THERMAL AND COST BENEFIT ANALYSIS OF A GEOTHERMAL PILOT PROJECT AT NORTHWEST TENNESSEE CORRECTIONAL FACILITY

Jason E. Gentry, Undergraduate Research Assistant, Center for Energy Management, University of Tennessee at Martin, Martin, Tennessee
Robert A. LeMaster, Associate Professor, Department of Engineering, University of Tennessee at Martin, Martin, Tennessee
J. Douglas Sterrett, Dean, College of Engineering& Natural Sciences, University of Tennessee at Martin, Martin, Tennessee

ABSTRACT

The Department of Corrections of the State of Tennessee is conducting an experiment at the Northwest Tennessee Correctional Facility (NWCX) that is intended to demonstrate the total life cycle savings that can be obtained by using geothermal heat pump systems to provide heating, ventilating, and air conditioning (HVAC) and domestic hot water (DHW). The University of Tennessee at Martin (UTM) Center for Energy Management has been participating in this project since 1999. This paper provides a description of the: 1) role of the Center for Energy Management and its interaction with the Department of Corrections and the system designer, 2) guilds and the associated inmate populations, 3) geothermal system, 4) instrumentation and data acquisition systems, 5) analysis methods, and 6) HVAC and DHW cost benefit data obtained for the 2003-2004 heating and cooling seasons. These intermediate results show that the traditional HVAC system used 46% more energy than the geothermal system and the resistive DHW system used 46% more energy than the geothermal system.

Key Words: energy management, geothermal, bore field, heat pump.

1 INTRODUCTION

In 1999, in an effort to reduce energy costs, the decision was made by The Department of Corrections of the State of Tennessee to conduct a pilot project. The pilot project would take place at NWCX located near Tiptonville, Tennessee. The UTM Center for Energy Management was contacted during the development stages and asked to help develop and maintain a plan to determine the cost benefits that could be realized by converting all of the facility to a geothermal system.

The Center for Energy Management is located in the College of Engineering and Natural Sciences at the University of Tennessee at Martin. This center was created in the summer of 2000 to provide energy-related services to regional government and industrial organizations. The Center gives faculty members in the Department of Engineering an opportunity to conduct applied research that is supported with undergraduate engineering students. The students are actively involved with projects that tie their coursework to the real world, and the center provides a necessary service to regional government and industrial organizations. The concept for the center began in the summer of 1999 when an Energy Management Administrator with the State of Tennessee Department of Finance & Administration, contacted the School of Engineering. The Department of Finance & Administration was looking for a resource that would provide the state with independent third-party analysis and verification of new energy management technologies.

NWCX is a medium custody correctional facility that houses 2,377 inmates. It consists of two compounds, a Main Compound that was constructed in 1992, and an Annex Compound that was constructed in 1980. The Annex Compound contains sixteen similarly built inmate-housing units, known as guilds, as well as a host of other buildings. The guilds are 576 m^2 (6,200 ft^2) brick buildings that are each similar in construction, and are located side by side along a circular arc. Each guild houses approximately forty-eight inmates who follow the same daily routine. A front view of three guilds can be seen in Fig. 1. The original HVAC systems for the sixteen guilds use water-to-air heat pumps that were installed during construction of the Annex Compound in 1980. The source water for the heat pumps is provided by a "central loop" system that uses a cooling tower and boiler to maintain the water within the desired range. Electric resistance hot water heaters are used to provide the inmates with DHW. The expense of operating and maintaining the cooling tower/boiler system and the age of the heat pumps prompted the Department of Corrections, working with the Tennessee Energy Management Office, to examine alternative methods for providing HVAC and DHW to the guilds.

Fig. 1. Guilds 5, 6, and 7 at NWCX . Guild 5 is on the left, 6 is in the middle, and 7 is on the right.

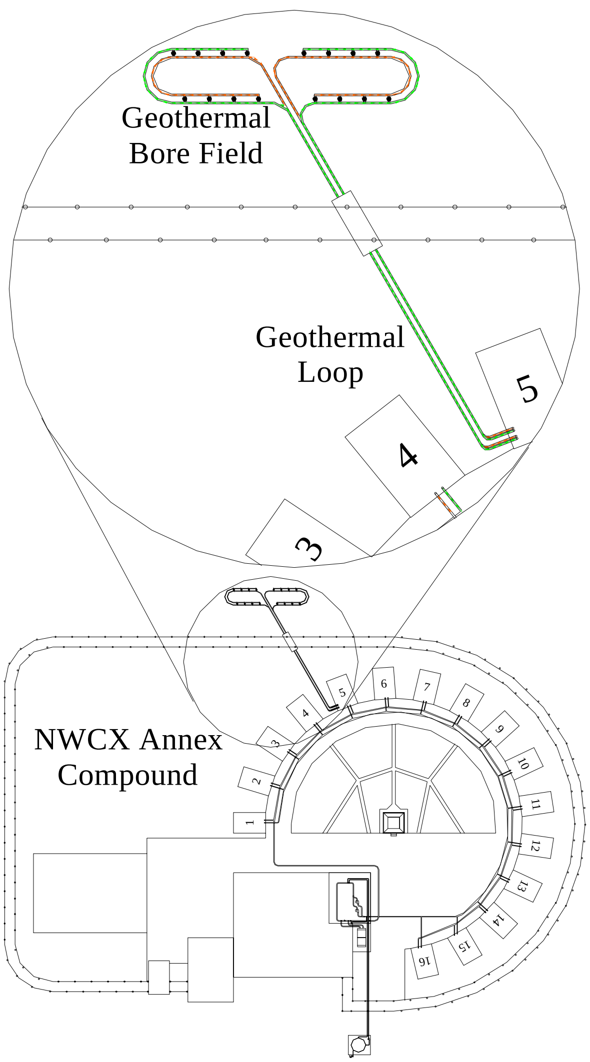

Fig. 2. NWCX Annex Compound with blown up view of Guild 5 and the geothermal bore field.

Three objectives were established for this pilot project. They are as listed:

1) Determine the cost benefit associated with using the geothermal system instead of the existing central loop as the water source for heat pumps used to provide HVAC for the guilds.
2) Determine the cost benefit associated with using a geothermal water source heat pump to heat the DHW used by inmates instead of existing electric resistance water heaters.
3) Determine the cost benefit of replacing the current heat pump units with newer more efficient heat pump units.

To help meet the first two objectives, in 2001 one of the guilds was isolated from the central loop and connected to a geothermal bore field. Guild 5 is the housing unit in which the geothermal closed-loop HVAC and DHW system has been installed. The system contains six, 10.6 kW (3 ton), water-to-air heat pump units for heating and cooling, a 21.1 kW (6 ton), water-to-water unit for conditioning fresh air brought in from outside through a blower coil, and one 10.6 kW (3 ton), water-to-water heat exchanger for heating the DHW. A horizontal run made of 7.6 cm polyethylene piping runs approximately 76 m in length connecting Guild 5 to the bore field. The geothermal bore field is a closed loop system consisting of sixteen, 91 m vertical bores, designed to handle the 95 kW (27 ton) load. The bore field is divided into two distinct sections. Each section containing eight bores with one main supply and return line for each section. The top supply-lines are buried approximately 1 m under the earth and the bottom return-lines are buried approximately 2 m deep. Figure 2 shows a layout of the Annex compound with a close up of Guild 5 and the geothermal bore field.

It should be noted that both guilds 5 (geothermal source heat pumps) and 6 (central loop source heat pumps) contain a make-up air system required to meet ASHRAE fresh air requirements (ASHRAE 1989).

2 INSTRUMENTATION AND DATA ACQUISITION SYSTEMS

The computations required to determine the cost benefit objectives of the project requires the measurement of the power used by the heat pumps, water circulation pumps, electric resistance heaters, fans, boiler, and central loop cooling tower. Several mass flow rate and water temperature readings are also required including those of the 6 HVAC heat pumps located in guilds five, six, and seven.

Architectural Energy Corporation (AEC) makes the remote data acquisition system devices being used on the project. Signals from measurement devices are sampled at two-minute intervals and are stored in AEC MicroDataLoggers. Each MicroDataLogger can accommodate up to four channels of data. Each MicroDataLogger is connected to an AEC SmartPort that provides an interface to a modem that is used to download the data from up to five MicroDataLoggers. Figure 3 shows a schematic of five data loggers connected to a SmartPort. At this time data is being collected from 79 different channels.

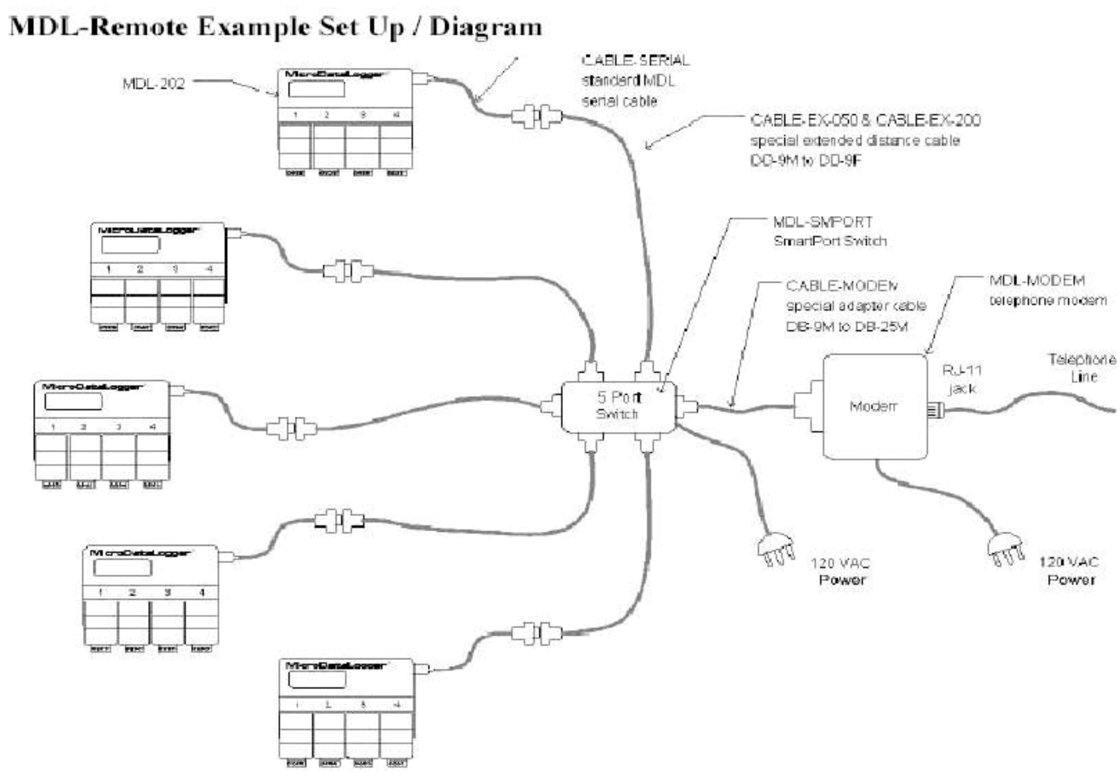

Fig. 3. Schematic of data loggers connected to a SmartPort

3 ANALYSIS METHODS

3.1 Objective 1

A literature review was conducted to determine if similar geothermal monitoring programs had been conducted elsewhere. While several programs had been completed (Hughes and Shonder 1998), (Shonder et al. 2000), they each made use of direct digital control systems to collect the data and none of the programs had attempted to compare similar buildings with and without geothermal systems. A literature review was also conducted concerning geothermal ground source heat pumps (Kavanaugh and Rafferty 1997), (OSU 1997). A comparison of the cost effectiveness of meeting HVAC and DHW systems in multiple buildings is difficult because of the differences in thermal load and construction. Although the prison guilds being considered in this demonstration project are of similar construction and are located next to each other, it was felt that differences in demand (e.g. thermostat settings, in-and-out traffic, hot water usage, etc.) would be difficult to control. Therefore, the metric used to compare the cost effectiveness of the geothermal system and the boiler/chiller system has to be normalized to the actual HVAC and DHW load for each guild for the respective guild.

As has been stated the first objective of the project was to determine the benefits that would be found by using a closed loop geothermal system in lieu of the existing system which is a closed loop conditioned water system that runs off a cooling tower and boiler. To determine this it was first needed to know or be able to solve for the heating/cooling load seen by the guilds. The heating/cooling load is defined as the rate at which heat must be added/removed from the guilds to keep the temperature inside the guilds within the desired range. To determine the load the energy sources related to the guilds were first realized and this was set equal to the load to give a function of these energy sources. Figure 4 shows all the different energy sources that are found to be entering and leaving Guild 5, which is the geothermal system.

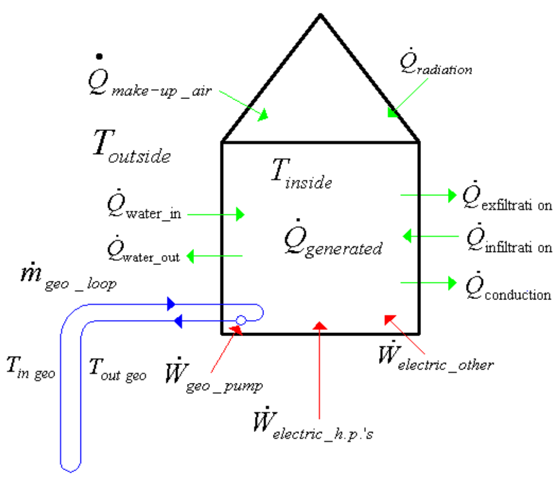

Fig. 4. Energy sources for Guild 5

The energy load that the geothermal source heat pumps must accommodate is given by the equation

$$\dot{Q}_{L} = \dot{Q}_{make-up\_air} + \dot{Q}_{water\_in} - \dot{Q}_{water\_out} - \dot{Q}_{conduction} + \dot{Q}_{infiltration} - \dot{Q}_{exfiltration} + \dot{Q}_{radiation} \tag{1}$$

In this equation, some of the terms can be measured in a reasonable manner and others cannot. Although a direct measurement of all of quantities is not possible, $\dot{Q}_L$ can be found from an energy balance and is given as

$$\dot{Q}_L = \dot{m}c(T_{out} - T_{in}) - \dot{W}_{hp} \quad \textbf{(2)}$$

Instrumentation has been installed so that all quantities found in Equation 2 can be directly measured or otherwise calculated indirectly through other measured quantities. The power required to maintain Guild 5 within the temperature range set by the building thermostats includes the geothermal loop circulation pump in addition to the heat pump power. Therefore, the total HVAC power required to meet the heating/cooling load given in equation 2 can be calculated from

$$\dot{W} = \dot{W}_{hp} + \left(6/8 \right) \dot{W}_{gp} \quad \textbf{(3)}$$

The factor (6/8) accounts for the DHW heat pump and the heat pump used to condition the fresh air, both of which use the geothermal conditioned water circulated by the pump.

Ultimately to meet the objective it was needed to be able to determine the cost to condition the air normalized by the conditioning load. The cost per unit of heating/cooling can be found using equations 2 and 3, along with a cost factor that represents the cost of energy. This normalized cost equation is given by

$$NCR = \frac{\int \dot{W} dt \cdot (CostFactor)}{\int \dot{Q}_L dt} \quad \textbf{(4)}$$

Guild 6 uses conditioned water from the central loop instead of from the geothermal loop. Other than this Guild 5 and 6 are very similar and therefore, Equation 2 can also be used to compute the heating/cooling load for Guild 6. In this case, the mass flow rate and temperatures for the central loop must be used. The power required to meet the Guild 6 heating/cooling load includes the six HVAC heat pumps located in Guild 6, plus a portion of the power required by the central loop circulation pumps and cooling tower. Therefore, the total power used to provide Guild 6 HVAC services is

$$\dot{W} = \dot{W}_{hp} + \left(20.33/358.5 \right) (\dot{W}_{cp} + \dot{W}_{ct}) \quad \textbf{(5)}$$

The factor (20.33/358.5) allocates the total wattage (tonnage) between the 127 heat pumps that use water from the central loop. Equation 5 can be used in combination with Equation 2 to find the Normalized Cost Ratio for Guild 6.

3.2 Objective 2

The second objective of the pilot project is to determine the cost benefit associated with using a heat pump with geothermal source water to heat DHW instead of the existing electric resistance hot water tanks. Comparisons between Guild 5, which was modified to a geothermal water source heat pump, and Guild 6, which uses electric resistance water heaters, were used to meet this objective. Figure 5 shows a schematic for the DHW water system used in Guild 5. Water Heater # 1 is heated with a water source heat pump connected to the geothermal loop. An electric resistance-heating element is still used in Water

Heater # 2 to raise the temperature another -15 °C (5 °F) from 49 °C (120 °F) to 52 °C (125 °F). An additional pump is also required to circulate water between Water Heater #1 and a heat exchanger in the heat pump. Instrumentation has been installed so that all quantities found in Fig. 5 can be directly measured or otherwise calculated indirectly through other measured quantities. The cost per Liter of water used can be computed from Equation 6 below.

$$NCR = \frac{\int (\dot{W}_{\#2} + \dot{W}_{hp} + \dot{W}_{circ\_pump} + \dot{W}_{HP\_pump})dt(CostFactor)}{Liters} \quad \textbf{(6)}$$

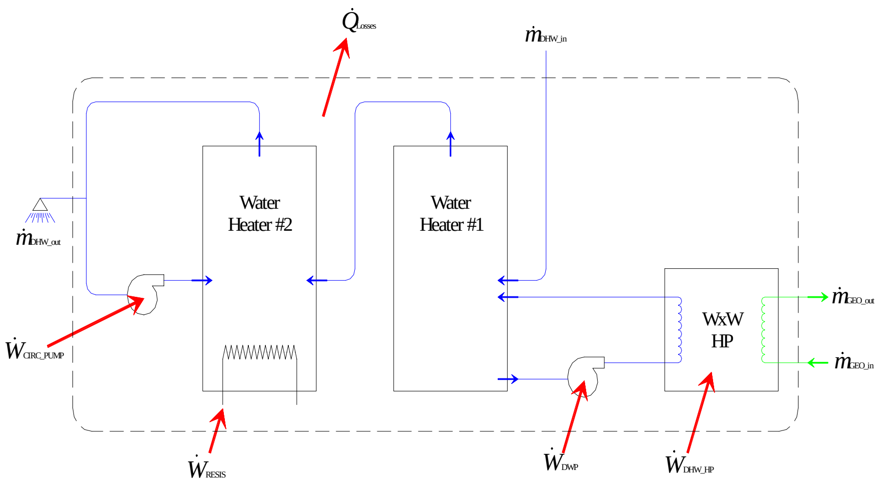

Fig. 5. Guild 5 Domestic Hot Water System

The system used for DHW in Guild 6 is typical of all of the guilds except Guild 5. Water at a temperature of 52 °C (125 °F) is continuously circulated from Water Heater # 1 through the hot water supply piping by the DHW circulation pump. As water is used, make up water is drawn into Water Heater # 2 from Water Heater # 1. The water in Water Heater # 1 is heated from the supply temperature to 49 °C (120 °F). The water is heated another -15 °C (5 °F) in Water Heater #2.

The cost per Liter of water used by Guild 6 is computed similarly to that above by dividing the cost of the power used by the DHW system by the Liters of water used. A totalizing flow meter was used to measure the Liters of water used, while watt-nodes were used to determine the power used by the circulation pump, and two water heaters. The equation for computing the cost per Liter for Guild 6 is

$$NCR = \frac{\int (\dot{W}_{circ\_pump} + \dot{W}_{\#1} + \dot{W}_{\#2})dt(CostFactor)}{Liters} \quad \textbf{(7)}$$

3.3 Objective 3

The third objective of the pilot project is to determine the cost benefit of replacing old heat pumps with newer, more efficient units. Comparisons between the power used by the HVAC heat pumps in Guild 6 and Guild 7 were used to accomplish this objective. The HVAC heat pumps in both Guild 6 and Guild 7 use source water from the central loop. During the geothermal implementation phase of the project, the HVAC heat pumps in Guild 6 were replaced with units identical to the new units in Guild 5. In addition to the heat pumps in Guild 6 being newer than those in Guild 7, Guild 6 has a conditioned fresh air intake system. Figure 6 shows a schematic of the Guild 6 HVAC and fresh air intake systems. The cost of operating the HVAC heat pumps normalized by the heating/cooling load can be computed using the equation

$$NCR = \frac{\int \dot{W}_{HVAC\_hp} dt(CostFactor)}{\int \dot{Q}_{L\_HVAC} dt} \quad \textbf{(8)}$$

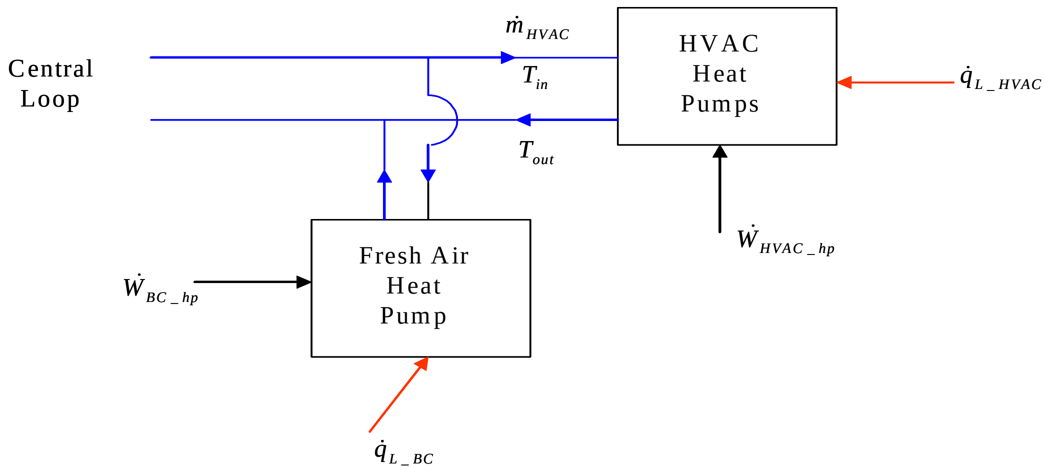

Fig. 6. Schematic of Guild 6 HVAC and Fresh Air Intake Systems

The schematic for Guild 7 would look identical to that of Guild 6 without the fresh air intake heat pump. Therefore, the normalized cost ratio for Guild 7 can also be computed using Equation 8.

4 COST BENEFIT DATA

4.1 Objective 1

Table 1 provides a comparison of the energy required to provide the HVAC services to Guilds 5 (geothermal loop) and 6 (central loop) for the two data acquisition periods during the first year including the first cooling and first heating seasons (LeMaster and Krebs 2003), (LeMaster et al. 2004). The energy for Guild 5 includes the six HVAC heat pumps, fresh air conditioning heat pump (blower coil), geothermal loop recirculation pump, and fresh air intake coil recirculation pump and fan. The energy for Guild 6 includes the six HVAC heat pumps, fresh air conditioning heat pump (blower coil), prorated portion of the central loop cooling tower fans, boiler, and circulation pumps, and fresh air intake coil recirculation pump and fan. The total HVAC energy used by Guild 6 during the first heating/cooling season was 51.6 % greater than that used by Guild 5.

Table 1. Total HVAC Energy Used by Guilds 5 and 6

Period		Total Energy	
Start/End Dates [Mn/Day/Yr]	**Start/End Times [Hr:Min:Sec]**	**Geothermal Loop [kW-hr]**	**Central Loop [kW-hr]**
3/15/2003 4/23/2003	00:00:00 07:24:00	1,756	4,248
4/24/2003 7/29/2003	00:00:00 08:22:00	19,225	32,290
7/30/2003 10/15/2003	00:00:00 08:16:00	17,349	27,089
10/16/2003 11/12/2003	00:00:00 09:22:00	3,281	5,687
11/13/2003 2/4/2004	00:00:00 08:40:00	10,369	11,611
2/5/2004 4/23/2004	00:00:00 08:08:00	5,674	6,460
	TOTAL	57,654	87,385

This difference can be seen in Fig. 7 below, which plots the kW-hrs. used by guilds 5 and 6.

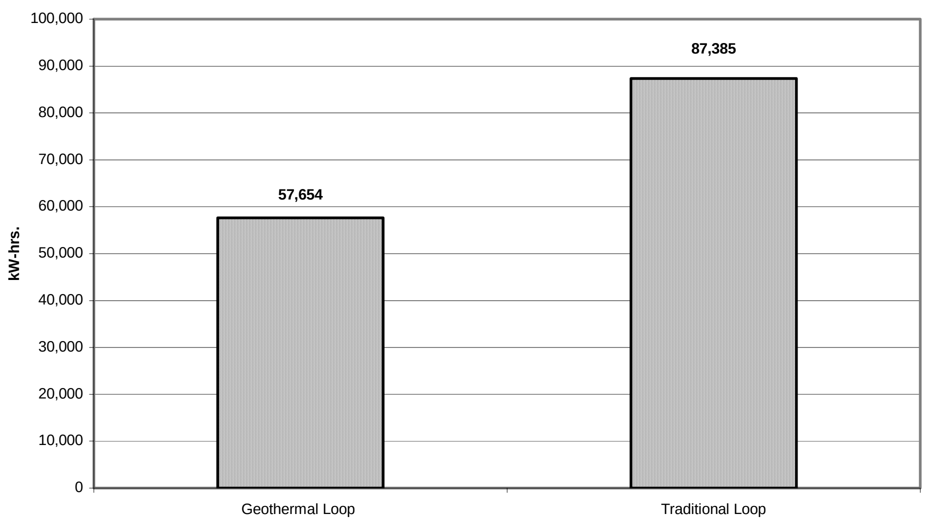

Fig. 7. Plot of kW-hrs. used by guilds 5 and 6 for HVAC

4.2 Objective 2

The second objective was to determine the cost benefit associated with using a heat pump with geothermal source water to heat domestic hot water instead of the existing electric resistance hot water heaters. A comparison of the energy required to provide a Liter of domestic hot water in Guilds 5 and 6 is provided in Table 2 (LeMaster and Krebs 2003), (LeMaster et al. 2004).

Table 2. Domestic Hot Water Comparison for Guilds 5 and 6

Period		Total Energy per Liter	
Start/End Dates [Mn/Day/Yr]	Start/End Times [Hr:Min:Sec]	Geothermal Loop [W-hr/Liter]	Central Loop [W-hr/Liter]
3/15/2003 4/23/2003	00:00:00 07:24:00	31	49
4/24/2003 7/29/2003	00:00:00 08:22:00	24	43
7/30/2003 10/15/2003	00:00:00 08:16:00	24	39
10/16/2003 11/12/2003	00:00:00 09:22:00	32	45
11/13/2003 2/4/2004	00:00:00 08:40:00	40	52
2/5/2004 4/23/2004	00:00:00 08:08:00	39	50
	TOTAL	190	278

An analysis of the data in Table 2 shows that the energy required to heat a Liter of hot water in Guild 6 is approximately 46.2 % greater than that required by Guild 5. Note that it is more expensive for both systems to provide hot water during the cooler months. This is most likely due to higher heat transfer rates between the hot water tanks and the surroundings. The heat transfer rates are proportional to the temperature difference between the hot water and the temperature of the air in the space surrounding the water tanks. This temperature difference is more during the cooler months. A comparison of the W-hr/Liter used by each can be seen in Fig. 8.

Fig. 8. Plot of W-hr./Liter used by guilds 5 and 6 for DHW

4.3 Objective 3

The third objective was to determine the cost benefit of replacing old heat pumps with newer, more efficient units. This comparison is being made between Guilds 6 and 7. The method described in the Analysis Methods section for performing this comparison could not be performed exactly as described because of difficulties in obtaining flow rate measurements with the portable flow meter used. Therefore, total power will be compared between the two guilds. This comparison is less than desirable since the additional heating/cooling load created by the fresh air intake system in Guild 6 could not be removed from the comparison. The addition of inline flow meters will correct this problem and future comparisons will be able to account for the differences in heating/cooling load.

Table 3 shows the total energy used by the six HVAC heat pumps in Guilds 6 and 7(LeMaster and Krebs 2003), (LeMaster et al. 2004). Note that the energy required to heat/cool Guild 7 is 51.7 % higher than that required to heat/cool Guild 6. The heating/cooling load for Guild 6 is expected to be higher than the heating/cooling load for Guild 7 due to the fresh air intake system. The % savings should be greater when the heating/cooling load is taken into account. A comparison of the kW-hrs used by each can be seen in Fig. 9.

Table 3. Total HVAC Energy Comparison for Guilds 6 and 7

Period		Total Energy	
Start/End Dates [Mn/Day/Yr]	**Start/End Times [Hr:Min:Sec]**	**Guild 6(New HPs) [kW-hr]**	**Guild 7(Old HPs) [kW-hr]**
3/15/2003 4/23/2003	00:00:00 07:24:00	1,659	2,382
4/24/2003 7/29/2003	00:00:00 08:22:00	20,890	31,423
7/30/2003 10/15/2003	00:00:00 08:16:00	18,699	28,686
10/16/2003 11/12/2003	00:00:00 09:22:00	4,075	6,290
11/13/2003 2/4/2004	00:00:00 08:40:00	7,907	10,556
2/5/2004 4/23/2004	00:00:00 08:08:00	3,802	7,198
	TOTAL	57,032	86,535

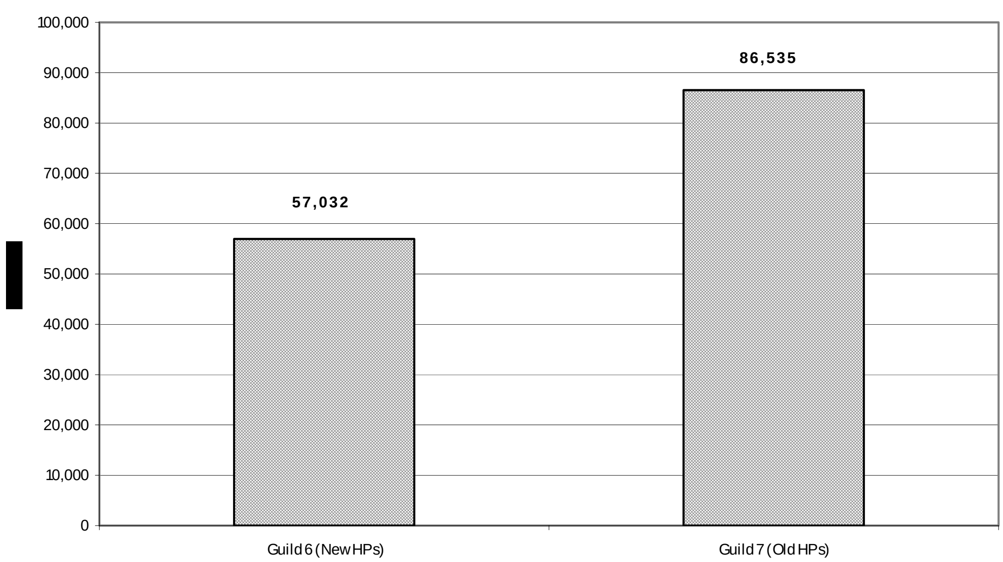

Fig. 9. Plot of kW-hrs used by guilds 6 and 7 for HVAC

5 SUMMARY

This paper provides an initial analysis of the data obtained for the period from March 15, 2003 to April 23, 2004 for the Geothermal Pilot Project at the Northwest Tennessee Correctional Complex. This reflects the first cooling and first heating periods in a planned two-year period. The comparisons for the first and third objectives were hindered because of difficulties associated with measuring flow rates using a portable flow meter. In line flow meters, that are now installed, will remove these problems for future analysis. New analysis will be able to measure more closely the HVAC comparisons.

Faculty and students from the Center for Energy Management are continuing work on the long-term monitoring of the geothermal pilot project at NWCX. At the present time new instrumentation is being installed within the bore field to obtain information regarding the bore field. Over the next few months efforts will focus on determining initial costs required to install a new geothermal system for building a new compound as well as maintenance costs required for the system. Also information will be gathered regarding initial costs of building a new compound with the traditional system as well as maintenance cost required. This information will help in determining the life cycle costs of each, and comparing the two.

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NOMENCLATURE

DHW	Domestic Hot Water
HVAC	Heating, Ventilation and Air Conditioning
NWCX	Northwest Tennessee Correctional Facility
TDOC	Tennessee Department of Corrections
c_p	Constant pressure specific heat
$\dot{m}_{geo\_loop}$	Mass flow rate in closed loop geothermal system
$\dot{Q}_{conduction}$	Energy transfer rate due to conduction through walls, etc.
$\dot{Q}_{exfiltration}$	Energy transfer rate due to loss of air from inside the guild
$\dot{Q}_{generated}$	Energy generated by biological functions

$\dot{Q}_{infiltration}$	Energy transfer rate due to outside air entering the guild from around doors, windows, or door traffic
$\dot{Q}_{make\text{-}up\_air}$	Energy transfer rate associated with fresh air intake into the guild
$\dot{Q}_{radiation}$	Net radiation heating rate
$\dot{Q}_{water}$	Energy transfer rate due to water entering or leaving the guild through inlet pipes, drains, or as moisture
T_{inside}	Inside air temperature
T_{in_geo}	Geothermal loop temperature entering the guild
T_{out_geo}	Geothermal loop temperature leaving the guild
$T_{outside}$	Outside air temperature
$\dot{W}_{electric\_h.p.'s}$	Power required to operate the electric heat pumps
$\dot{W}_{electric\_other}$	Power required to operate all other electrical equipment in the guild
$\dot{W}_{geo\_pump}$	Power required to operate the geothermal loop circulation pump