

Figure 1: A well pump supplies water to my GHP at 9.5 GPM whenever the HP is operating. The water comes from the well at ~50 ^{o}F, heat is extracted at a rate = HE (Eq. 2), and is cooled about 7 to 10 ^{o}F. The water is dumped into another well where it renters the aquifer and is warmed up by the earth before it returns to the source well.

Methods

Measurements were done in my newly constructed home in Ellenburg, Clinton County, NY 12935. This home is heated with an open loop geothermal heat pump.

A Personal DAQ3005 was used to monitor DC voltages from various sensors (See http://www.iotech.com/catalog/daq/persdaq3000.html). Over the voltage ranges in this study the 16-bit DAQ3005 can measure to better than 0.01% of full scale. The GeoMax2 requires 230 VAC @ 20 A or less for normal operation. Power consumption (kW) of the

GeoMax2 was computed from RMS current (A) and voltage (V). To insure a more predictable performance the stage-2 heating was disabled by disconnecting the stage-2 control line between the thermostat and the GeoMax2 control panel. RMS current was measured with a model ACT, see:
http://web1.automationdirect.com/adc/Overview/Catalog/Sensors_-z-_Encoders/Current_Sensing_Transducers/AC_Current_Transducers
The ACT coil was placed next to the circuit breaker on the service panel that supplies power to the GeoMax2. The coils were set to a calibration of 0-20 A = 0-10 VDC. RMS V was measured using a custom built circuit consisting of a 115 VAC to 12 VAC step down isolated transformer (0.35 watt) going to a full wave rectifier and terminated by a 25 K resistor going to a 40 µF capacitor to ground in parallel with another 25 K resistor to ground. The DC output was calibrated with a Variac voltage transformer and a Digital VOM accurate to 0.2%. See Fig. 2 below.

Two of the above circuits were used to measure V_{AC1} and V_{AC2}, one to measure the RMS Voltage on each side of my service panel. Power was computed from:

$$power = A_{RMS} (V_{AC1}+V_{AC2})$$

Another ACT coil was used to measure current to my water pump. Since water has to be supplied to the GeoMax2 during operation, the power consumption of the water pump is an important part of the energy requirement of geothermal heating.

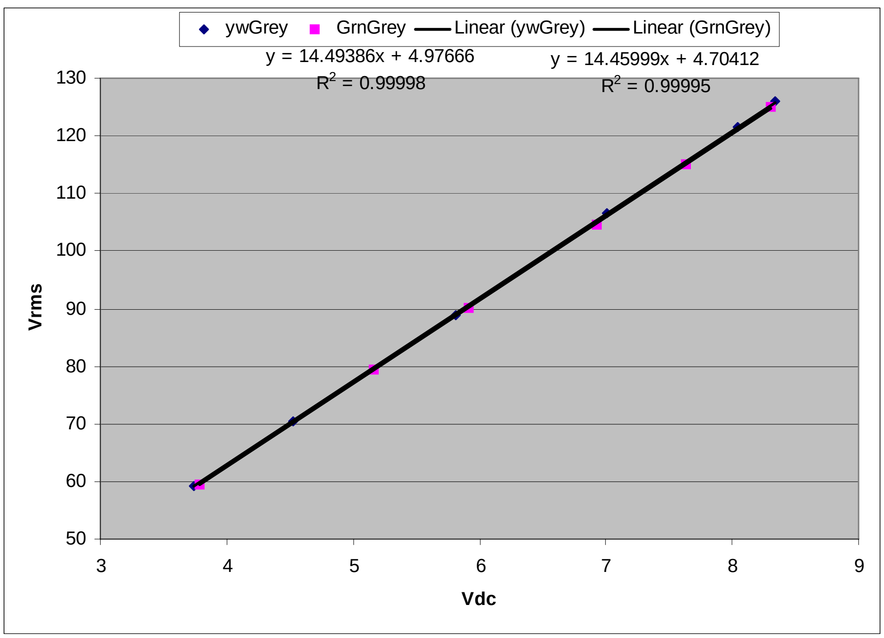

Fig. 2: Typical calibration of my custom-built sensor for converting V_{RMS} to V DC. The normal operating range is 110 to 120 V AC @ 60 Hz

Temperatures were also measured of (1) water flowing into the GeoMax2, (2) water flowing out of the GeoMax2, (3) air intake from the house into the GeoMax2 heat exchanger, (4) air discharge from the GeoMax2 to the house. Temperatures were measured using LM335 sensors calibrated to an output of 10 mV/^{o}K, hence 0 ^{o}C corresponded to a voltage of 2.7316 V DC and 20 ^{o}C to 2.9316 V DC. A high sampling rate per second averaged every second insured temperature measurements to ± 0.1 ^{o}C (±0.2 ^{o}F)

All DC sensor voltages were logged on the DAQ3005 at the rate of 200 measurements per second and averages of 200 readings were saved on a computer once per second, thus permitting a second-by-second evaluation of power (kW) and energy (kWh) usage.

Water supply to the GeoMax2 was provided at 9.5 GPM, however pump pressure variations resulted in a variation of flow from about 9.2 to 9.8 GPM. Water flow was monitored manually with a basic inline water flow meter accurate to 2.5% in mid-range (http://www.lakemonitors.com/basicinline.htm). The recommended water flow rate for my system was 7.5 GPM provided the well water is ~ 50 ^{o}F, however my input water was too cold in mid-winter consequently the compressor shut down to avoid freezing water inside the heat-exchanger. Hence I had to boost the flow rate in order to extract heat at the desired rate with a smaller temperature drop (SEE Eq. 2).

The Geomax2 regulated air flow thorough a variable power ECM Motor and normally supplies air at 1500 CFM ± 5%. (GPM = gallons per minute, CFM = cubic feet per minute).

Local climate was measured with a Davis Vantage Pro2 Plus wireless weather station: http://www.davisnet.com/weather/products/vantage2_plus.asp This station measured air temperature in a fan-aspirated weather shield mounted on a tower 300 ft from the house. Data were logged with Virtual Weather Station software every 5 s, which produced daily reports including heating degree days HDD base 65 ^{o}F.

Results & Discussion

Power up sequence

From 30 April to 13 May 2008 the GeoMax2 powered up 451 times. The power use versus time is shown below:

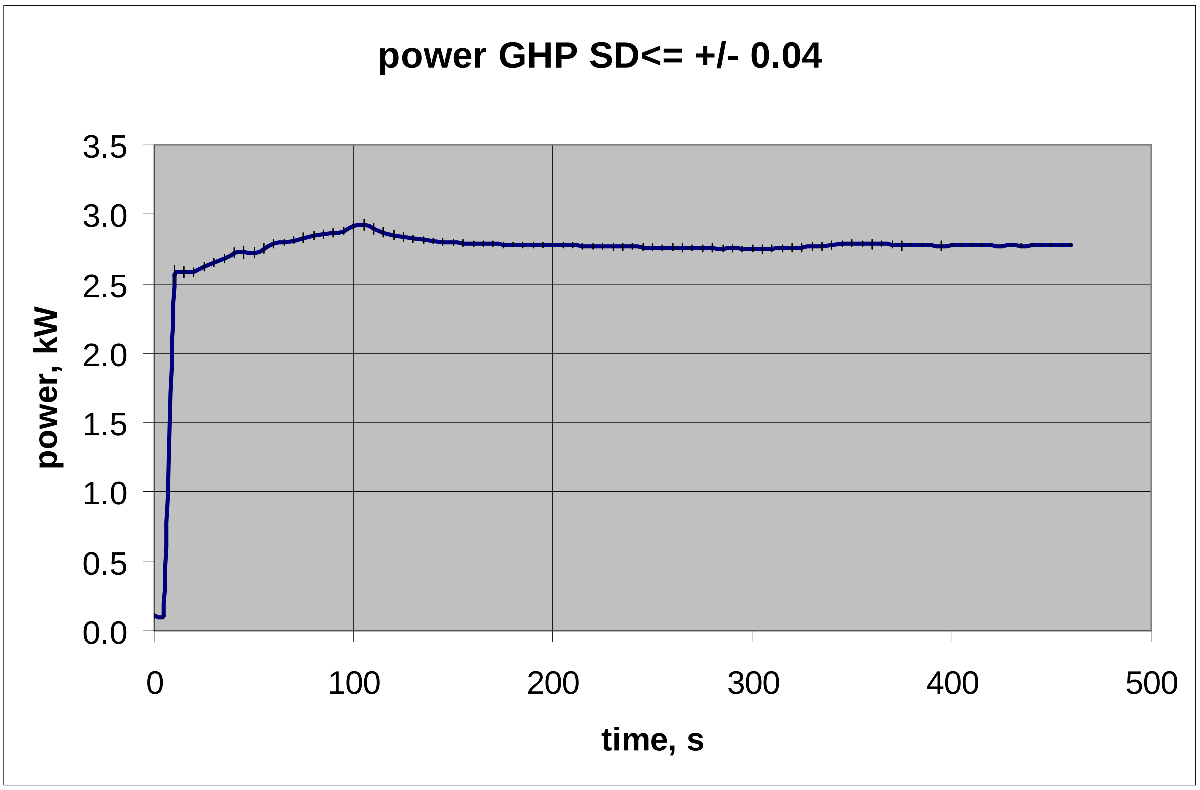

Fig 3: Time 0 in this graph = 10 s before power supplied to the compressor. The time course power up sequence is very uniform with a standard deviation of $\leq \pm$ 0.04 kW. The vertical lines give sd every 5 s. The solid line is the mean trend of N = 451 start up events.

The corresponding changes in air temperature and water changes are given in Figs 4 and 5 respectively.

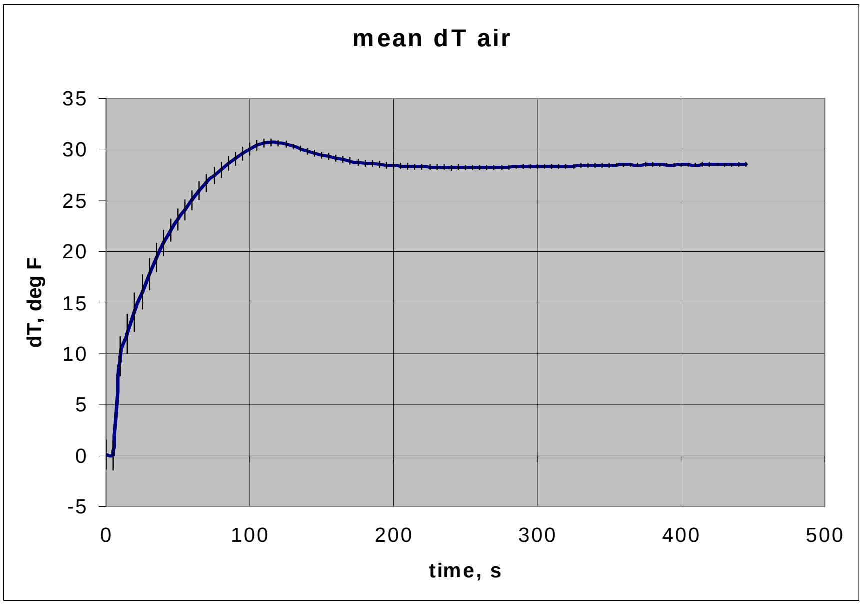

Fig. 4: dT = (Temp air out – Temp air in). Time 0 = 10 s before power supplied to the compressor. Line gives mean trend without points. Vertical bars are standard deviations at 5 s intervals. N = 451.

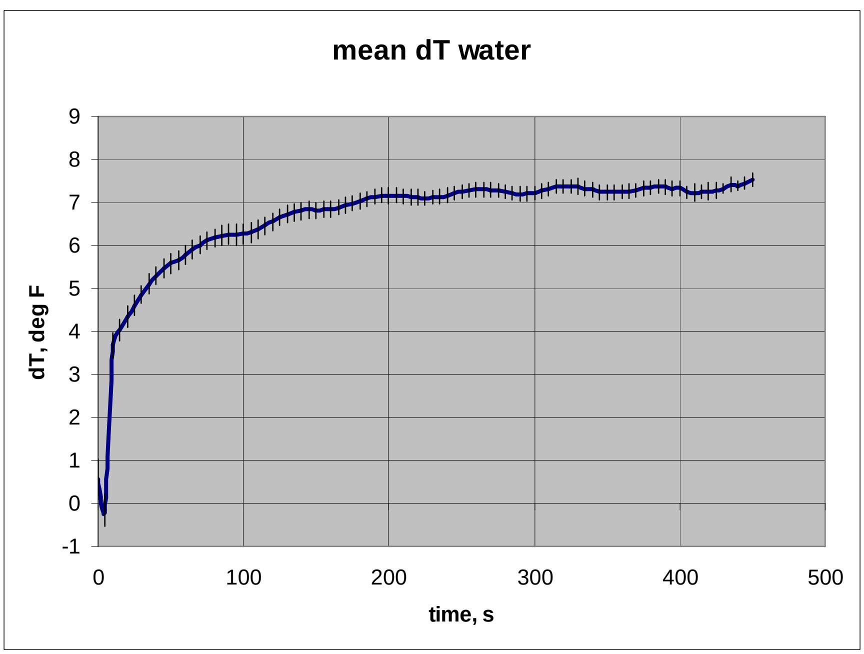

Fig. 5: dT = (Temp water in – Temp water out). Time 0 = 10 s before power supplied to the compressor. Line gives mean trend without points. Vertical bars are standard deviations at 5 s intervals. N = 451. The input water temperature was a constant 48 ^{o}F during these measurements.

Power up sequence: Discussion

The GeoMax2 extracts heat from well water thus lowering the temperature of the water. The heat-energy unit most frequently used in the USA is the BTU (British Thermal Unit), which is defined as the amount of heat needed to change 1 pound of water by 1 ^{o}F. Since one gallon of water weights 8.35 lb, BTU/h can be computed from

$$BTU/h = 500\ GPM * dT_{water} ,$$

because 8.35 lb/gal x 60 min/h = 500. Since the mean dT_{water} after 300 s is about 7.3 ^{o}F the rate of heat extraction (HE) from the well water is

$$HE = 500x9.5x7.3 = 34,575\ BTU/h.$$

The accuracy of this measurement is limited by the accuracy of water-flow measurement (±2.5%) and water temperature measurement (±0.2 ^{o}F out of 7.3 ≅ ± 3%). The combined error (E) of two numbers multiplied or divided is given by $E\% = \sqrt{A^2 + B^2}$, where A and B are the individual errors. So the combined error is about 4%, hence the value plus error of HE = 34,575 ± 1350.

The corresponding formula for heat discharge to the house is

$$BTU/h = 1.06\ CFM\ dT_{air},$$

Since the mean GeoMax2 pumps air at 1500 CFM and dT_{air} = 28.4 ^{o}F after 300 s, the mean rate of heat supply (HS) to the house is given by

$$HS = 1.06\ X\ 1500\ CFM\ X\ 28.4 = 45,160\ BTU/h.$$

The power consumption at 300 s = 2.75 kW and 1 kW = 3,410 BTU/h, hence the GeoMax2 uses 2.75 X 3410 = 9,378 BTU/h of electrical energy to provide 45,160 BTU of heat to the house. This corresponds to a coefficient of performance of

$$COP = 45,160/9,378 = 4.82.$$

The combined uncertainty of absolute temperature measurement was about ± 0.2 ^{o}F out of 28 ^{o}F ≅ 0.7%, but the error in CFM ≅ 5%, hence the overall certainty on the COP is about 5.05%: COP = 4.82 ± 0.24.

Energy consumption of the water pump vs the GeoMax2

The overall efficiency (E) of the GeoMax2 can be defined as:

$$E = 100\%\ HS/(P_{GM} + P_{WP}),$$

Where P_{GM} = the power consumption of the GeoMax2 compressor and P_{WP} = the average power consumption of the water pump. However, the water pump turns on and off frequently (about once per minute) when the GeoMax2 is on. In order to get an accurate estimate of P_{WP}/P_{GM} I monitored the total energy use of the GeoMax2 and the water pump over a 10.5 day period when no one was in the house and hence the pump came on only when water was demanded by the GeoMax2. During this 10.5 day period the average daily energy consumption of the GeoMax2 and water pump was 10.02 kWh and 3.85 kWh per day, respectively. Assuming P_{WP}/P_{GM} = 3.85/10.02, I have estimated average P_{WP} = 1.06 kW. Hence the combined power of the GeoMax2 + water pump = 3.81 kW = 12,990 BTU/h. Hence we can calculate:

EFFICIENCY of GeoMax2 = 100% X (45,160/12,990) = 348%

The probably error in power measurements is ≅ 0.2%, uncertainty of the air temperature measurement is 0.2 to 0.3 ^{o}F out of 28 ^{o}F ≅ ±1% but the uncertainty on the control of air flow is about 5% (of CFM), hence the overall uncertainty in E is probably about 348% ± 18% (= 5.1% x 348%).

Estimated Annual Heating Cost in my Home

The number of BTUs needed to heat any given home depends on the heat loss from the insulated envelope of the house and the HDD = heating degree days. I monitored the energy consumption of the GeoMax2 and the water pump over 40 days when the total number of HDD was 2,216. The energy consumption per HDD was 0.93 kWh/HDD. The average winter in Ellenburgh, NY, has 8010 HDD, hence during the average winter my home can be heated at an energy cost of 7,449 kWh. At the current price of electrical energy (17.1 cents per kWh) the annual heating cost is $1,274 per year.

Revision: The study continued into the winter of 2008/9 and I found increased usage of kWh per HDD as shown in Figure 6. Note that slightly more energy is used per HDD versus the previous 40 days in winter of 2007/8.

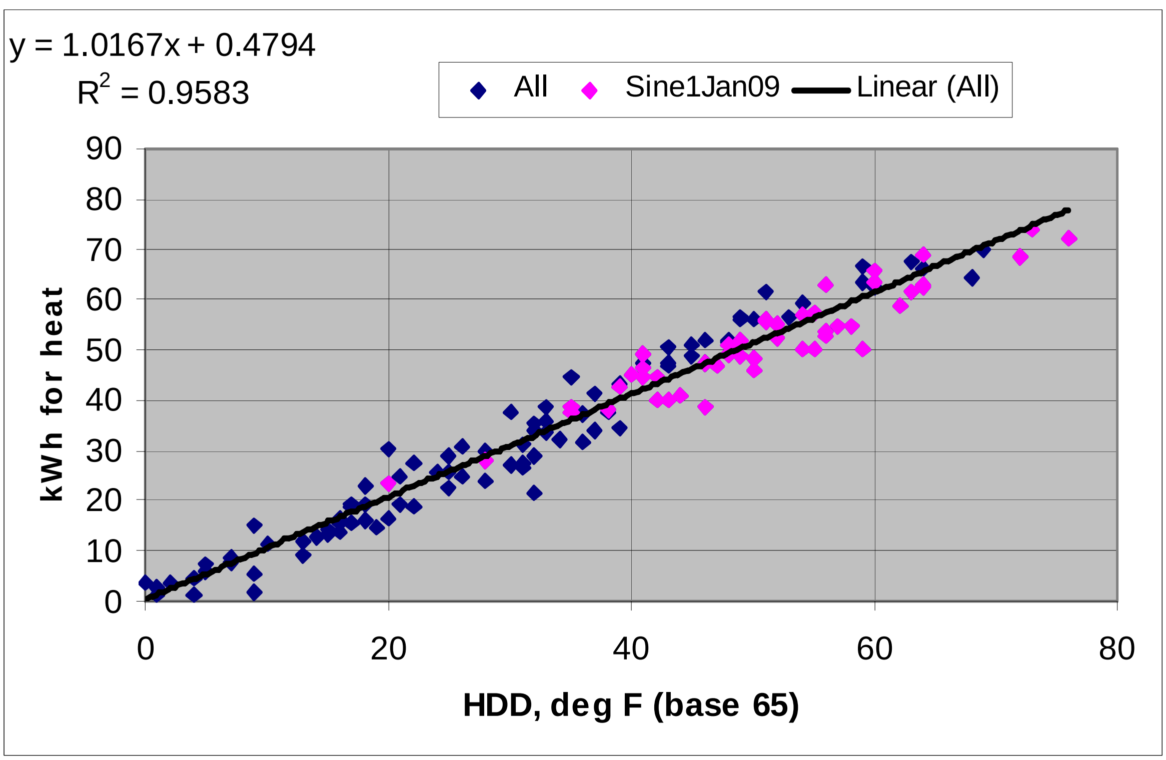

Figure 6. Energy use of the geothermal heat pump and water pump were logged each day and plotted versus heating degree days (HDD) measured on site from Sept 2008 to April 2009.

I will probably never prove the reason for the increased energy usage (0.93 kWh/HDD to 1.01 kWh/HDD). Wind had blown some fiberglass insulation out of my roof in a section were only vapor barrier held it in place. This was detected on 24 Dec 2008 and repaired by 1 Jan 2009. The house has settled making doors and frames less square and opening up small cracks for cold air to enter. However the efficiency of the GHP may have declined too. When I get time I will analyze data like in Fig. 3 (dT air) and Fig. 4 (dT water) to see if I can detect a decline in efficiency. I have acid-cleaned the cold-water heat exchanger and found no buildup of scale that might explain a decline of efficiency of heat extraction from the ground water.

Is My GeoMax2 Sized Appropriately for My Home and Climate?

Of course I did the appropriate calculations initially. I computed R-values of wall, roof, windows, basement etc and did the projections for the coldest probable days. However, you never know if your builder can deliver on the promised R-values. So the ultimate test is to see what percentage of the time the GeoMax2 is on in real-world situations. Hence for the month of February 2008, I measured the % of the time on versus HDD. The data in Fig. 7 are quite linear and have been extrapolated to the right to the coldest it is likely to be in Ellenburg, NY.

The data collected Fig. 8 shows that the GHP is now expected to be on about 10% more for each HDD. I have the non-confirmed impression that the output air temperature is 2 or 3 deg F less than it was the previous winter (Fig. 3) so this may explain part or all the increased time on. There is still enough reserve capacity to heat the house when stage 2 heating is turned on. So I guess I will have to get around to enabling stage 2.

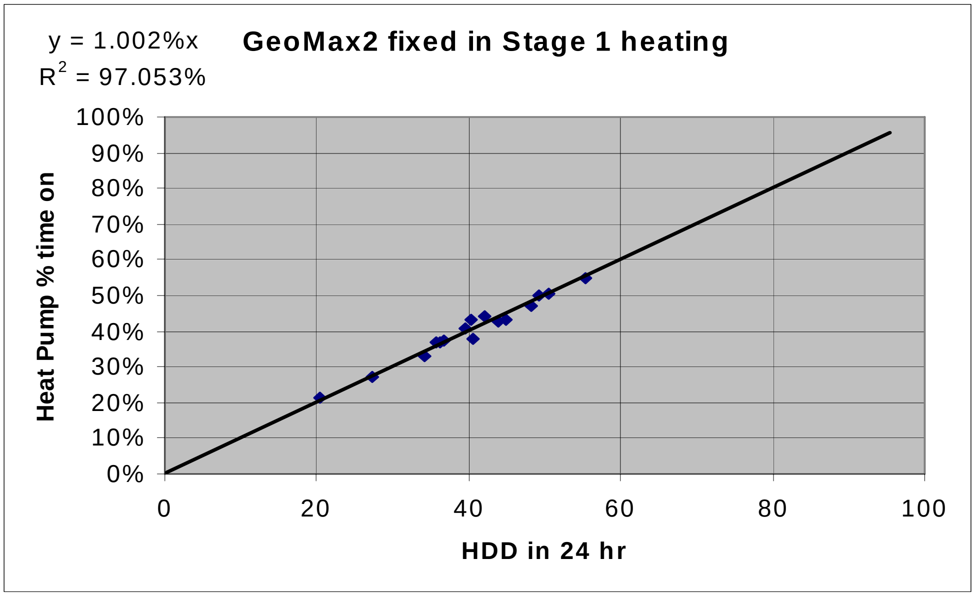

Fig. 7: A plot of % time on (stage-1 heating) versus HDD on various days in Feb. 2008. The linear regression is extrapolated to the right to the coldest temperatures expected in Ellenburg. The furnace is expected to be on 95% of the time on the coldest days. If stage 2 heating is turned on, an extra 25% BTU/h will be generated as a margin of safety.

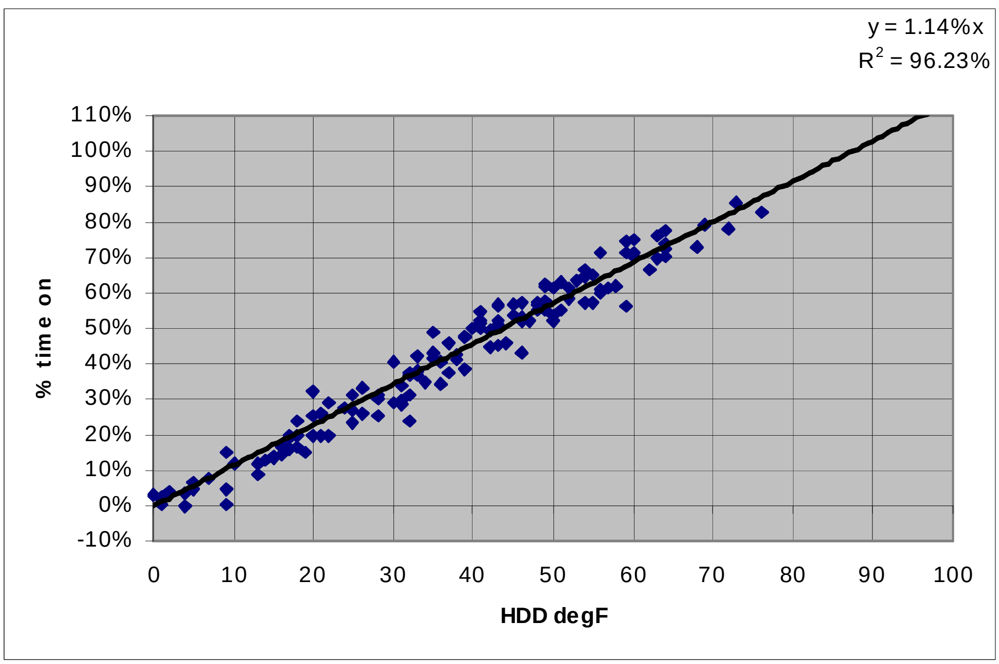

Fig. 8: Data as in Figure 7 but for 2008/9 heating year. Note the increase in slope (% time on per HDD).

How must does the GHP assist the hot water tank?

The concept of a de-superheater was introduced in Fig. 1. The de-superheater is supposed to increase the overall efficiency of the GHP by maintaining the output temperature at the hot end of the refrigeration cycle at an optimal value. The 'excess' heat goes to heat the water in the hot water tank (HWT). The net effect of this system is to reduce the kWh of heat energy going into the HWT depending on how long the GHP runs each day. How this works is documented in Fig. 9 below.

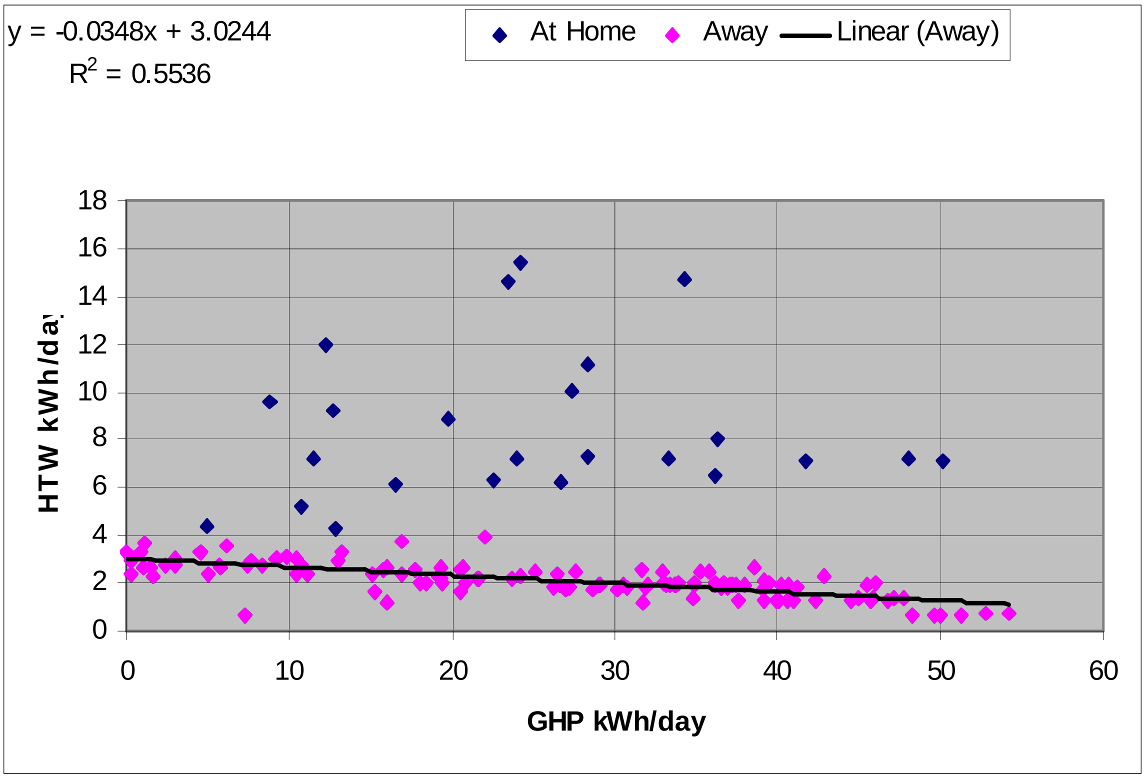

Figure 9. We spent a lot of time away from home in the winter of 2008/9 so energy use in the HWT was limited to just maintaining the set temperature (pink triangles). We kept the HWT on while away to document how much the GHP contributes to maintaining the hot water temperature.

On days that we were away from home outside of the heating season (GHP usage of 0 kWh/day) the amount of energy needed to keep the tank heated was 3.02 kWh/day (= the y-intercept in the regression). On some of the colder days, when the GHP used 55 kWh/day, the amount of heat needed to maintain hot water temperature was reduced to 1 kWh/day. When the GHP uses 55 kWh per day the duty cycle is on 60% of the time and off 40% of the time (Figure 8). From this I conclude that the GHP reduces energy consumption of the HWT by about 1.5 kWh on the typical winter day. In contrast, when we are at home the HWT energy usage is about 8.49 kWh/day (3090 kWh per year for two people). The label on the HWT suggests the average family of 4 would use 4500 kWh per year.

Conclusions:

The overall efficiency of a GHP will change from site to site. The factors determining this are the temperature of the heat exchange fluid (48 ^{o}F in my open loop well application). But in closed loop systems the fluid temperature is often lower (28 to 42 ^{o}F) causing a reduction in COP. COP is also influenced by pumping rate; COP increases with pumping rate. However there is a tradeoff in overall efficiency because high pumping rates require more energy to pump water. The pump in my application was an energy efficient Grundfos SEQ series pump operating at household water pressure (50 psi). The efficiency of the GHP would be improved by reducing the pump pressure for the GHP to, say, 20 psi and adding a booster pump to for the domestic water supply. More testing would be required to determine if this might a cost-effective solution in terms of dollars saved in annual heating costs versus cost of the extra hardware. The factory claims an overall COP of 4.4 for the GeoMax2 in stage-1 heating. The figure I got was 4.82 ± 0.24. The factory value was based on different test conditions: slightly warmer water (50 ^{o}F vs 48 ^{o}F at my site) but lower water flow rate (probably 7.5 GPM vs 9.5). It is not clear if my COP is significantly higher from the factory value because no statistics are available from the factory.

Based on two months of readings in the winter of 2007/8 I extrapolated the energy use for a typical winter in my location with 8010 HDD to be 7,450 kWh whereas the revised estimate based on the winter of 2008/9 is closer to 8090 kWh. Both figures has to be revised downward by about 2% as pointed out to me by Peter Parsons, Memorial University, Newfoundland, Canada. Peter said that my method of computing power (kW = RMS current x RMS voltage) will overestimate my energy use because both the water pump and compressor motor in the GHP are reactive loads. See Appendix 1 below for details.

APPENDIX 1

Hi Peter,

I think I have your answer about "power factors", or how much I am off on power use of my water pump (WP) and geothermal heat pump (GHP) when you take into account the reactive components in the load, i.e. the electric motors. I am also sending this message to my brother who might be interested in how motors distort current sine waves!

I used a Model TDS2004 Tektronix (4-channel) scope to measure 2500 values of voltage and current over ~3 cycles while the GHP and WP were on. Voltage was measured with a Tektronix model P5200 differential voltage probe and current with a Fluke model 80i-110s current probe. The Fluke probe is rather cheap and might read a little low. I should check this out in an EE lab at UofA!

'My sensors' used in SWIEP report R#19 were CT coils for RMS current (I) and a custom built circuit for RMS voltage (V). I computed power from RMS values of I and V without taking into account the reactive load, which as you say would overestimate power. I have now measured how much it is over (1.7% for the GHP and 3.5% for the water pump). See my attached Excel file. Note that V waveforms are only slightly distorted sine waves, but the current waveforms are quite distorted.

True Power was calculated from the sum of v*i over 2 full cycles (60 Hz) where v and i are the instantaneous values from the digitized oscilloscope values. I think what I did in the Excel files is clear but feel free to ask if you don't follow the computations. My documentation is rather brief! Download the Excel sheet from SWIEP.

--Mel

	GHP, Vac	**WP, Vac**	**GHP, Aac**	**WP, Aac**
My sensor	239.40	235.70	12.58	7.49
True RMS	239.49	235.87	12.58	7.27

	GHP. kW	**WP, kW**
True Power	2.961	1.706
RMS VxA	3.013	1.715
My sensor VxA	3.012	1.765
%error	1.73%	3.49%

Graphs of the raw data are shown in Figure A1 below.

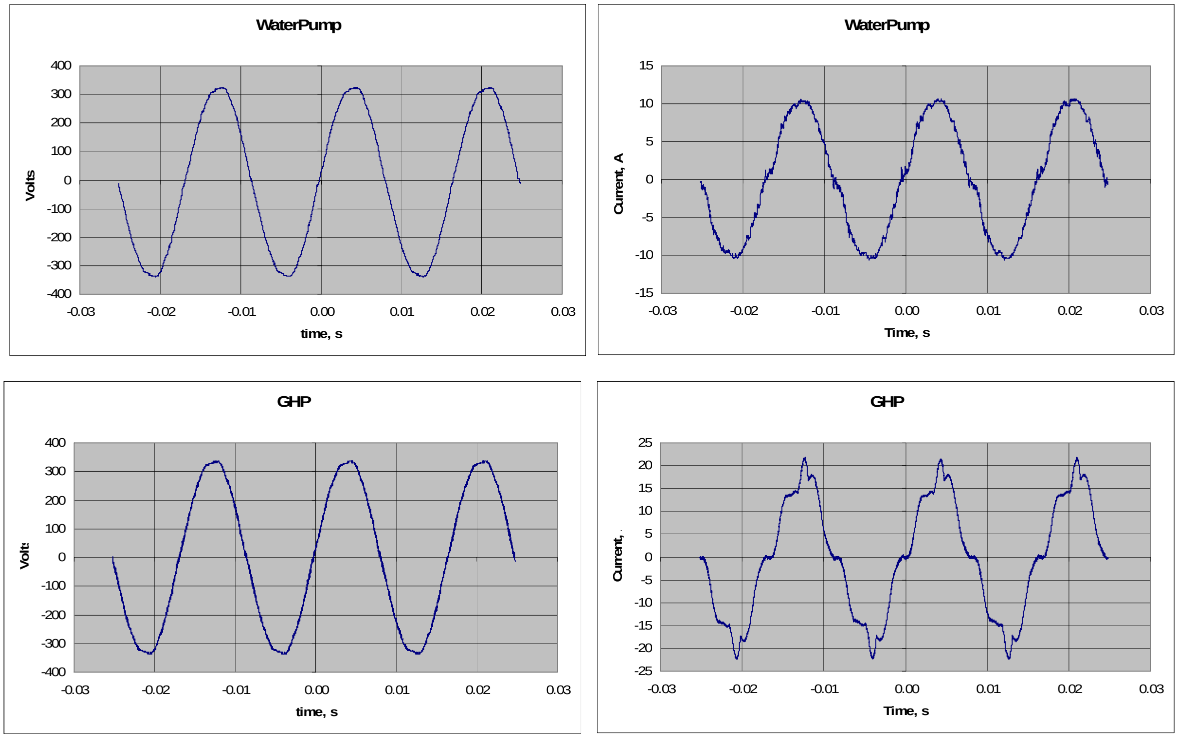

Figure A1: Shows approximately 3 cycles of AC voltage and current measured after the water pump and geothermal heat pump had been on long enough to stabilize. The graph consists of 2,500 reading made by a 4-channel digital oscilloscope.