AC 2012-3381: A COMPUTER SIMULATION PROJECT ON UNDERGROUND HEAT PUMPS

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A Computer Simulation Project on Underground Heat Pumps

Introduction

Geothermal energy may be the most visibly striking of all the alternative energy sources. The idea of capturing the energy from a geyser or even from the flowing lava of an erupting volcano is very exciting to students. However, the truth is that in the United States there is very limited access to hot geothermal sources. On the other hand, the possibility exists throughout the United States to use the earth as a heat reservoir for a heating or cooling system. This geothermal energy utilization is often called "cold geothermal energy".

In this paper a computer based project for a comparative cost analysis between conventional heating and cooling systems and cold geothermal systems is presented. This project was assigned to senior level students in a mechanical engineering alternative energy class. The class is titled "Design of Alternative Energy Systems" and has been taught for eight years. Its development is documented in [1]. It is a 3 credit, semester long class that serves as a design elective in the mechanical engineering program. It is very project oriented, and the students work on as many as five different design projects during the semester. It is a well enrolled class with an average enrollment of 45 to 50 students. It requires thermodynamics and fluid mechanics as prerequisites and heat transfer as a co-requisite. The course learning objectives that specially deal with geothermal energy are:

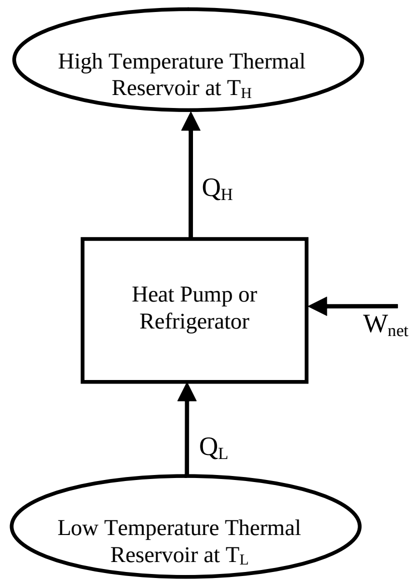
a. Students are able to understand the nature of the earth as an energy source or sink.
b. Students are able to understand and evaluate different types of geothermal energy systems.
c. Students are able to calculate the performance of geothermal energy systems.
d. Students are able to design a geothermal energy system.

The paper continues with a review of underground heat pump technology. The project statement is then presented, including the grading rubric and results. The paper concludes by summarizing student feedback and providing lessons learned.

Underground Heat Pump Technology

One of the best applications for geothermal energy is to use the fact that below the surface ground reaches a very steady temperature of 14°C. Hence, the underground can be used as a heat reservoir for either a refrigerator or a heat pump system. Recall that either a heat pump of a refrigerator can be modeled with the interaction diagram shown in Figure 1.

Figure 1 Interaction Diagram for a Heat Pump or Refrigerator



The difference between a heat pump and a refrigerator is the "product" of the system. In a refrigerator the product is the heat being removed from a cold space, Q_L. For a heat pump the product is the heat being added to a hot space, Q_H. In terms of performance characteristic, both systems use a coefficient of performance, COP, but due to the difference in product it is defined differently for the two systems. We have

$$(COP)_{HP} = \frac{Q_H}{W_{net}} = \frac{\dot{Q}_H}{\dot{W}_{net}} = \frac{q_H}{w_{net}}$$

$$(COP)_{Ref} = \frac{Q_L}{W_{net}} = \frac{\dot{Q}_L}{\dot{W}_{net}} = \frac{q_L}{w_{net}}$$

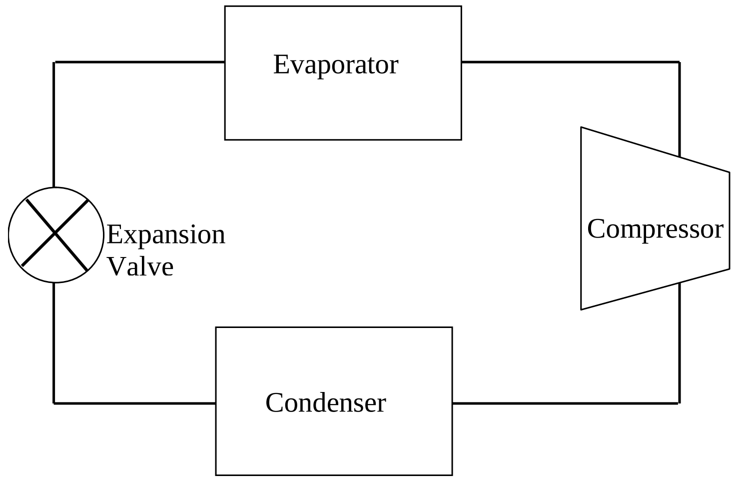
In the geothermal industry, some confusion exits since the phrase "underground heat pump" refers to a system that sometimes operates as a refrigerator and sometimes as a heat pump. Ideal operation of a heat pump or refrigerator occurs when they operate on the basis of a Carnot cycle and we have

Heat Pump $$COP_{HP,max} = \frac{1}{1 - \frac{T_L}{T_H}}$$

Refrigerator $$COP_{Ref.max} = \frac{1}{\frac{T_H}{T_L} - 1}$$

Most heat pump or refrigeration systems operate on the basis of the vapor compression cycle. This cycle is shown schematically in Fig. 2.

Figure 2 Block Diagram for a Vapor Compression Refrigeration Cycle



with the working fluid of the cycle (called a refrigerant) moving clockwise around the cycle. Let us traverse the cycle to gain a better understanding of what is going on.

Inlet to Expansion Valve: Fluid enters as a liquid; design point would call for it to be saturated liquid.

Expansion Valve: Ideally modeled as an adiabatic device, this throttles the fluid's pressure down so that is can boiler in the evaporator at a low temperature.

Expansion Valve Exit: The fluid normally leaves the valve as a low quality, two phase mixture.

Evaporator: Ideally the evaporator is at constant pressure, where the remainder of the liquid is boiled off and in doing so absorbs heat, Q_L.

Evaporator Exit: Design point would call for it to be saturated vapor.

Compressor: Raises the pressure of the working fluid, so that is might condense at a high temperature in the condenser. Ideally, it is an isentropic device.

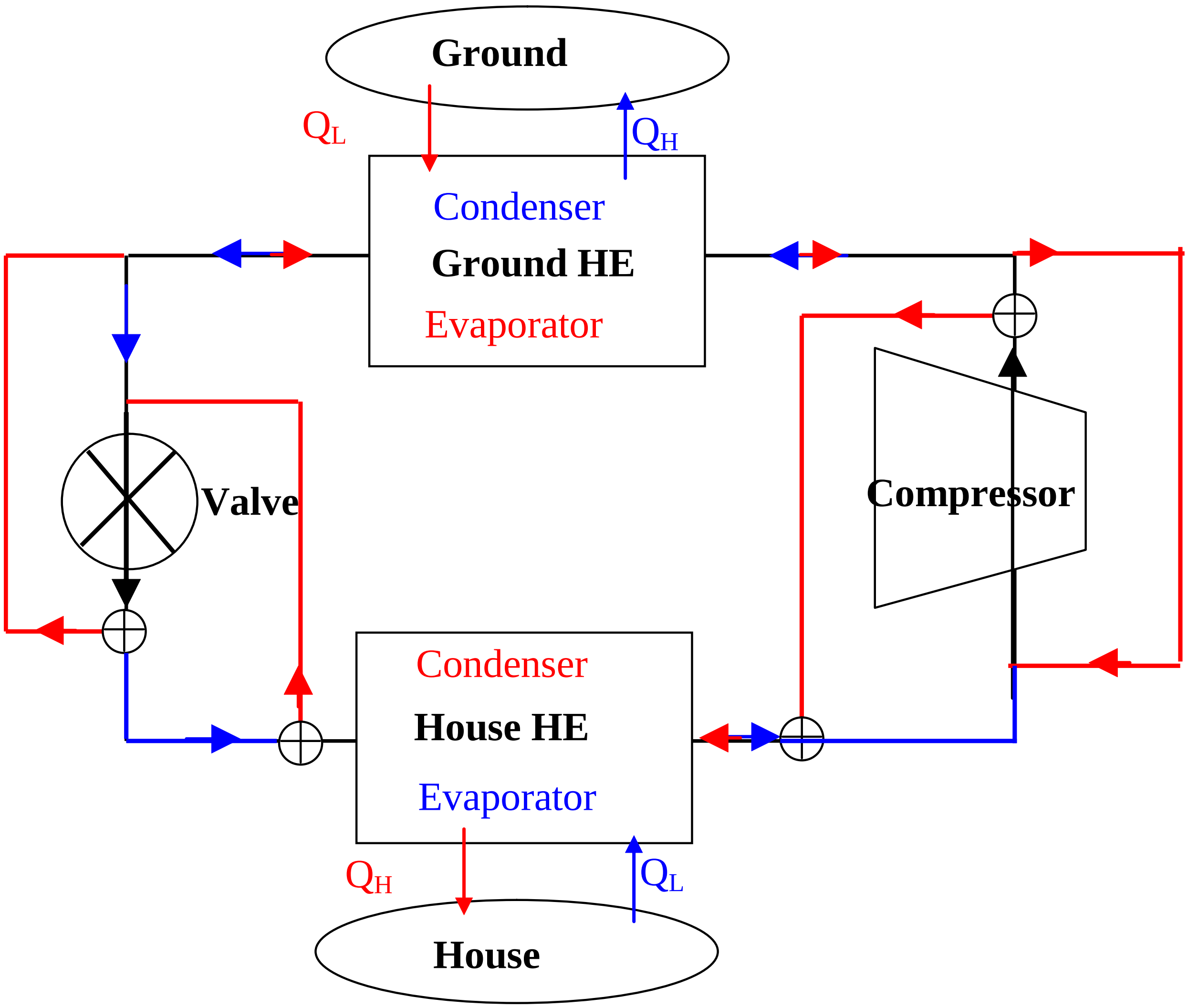
Compressor Exit: The fluid will exit as superheated vapor.

Condenser: Ideally the condenser is at constant pressure, where the superheated vapor is condensed to liquid and in doing so rejects heat, Q_H.

Certainly a key element of the vapor compression refrigeration system is the working fluid whose boiling or condensing temperature can be adjusted via the operating pressure. In fact, the ability for a refrigerant to change phase at a different temperature by adjusting the pressure is the magic that allows refrigeration to happen.

An underground heat pump system is composed as a heat pump for heating purposes and a cooling loop for air conditioning. A schematic might look something like Fig. 3.

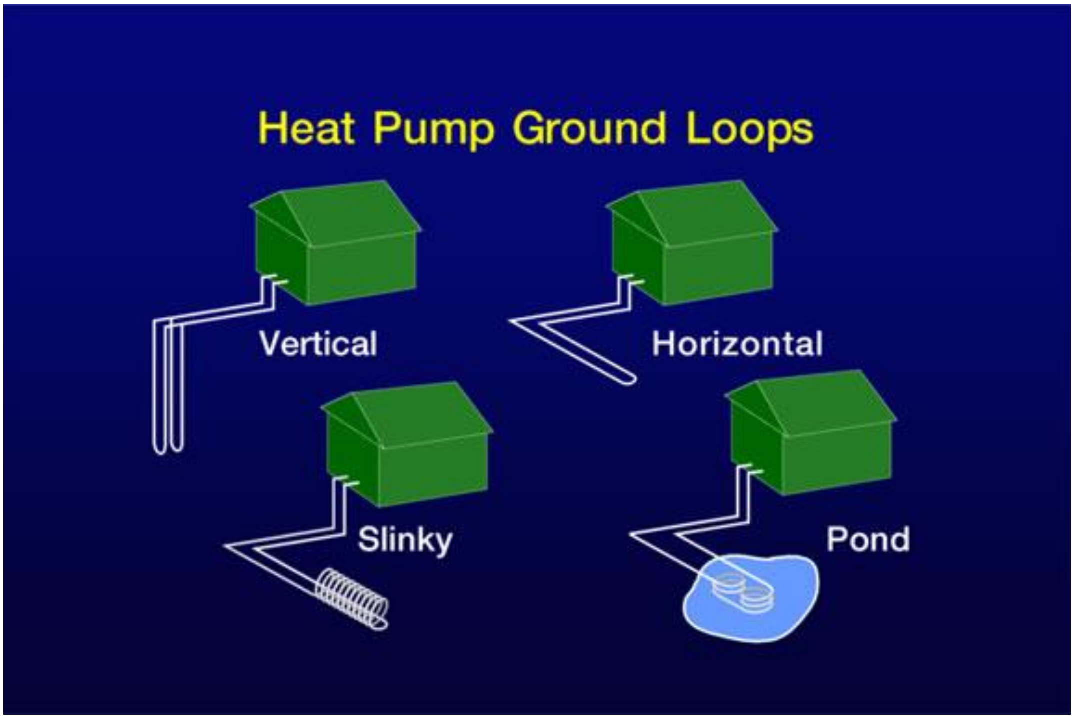
Figure 3 Cold Geothermal Heating/Cooling System



Blue represents the cooling system.
Red represents the heating system.
⊕ **Two way valve**

There are many different configurations for an underground heat pump system. Four of the more common are shown in Fig. 5.

Figure 5 Underground Heat Pump Heat Exchangers [2]



One of the design considerations in an underground heat pump system is the amount of ground required for the heating or cooling. For example, we know that in the cooling operation we will dump heat to the ground raising its temperature. If the ground temperature increases too much then its ability to cool will decrease and we may eventually have problems achieving the desired cooling of our house. To determine how much earth we need to have access to with our underground heat exchanger, we can perform an overall energy balance on the ground. Then

$$m_{earth} c_{P,earth} (\Delta T)_{earth} = \dot{Q}_{HE} \tau$$

where τ is the time period over which the heat exchanger operates.

Project Assignment

The project statement is provided in Appendix A. The project requires the students to use two computer programs, one that calculates the heating and cooling loads and one that performs the refrigeration cycle calculations for the heat pump/refrigerator. The students are required to document their calculations with a technical memo covering:

- Determination of Cooling & Heating Load Parameters
- Basic Geothermal System Design
- Breakeven Cost vs Heat Exchanger Temperature Difference
- Breakeven Cost vs Unit Gas Cost
- Payback Period vs Unit Gas Cost
- Comparison of Geothermal Systems

Teams of two students are assigned by the professor. The team has to carry out two cases. They may consider two different houses (square footage and stories) in one city, or the same house in two different cities. If the team chooses two different cities, they are encourage to select one city in the north (New York City, Detroit, Chicago, or International Falls) and one in the south or west (Los Angeles, Miami, Salt Lake City, Seattle, Phoenix, or Portland). The team is also provided with a recommendation regarding wall configuration, specifically insulation thickness and thermal conductivity, as well as furnace and air conditioner performance characteristics.

The team's first step is to estimate the heating and cooling loads for their houses. They do this using an in-house DOS executable program called TEEHouse [3] that is used for the conventional thermal design course for the program. The user's guide for the program can be found in Appendix B. Figure 6 shows some typical results for TEEHouse

Figure 6 Sample Results form the TEEHouse Program

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 ********* HEAT TRANSFER ANALYSIS ***********

AVERAGE DAILY SOLAR FLUX:                        162.2 W/m^2/K
AVERAGE DAILY TEMPERATURE:                       288.1 K
AVERAGE NIGHTLY TEMPERATURE:                     277.3 K
COOLING LOAD AVERAGE ROOF HEAT FLOW:            1021.3 W
COOLING LOAD AVERAGE WALL HEAT FLOW:            1696.9 W
COOLING LOAD AVERAGE INFILTRATION HEAT FLOW:     246.7 W
NUMBER OF COOLING DAYS:                           60.0
HEATING LOAD AVERAGE ROOF HEAT FLOW:             643.5 W
HEATING LOAD AVERAGE WALL HEAT FLOW:             528.0 W
HEATING LOAD AVERAGE INFILTRATION HEAT FLOW:    1104.3 W
NUMBER OF HEATING DAYS:                          214.5

 ********** COST DATA ************

NATURAL GAS COSTS:      $  4864.54
FURNACE COSTS:          $   905.00
ELECTRICITY COSTS:      $   975.44
AIR CONDITIONER COSTS:  $   805.81
ROOF INSULATION COSTS:  $   399.00
ROOF MATERIAL COSTS:    $   798.00
ROOF TOTAL COSTS:       $  1197.00
WALL INSULATION COSTS:  $   267.29
WALL MATERIAL COSTS:    $   534.58
WALL TOTAL COSTS:       $   801.87
INSULATION COSTS:       $   666.29
MATERIALS COSTS:        $  1332.58
TOTAL COSTS:            $  9549.66
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These results provide the team with the following information:

Cooling Load: 2964.9 kW
Heating Load: 2275.8 kW
Cooling Days: 60
Heating Days: 214.5

Since breakeven cost is used in the required economic analyses for the project, the economic data for TEEHouse is not used.

To design the underground heat pump system, the team used the MATLAB program **ColdGeothermal**. This is an in-house program that will carry out the vapor-compression refrigeration cycle calculations. This program will calculate several economic factors, including the breakeven cost for the cold geothermal system compared to a conventional system and the payback period required for a cold geothermal system at the user supplied estimated capital cost. Using **ColdGeothermal** the team can carry out the required thermoeconomic analysis, examples of which are shown in Figs. 7 and 8.

Figure 7 Breakeven Cost versus Heat Exchanger Temperature Difference

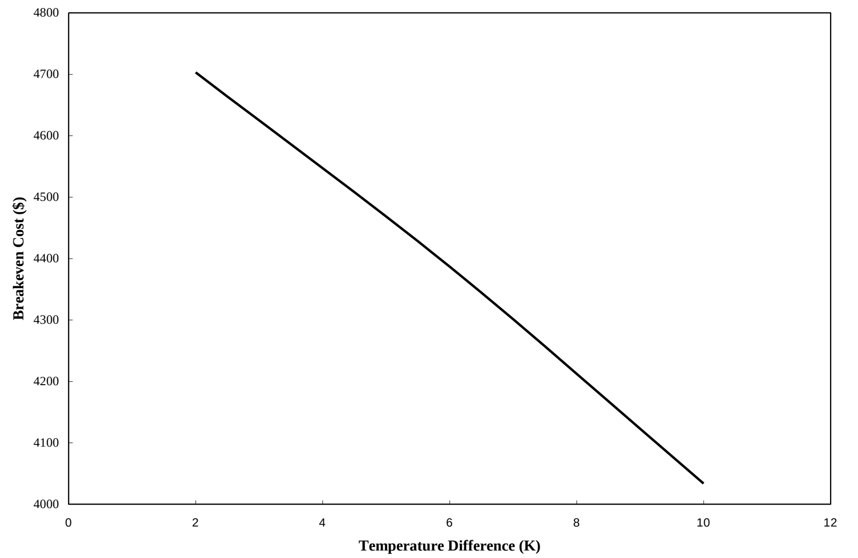
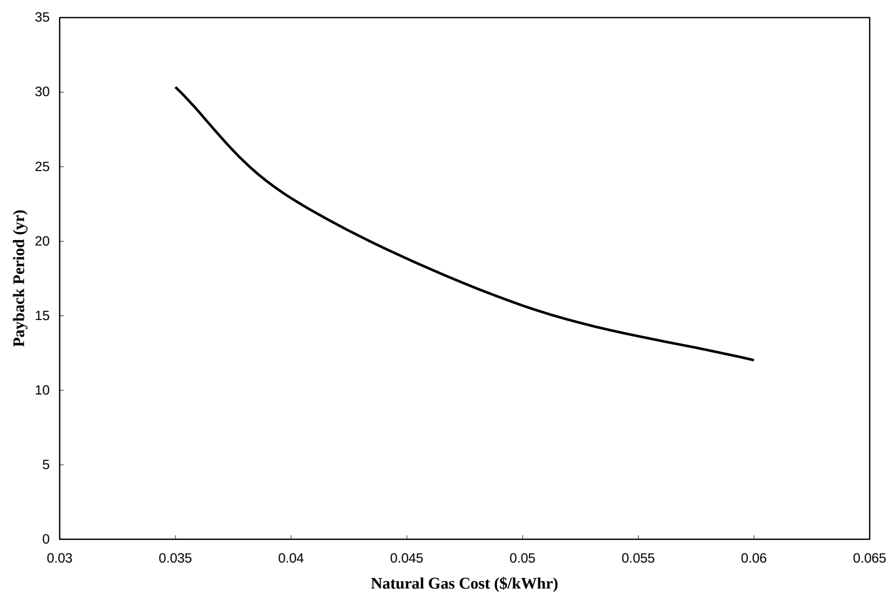


Figure 8 Payback period versus Natural Gas Cost



The team must submit a technical memo, which is graded using the rubric of Fig. 9.

Figure 9 Report Grading Rubric

ME 417

Design of Alternative Energy Systems

Project Grade Evaluation
Project 3 Design of a Cold Geothermal System

Student Names: ____

Topic	Assigned Score Site #1	Assigned Score Site #2	Maximum Score
Determination of Cooling & Heating Load Parameters			20
Basic Geothermal System Design			10
Breakeven Cost vs Heat Exchanger Temperature Difference			10
Breakeven Cost vs Unit Gas Cost			10
Payback Period vs Unit Gas Cost			10
Comparison of Geothermal Systems			10
Quality			10
Total			80

Student Results and Feedback

Figure 10 shows the grade distribution for the project. The teams performed very well on the project, with an average score of 93.7 and a median score of 95.5.

The class was surveyed and the following questions were asked:

Based upon completing the Cold Geothermal Project, please grade yourself using the MSU grading system, 0.0 to 4.0, with 0.5 intervals.

You are able to understand the nature of the earth as an energy source:

You are able to understand and evaluate different types of geothermal energy systems:

You are able to calculate the performance of geothermal energy systems:

You are able to design a geothermal energy system:

Any suggestions to improve the Cold Geothermal Project:

The results of this survey are shown in Table 1. We see that the student reaction was quite positive.

Figure 10 Assignment Grade Distribution

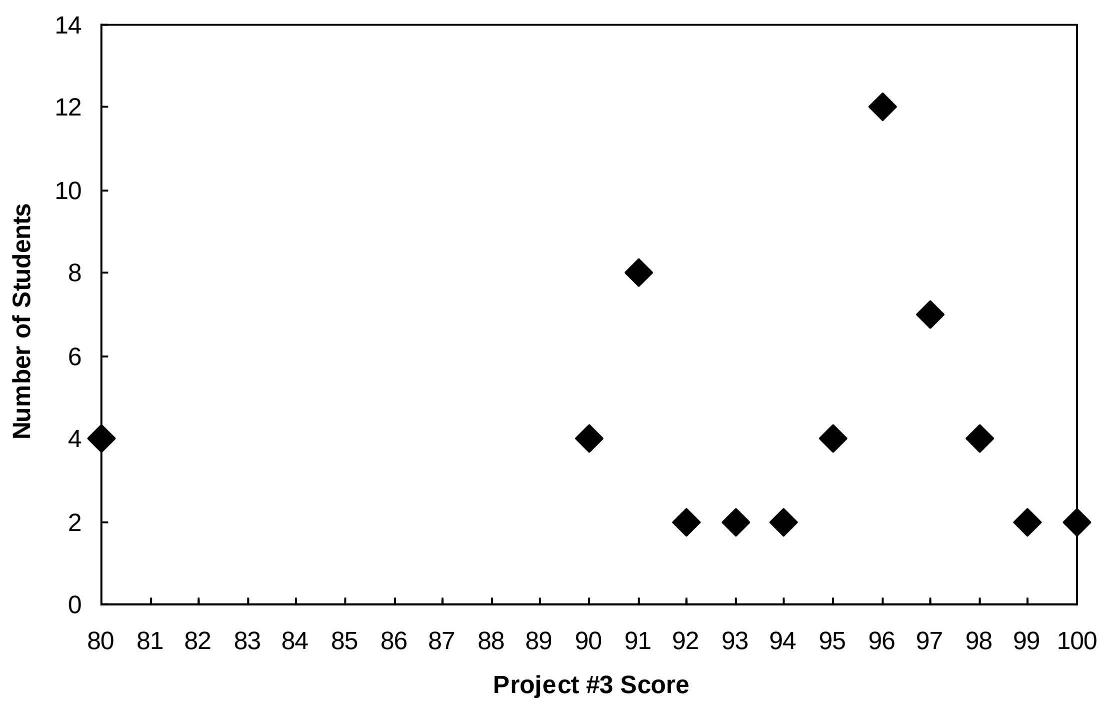


Table 1 Class Survey Results

Question	Average Score
You are able to understand the nature of the earth as an energy source:	3.78
You are able to understand and evaluate different types of geothermal energy systems:	3.44
You are able to calculate the performance of geothermal energy systems:	3.78
You are able to design a geothermal energy system	3.19

Lessons Learned

- The cold geothermal project provides the students with a project based experience in learning about geothermal energy.
- Using two pieces of software did not seem to confuse the students.
- Some of the students wanted the project to also include the underground heat exchanger design.
- The project reinforces the need for engineering economics, which is taught as part of the course.
- The ability for the students on a team to work independently on their part of the project was viewed very favorably by the students.

References

1. Somerton, C.W. and Bénard, A., "Developing a Design Based Alternative Energy Course", *2006 ASEE Annual Conference Proceedings*, Chicago, June 2006.
2. http://www.geothermal.marin.org/GEOpresentation
3. Somerton, C.W., Genik, L.G., Thelen, W., Lewis, D., and Strawn, S., "TEEHOUSE: Thermal Environmental Engineering Design and Cost Software for a Building", *2002 ASEE Annual Conference Proceedings*, Montreal, June 2002

Appendix A Cold Geothermal Project Assignment

ME 417

Design of Alternative Energy Systems

Project 3 Design of Cold Geothermal Systems
Due Monday, March 28, 2011

People for Ethical Energy (a consumer advocacy group) is concerned with the pricing of cold geothermal heating and cooling systems. PEE is most concerned if these systems actually pay for themselves through natural gas savings as advertised by the installers. They have hired the engineering firm of Bénard and Somerton to provide a comparative cost analysis between conventional heating and cooling systems and cold geothermal systems. Two associates of the firm have been assigned to beta test the analysis package developed by the firm. The team should consider one or two of the following residential dwellings for the optimization study,

1 story small house, 600-800 ft2 (55-75 m2) living space
1 story medium size house, 1000-2000 ft2 (90-185 m2) living space
2 story medium size house, 1000-2000 ft2 (90-185 m2) living space
1 story large house, 2500-5000 ft2 (230-465 m2) living space
2 story large house, 2500-5000 ft2 (230-465 m2) living space

located in one or two of the following cities:

1. New York City
2. Detroit
3. Chicago
4. Los Angeles
5. International Falls
6. Miami
7. Salt Lake City
8. Seattle
9. Phoenix
10. Portland

To clarify, the team could consider two different houses located in the same city as their two cases or the same house located in two different cities for their two cases. If the team chooses two different cities, one city should be in the north (New York City, Detroit, Chicago, or International Falls) and one in the south or west (Los Angeles, Miami, Salt Lake City, Seattle, Phoenix, or Portland).

To begin, the associate must determine the heating and cooling loads for this site. The program **TEEHouse** can be used to do this. The following input parameters are suggested:

HOUSE AIR CHANGE PER HOUR: 0.5
DESIGN STUDY: ANNUAL HEATING AND AIR CONDITIONING
DESIRED INTERIOR AIR TEMPERATURE FOR COOLING: 296 K
DESIRED INTERIOR AIR TEMPERATURE FOR HEATING: 293 K
NATURAL GAS COST ($/kW*hr): 0.035
ELECTRICITY COST ($/kW*hr): 0.055

ANNUAL INTEREST RATE (%): 5
BUILDING LIFETIME (yrs): 20

The wall and roof both have one layer of Type A insulation of thickness 75 mm. Use furnace type 2 and air conditioner type 2.

Record the following information from the output:

COOLING LOAD AVERAGE ROOF HEAT FLOW:
COOLING LOAD AVERAGE WALL HEAT FLOW:
COOLING LOAD AVERAGE INFILTRATION HEAT FLOW:
NUMBER OF COOLING DAYS:
HEATING LOAD AVERAGE ROOF HEAT FLOW:
HEATING LOAD AVERAGE WALL HEAT FLOW:
HEATING LOAD AVERAGE INFILTRATION HEAT FLOW:
NUMBER OF HEATING DAYS:

From this data the total cooling and heating loads can be calculated.

To design the cold geothermal system, the team will use the MATLAB program **ColdGeohtermal**. The following base conditions should be used in the design analysis:

Interest Rate: 0.05
System Life: 20 years
Natural Gas Cost: 0.035 $/kWh
Electricity Cost: 0.055 $/kWh
Heat Exchanger Temperature Difference: 10°C
Estimated Capital Cost of Cold Geothermal System: $5,000

The program will then calculate several economic factors, including the breakeven cost for the cold geothermal system compared to a conventional system and the payback period required for a cold geothermal system at the user supplied estimated capital cost. In addition to the base results, the team should conduct the following studies:

Breakeven Cost versus Heat Exchanger Temperature Difference (range: 2°C-12°C)
Breakeven Cost versus Unit Gas Cost (0.035 $/kWh – 0.07 $/kWh)
Payback Period versus Unit Gas Cost (0.035 $/kWh – 0.07 $/kWh)

Getting Started

- Decide whether the team will do two houses in one city or one house in two cities.
- Select the house(s) and city (or cities).
- For each case run the **TEEHouse** program to determine the heating load, cooling load, heating days, and cooling days.
- Run the **ColdGeothermal** program to design the cold geothermal system and evaluate its costs.
- Using the data from the **ColdGeothermal** program evaluate the economic feasibility of the cold geothermal systems.

Appendix B Users Guide for TEEHouse

User's Guide for TEEHOUS.EXE

The software TEEHOUS.EXE is an interactive DOS program for the design and cost analysis for the heating and air conditioning systems for a building. It allows for the optimization of insulation type and thickness, furnace type and air conditioner type. The program may be run by clicking on the program icon labeled TEEHOUS.

The initial menu requests geographic and other information concerning the building. The building may be specified as either a one story or two story structure. The air change per hour (ACH) is also specified to calculate the infiltration heat transfer. Two design studies are possible: single day analysis for which the user will provide the specific day to carry out the calculations and an annual year analysis for which the heat transfer calculations are carried out on a half day basis for the entire year. The single day analysis will consider only a heating or cooling optimization (depending of the day chosen) while the annual year analysis will perform both a cooling and heating optimization. If the annual year analysis is chosen an inside temperature for both heating and cooling will be inputted. Next economic information is requested including natural gas costs, electricity cost, interest rate and building lifetime (the later for the time value of money calculation required). Finally, the insulation, furnace, and air conditioning choices are inputted. Calculations are then performed and results are displayed to the screen. Results are also written in appending form to the file TEEHOUS.TXT which will be created in the default directory. The user is then prompted for another program run where the furnace or air conditioner choices may be changed or the roof and/or wall configuration may be changed. If the user wishes to change both the roof and wall configuration, he/she needs to respond no to the questions concerning changing the roof configuration or changing the wall configuration.

Heat transfer calculations are performed assuming that only the insulation contributes to the thermal resistance of the walls or roof. Also sunlight is assumed to only fall on the roof. If the annual year analysis is chosen, the normal high temperature is used for the day time calculations and the normal low temperature used for the night time calculations. The solar flux is calculated as the average solar insolation between 9:00 am and 4:00 pm local time and is used only for the day time calculations. The cost presented in the output is the present value cost of the system utilizing the appropriate time value of money factor to convert the annual fuel and electricity costs into present value costs.