Abstract

This project was undertaken in a view of the great importance that renewable sources of energy are acquiring in the modern world. With a threat of the greenhouse warming and extensive air pollution caused by combustion of fossil fuels, global economies search for a relief from the dominion of fossil fuels in the energy market. In this situation, the renewable energy sources come into a spot-light as a long awaited panacea. Geothermal energy is one of the renewables that has been successfully serving people's energy needs for centuries. This resource is distinguished from others by having a minimal adverse impact on the nature, numerous economic benefits, and a variety of applications. Because its ultimate origin is the internal heat of the Earth, the exploitation and utilization of geothermal energy can be initiated almost in any place of the world, though its applications will depend on the temperature content and geological nature of a reservoir. The employment of geothermal heat ranges from generating electricity to space heating and cooling via a geothermal heat pump. The energy content of a geothermal reservoir determines the type of application that it can support. Such an assessment of geothermal resources of a particular case study is a scope of this project. In this report I will provide a scientific background for and an overview of the current development of geothermal resources and technologies in the world and the United States. Using the example of a geothermal heat pump installed at the Center for Science and Education in the Black Rock Forest, NY, I will determine the magnitude of the geothermal gradient and the flow of energy into geothermal wells at this location. To do so I will reconstruct the geothermal gradient from a borehole log obtained during the

drilling of a monitor well at the indicated site. Then I calculate the amount of energy per unit time available for the carrier fluid to absorb inside of the geothermal wells. I also discuss the results of my research, its drawbacks, and uncertainties and suggest the guidelines for the future research projects in this subject.

After I reconstructed the depth profile of the borehole from the recorded pressure, I observed that the temperature profile showed a non-linear increase with depth. Therefore, a specially designed computer program was written to analyze the collected temperature data, and it delivered the temperature gradient value of 17.472 °C/km. This translates into a heat flow equal to 61.32 mW/m² and an energy flow of 26.86 W across the total area of 6 geothermal wells. One of the important implications of these results is that they do not reveal how long this site will be able to support this rate of energy flow. The observed heat flow results from the heat accumulated in granite rocks for billion of years, and though it will fuel the installed geothermal heat pump for many years, the mining of this resource cannot last forever.

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Introduction

Geothermal heat is one of the environmentally clean energy resources, which is available for exploitation worldwide. If harnessed, it could heat our homes and homes and offices and provide electricity to run machines for as long as we live and for many generations ahead. Did you know that the amount of geothermal energy stored in the Earth's crust is 50,000 times larger than the energy of all fossil fuels combined? (www.eren.doe.gov/geothermal/geopowerdepths.html) Men skim only a tiny fraction of this energy pool. Geothermal energy follows hydroelectricity and renewable biomass energy in the total amount of energy produced. (www.oit.edu/~geoheat/whatgeo.html) The multifaceted nature of this resource allows us to use it in many different ways: to produce electricity, to supply heat for district heating, and for industrial and agricultural processes. Geothermal energy already accounts for 44 billion kW of electricity production worldwide, 35% of which falls in the developing countries. Moreover, this capacity is growing at 9% per year. (Dickson and Fanelli, p.4) Power plants at Larderello, Italy and the Geysers, USA (500W) represent the most notable examples of the geothermal electricity production. In the United States alone, geothermal energy generates 2700 MW of power, which is equivalent to three conventional coal-fired or nuclear power plants. (www.eren.doe.gov/geothermal/geopowerdepths.html)

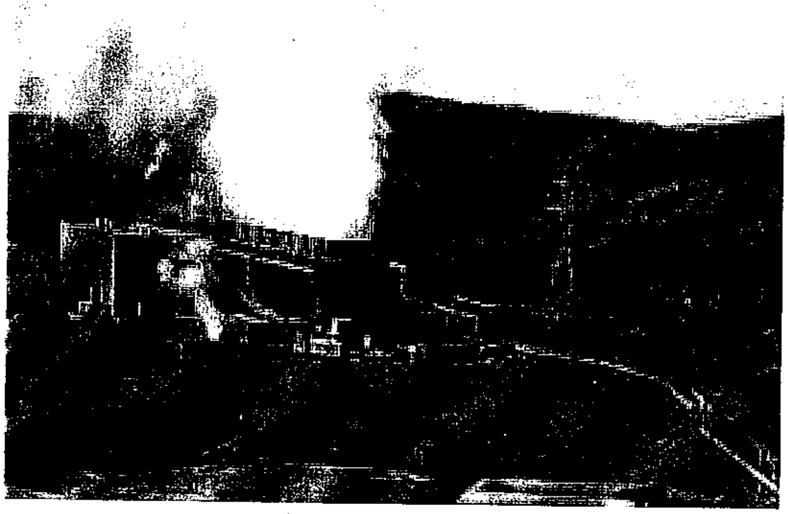
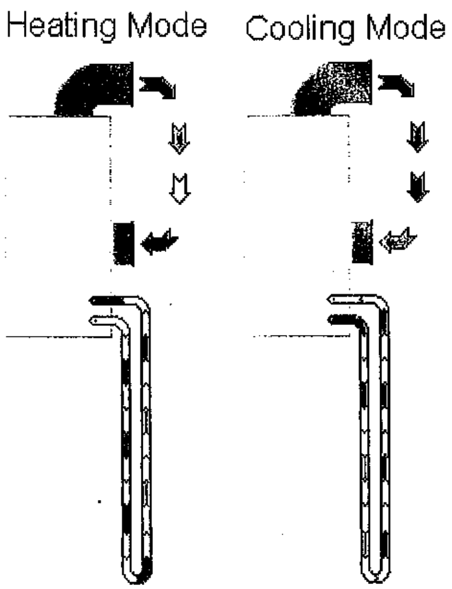


Figure 1: Geothermal Power Plant at the Geysers, California.

Non-electric applications of geothermal energy include space and greenhouse heating, fish farming, food processing, and other industrial processes. All of them are collectively called direct-use applications, because as their heat source they directly utilize ground water in the temperature range of 30-100 °C. In 1990 the direct-use installed capacity worldwide totaled to 11,000 MW. Since then it has been rapidly growing because this resource is available at many more locations than high temperature geothermal reservoirs. In the United States, all direct-use applications of geothermal energy save around half a million barrels of oil using the installed capacity of 500 MW. (Dickson and Fanelli, p.5-6) This number excludes geothermal heat pumps – the most universal and ingenious devices for exploitation of the Earth's heat! A heat pump serves for space heating and cooling purposes and hot water supply. It uses the ground as a heat reservoir in winter and a cooling sink in summer.



The attraction of the geothermal heat pumps lies in that they can perform well on even a small thermal gradient, which makes them functional everywhere. In addition, they can save up to 30-60% on energy costs associated with district heating and cooling. They are environmentally safe, effective, and noiseless systems for home and office heating. (www.geoexchange.org/public/how_it_works.html)

Figure 2: Operation of a geothermal heat pump in heating and cooling modes.

Geothermal energy brings many environmental and economic benefits to its consumers. When compared to fossil fuel combustion or nuclear fission, geothermal electricity generation releases much less harmful pollutants into the environment. Often geothermal fluids contain gasses such as CO_2, H_2S, and CH_4 and various dissolved substances that present a danger to the environment. Nevertheless, most geothermal plants operate on a closed-loop cycle, which is designed to re-inject the waste products of geothermal production back into the reservoir. Another technological innovation, a downhole heat exchanger, allows one to extract heat from a geothermal fluid without bringing it to the surface, so that all the chemical pollutants remain underground. People who live next to geothermal plants enjoy clean air because geothermal plants can comply with the strictest air emission standards.

Another possible environmental effect is thermal pollution, which results from a discharge of warm waste waters from a utilization plant into a local river or lake. This can adversely affect the local ecosystem because temperature variations of water can cause the disappearance of many temperature sensitive organisms and plants. This in turn can disrupt the food chain of other members of the ecological community and can cause it to deteriorate. This can be avoided if the waste waters are allowed to cool before being discharged into the river or lake.

The land subsidence and increased seismic activity are also thought to be the consequences of the development of geothermal reservoirs. Incidents of earthquakes and tremors observed around some geothermal power plants prove that man's engineering activities, associated with the development and exploitation of high-temperature geothermal reservoirs, can induce additional seismicity in seismically active or previously aseismic zones. Induced seismicity results from a modification of various stress forces acting on a point of the lithology: a man's tempering on the earth surface such as mining, impounding of water, and underground explosions can magnify those forces up to the point when the subjected rock formations are unable to withhold them. Then an earthquake or tremor event occurs. A notable example of induced seismicity due to geothermal development is a power plant at The Geysers, California. Most of the seismicity in that area is being induced and is linked to a decline in reservoir pressure and temperature. Re-injection of spent geothermal fluid back into the aquifer was expected to combat the drop in steam production. Nevertheless, recent models show that, in addition to changes in volumetric and shear stresses associated with steam production, re-injection of cold water evokes thermo-elastic forces that can further augment seismicity. While induced seismicity can bring negative social and economical implications for the development of big-scale geothermal operations, the direct use applications usually do not entail such disastrous effects on the seismic stability of an area. (www.esci.keele.ac.uk/courses/geol317/induced.html)

Even though geothermal energy does not require a massive infrastructure of facilities and equipment, its exploration, development, and production have a disturbing effect on the surrounding wildlife and landscape. Drilling of wells, installation of pipelines, and construction of a plant entails the development of access roads and drilling pads. All these operations interfere with the local plant and wildlife and affect the local landuse practices. Nevertheless, when compared to fossil fuel and nuclear plants, the severity and extent of land disturbance associated with geothermal plants is less and is primarily a function of their electric capacity, number and density of the wells, and the topography of the sites. Moreover, The Geothermal Steam Act was passed in 1970 to ensure that geothermal development does not trespass environmentally sensitive areas. Another adverse environmental effect related to construction and operation of a geothermal power plant is the noise that can scare animals away from the power plant site and is aesthetically unpleasant for people. The direct-use applications are usually quiet and self-contained. (Collie, p.35-70)

In addition, the development of national geothermal resources brings social and economic benefits. It strengthens the national security of the United States because it relieves our dependence on foreign fuel supplies. Today half of the nation's trade deficit comes from the imports of oil, which translates into a permanent loss of wealth to the country. Further development of the domestic energy supplies would protect us from the uncertainties about the future availability of fossil fuels, boost our economy and create additional jobs for people. (www.eren.doe.gov/geothermal/geopowerdepths.html)

So what is the source of geothermal energy? It comes from the heat released during the decay of long-lived radioactive isotopes of uranium, thorium, and potassium in the crust and mantle of the Earth. They have supplied the Earth's interior with heat since the creation of the Earth and will continue to do so for many billions of years. Strictly speaking, geothermal energy is not a renewable resource, but on this time scale it can be considered inexhaustible. "It seems probable that the total heat content of the Earth… is of the order of 12.6×10^{24} MJ and that of the crust is of the order of 5.4×10^{21} MJ. The thermal energy of the Earth is therefore immense, but only a tiny fraction can be utilized by man." (Dickson and Fanelli, p.3)

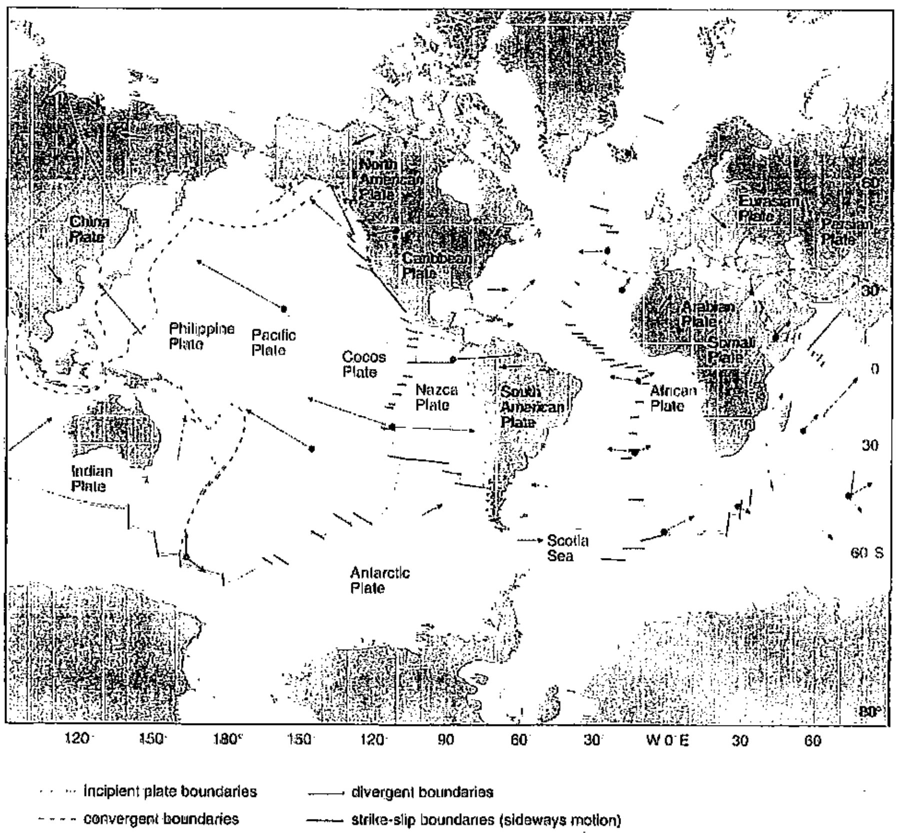


Figure 3: Map of the Earth's lithospheric plates where large dots indicate major high-enthalpy geothermal energy producing areas.

The most spectacular manifestations of geothermal energy are volcanic eruptions, geysers, and hot springs. Most of them are encountered in the areas of high geothermal activity located on the edges of tectonic plates (Figure 3). Where two plates meet, the crust is forced to converge downward, creating trenches and arcs. In the arcs, the upwelling of molten magma brings heat to the surface. Eruption of magma also occurs at the hot spots. If surface water penetrates into the rock fissures caused by tectonic forces, it is heated to very high temperatures and bursts out as a geyser or a hot spring. Such sites possess a huge potential for exploitation of geothermal energy, but there are only a dozen of them in the world. The west coast of North America is one of them.

Above 150 °C, there are four high-temperature geothermal reservoirs recognized: magma, hot-dry rock, water-dominated, and vapor-dominated. Magma is a molten rock material that comes from the Earth's mantle. In some places it comes close enough to the surface to be reached by drilling. Its temperatures, from 700 °C to 1600 °C, promise an enormous energetic potential, but no technology has been developed yet to harness it. Nevertheless, where magma reaches close to the crust, it heats up the overlying rocks and greatly enhances the thermal gradient. In such locations, the rocks could be fractured, and geothermal heat could be mined. Water would be injected into the wells and used as a heat transfer medium. This hot-dry rock technology could extend the areas where the extraction of geothermal heat is feasible, but it still has to demonstrate itself.

Where deep buried aquifers exist, water-dominated or vapor-dominated geothermal systems may form.

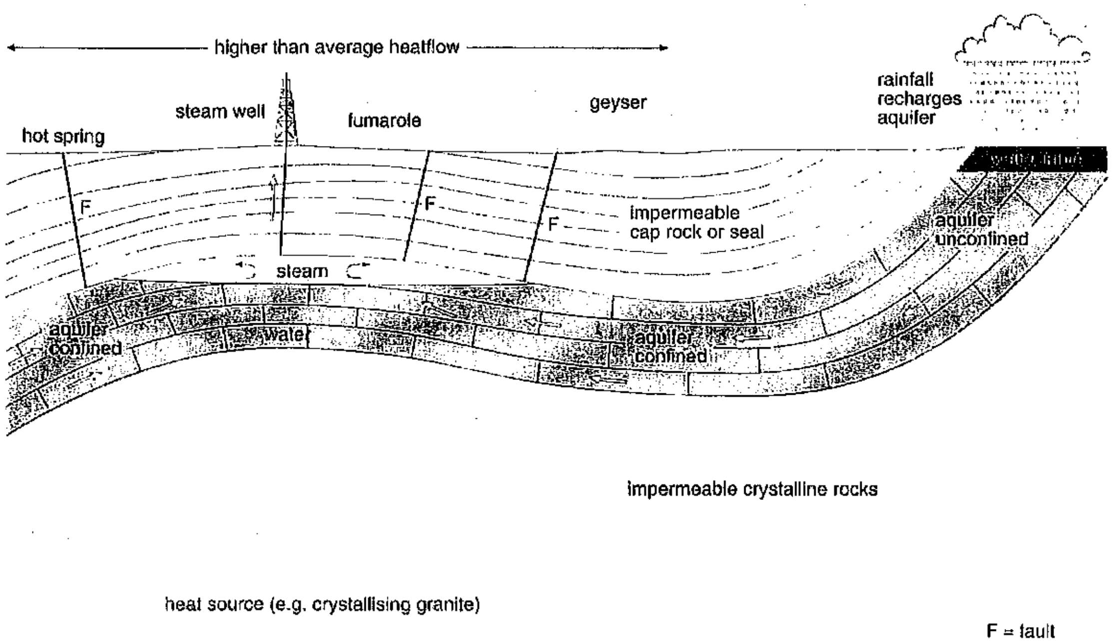


Figure 4: Simplified schematic cross-section to show the essential characteristics of a geothermal site.

Meteoric water percolates through permeable rocks and accumulates in an aquifer. At the bottom the ground water lies in contact with high temperature rocks, which induce a thermal convection of the water column. Eventually an equilibrium is reached with temperatures ranging from atmospheric up to 350 °C. High hydrostatic pressure prevents superheated water from boiling. The water table could be reached by drilling and the hot water could be pumped to the surface. Depending on the temperature, this water could be used for electricity generation or directly used for district heating. Usually, after the heat content of the water is extracted, it is injected back to recharge the reservoir. Far less common are natural steam reservoirs, where hydrostatic pressure in the aquifer is not high enough to prevent water from boiling. There steam forms, leaving the concentrated brine behind. If mined, this steam could drive gas turbines and generate electricity. (GRTUS, p.1-4)

But geothermal energy is not limited only to the areas of high geothermal activity. The thermal engine in the Earth's mantle radiates heat in all directions, and it slowly diffuses to the surface. Even though the temperature at the center of the Earth is 4,000 °C, the average temperature at the surface is only 15 °C. This occurs because solid rocks that compose the crust have a low thermal conductivity and capture the heat. Thus, there is a vertical temperature gradient, which increases toward the earth's center by 30 °C/km. The average value of worldwide heat flow is 60 mW/m^2. Even though the temperature of the upper few meters of the crust is influenced by seasons, heat flow maintains constant temperature within deeper layers all year around. (Dickson and Fanelli, p.3,8)

Temperature does increase with increasing depth, but usually very slowly. Geothermal heat pump technology takes advantage exactly of this thermal property of the Earth.

A geothermal heat pump (GHP) is an alternative solution to space heating and cooling needs. The GHP consists of three parts:

1. An earth connection, which transfers heat from the ground to the fluid.
2. A geothermal heat pump that moves the fluid between the wells and a building.
3. An earth connection distribution system that circulates air around the building.

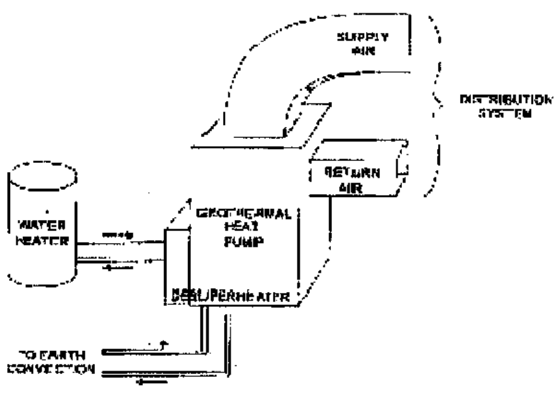


Figure 5: Drawing of a typical geothermal heat pump system.

The earth connection is a series of pipes called a loop. There are different types of loops available: horizontal and vertical ground closed loops or pond-closed loops. The choice of the loop configuration depends on building structure and needs. The bigger the building or the more extreme the climate is, the larger the loop system should be. Pipes in the loop are usually made of a very durable plastic with water and/or environmentally safe antifreeze running in. One of the assets of the GHP is that the loop system is closed so that a possibility of leakage of the earth connection fluid into the environment is minimized almost to zero. While flowing through the pipes, the fluid either absorbs heat from the ground or releases it, depending on the mode of operation.

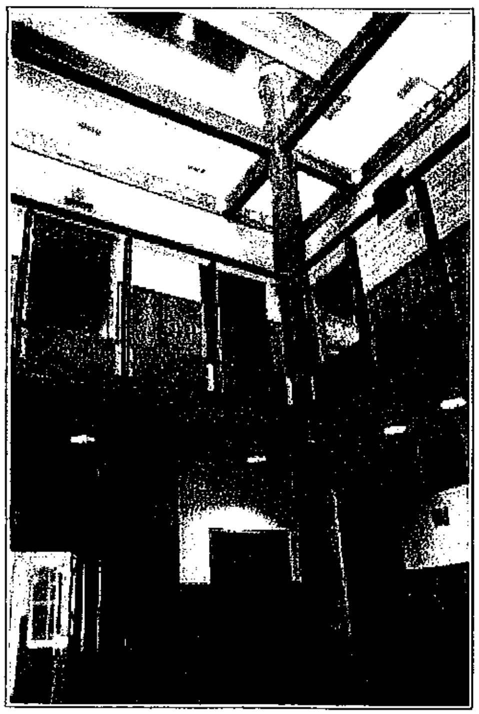
The heat pump serves to extract heat from the carrier fluid via a vapor compression cycle. A cold fluid refrigerant passes through a heat exchanger where it absorbs heat from the earth connection fluid. Because the refrigerant has a low boiling point, this heat is enough to turn it into a gas. From there it passes into a compression chamber where it is pressurized so that the temperature of the gas reaches 180 F. Finally, the gas enters the other refrigerant-to-air heat exchanger where heat is released into a distribution system. After emptying its heat content, the gas cools off and returns into a liquid form, and the cycle starts again. In a cooling mode, the cycle is reversed. Warm or cool air is then distributed around the building via air ducts. (**www.geoexchange.org**)

Even though the internal mechanism of the GHP is complex, it is very easy to operate and maintain. Because the loop system is completely submerged into the ground and the heat exchangers are located indoors, the heat pump can withstand harsh weather conditions without a breakdown. Usually GHP manufacturers provide 25-50 years warranty for the piping and over 20 years for the heat pipe itself. For the period of its lifetime, the GHP reduces energy consumption by 25-75% because 70% of the energy used by the pump comes from the ground, and the rest is supplied by electricity. This translates into a 30-60% savings in heating and cooling bills for GHP owners. It has been estimated that 100,000 GHP units save 24 trillion BTU in electrical energy and around $500 million in district heating costs over the 20-year period. Besides economic benefits, GHP industry helps to reduce air pollution that results from burning fossil fuels for district heating and cooling. Over 40% of all the US CO_2 emissions come from the district heating sector, but a rapid expansion of the GHP market could significantly cut our carbon emissions. Because no fuel combustion is involved, the GHP itself produces zero emissions. There are small amount of emissions associated with manufacturing of the GHP. However, the only emissions occur at a power plant that supplies electricity. If 400,000 GHP units were installed every year, it would save 1 million metric tons of greenhouse gases from being released into the environment annually. To sum up all its advantages, GHP technology is environmentally clean and the most energy efficient technology for heating and cooling of residential and commercial buildings available today. (**www.eren.doe.gov/geothermal/ghp_enviro.html**)

Methods

As explained earlier, a geothermal heat pump takes advantage of the ground being at a nearly constant temperature all year around. It means that even locations with a small geothermal gradient can support basic GHP operation. To decide whether the GHP can effectively substitute for conventional heating and cooling systems of a building, the geothermal and geological properties of a site must be considered. One of the geological factors that affects applications, capacity, and lifetime of the system is the magnitude of a geothermal gradient and, consequently, the heat flow at that specific location. The geothermal gradient determines the amount of heat stored in rocks. Knowing the geothermal gradient helps to estimate how much of the geothermal resource is available for the heat pump to tap. This project intends to look at the case study of the GHP installation in the Center for Science and Education at Black Rock Forest in Cornwall, NY. With the aid of a borehole dataset, I will attempt to assess how much heat could be extracted from the ground by the GHP.

Black Rock Forest is a nature preserve dedicated to conservation of the pristine ecosystem of the Hudson Highlands for public and private education and scientific research. Extending over an area of 3750 acres, it lies on the west bank of the Hudson River 50 miles north of New York City. The Black Rock Forest hides in the mountainous central region of the Hudson Highlands. The geology of the forest is characterized by ancient deposits of Precambrian granites and gneisses, which are more than one billion years old. Over that period they have been severely folded and faulted.



In the middle of the forest, on top of a high hill stands the Black Rock Forest Center for Science and Education – "a building that conveys an environmental conscience." While serving the needs of scientists and educators, it also complies with strict standards of environmental ethics so as to minimize human disturbance of this nature preserve.

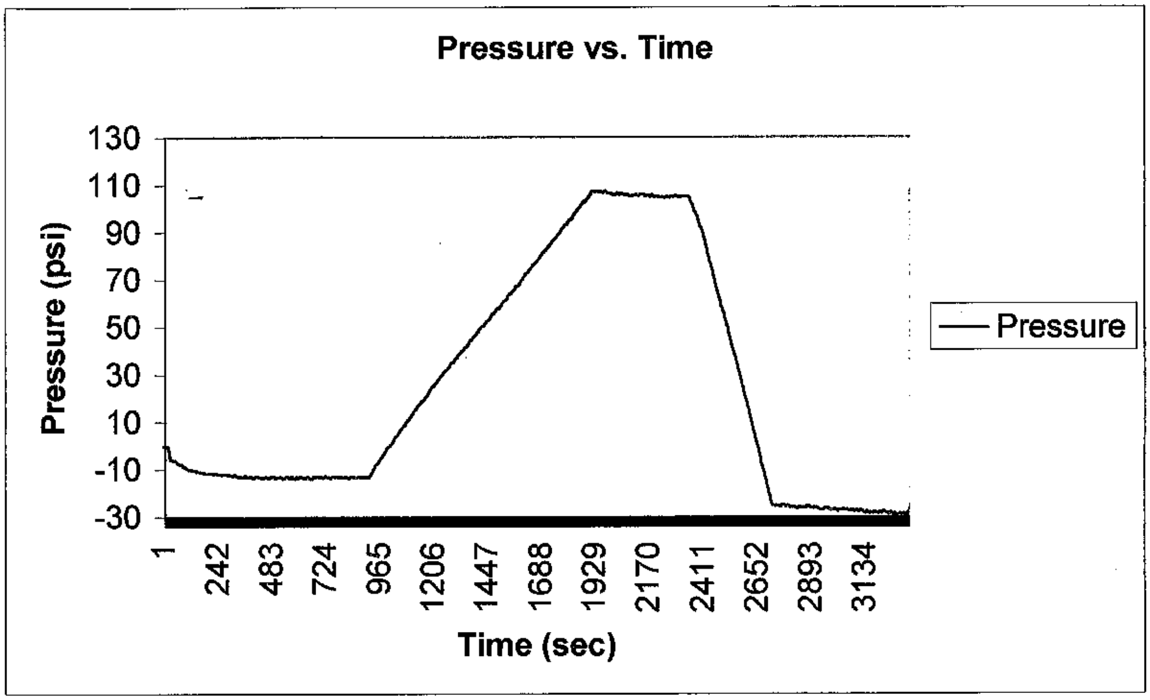
Figure 6: Inside of the Center for Science and Education at the Black Rock Forest.

With the help of modern technology and thoughtful planning, the center acts as an operative model of the harmonious existence of men and nature. The center's architecture is designed to utilize most of the incident solar radiation for space lighting. Self-composting toilets installed at the center allow for environmentally clean disposal of sewage wastes. Finally, heating and cooling of the building is achieved by a geothermal heat pump that does not release any pollutants into the environment. (www.blackrockforest.org)

The geothermal pump was installed at the center in the fall of 1999. It is a typical middle size heating/cooling system for a commercial building manufactured by Water Furnace International Inc. It includes 6 geothermal wells, a heat exchange unit, and a ventilation system for the heat distribution. Special sensors monitor the humidity and temperature of the ambient air inside the building. The geothermal wells are 152.4 meters deep and located on the lawn behind the center. The choice for a heat carrier fluid fell on alcohol, because its freezing point is lower than that one of water, so that the system can function well even in the coldest months of winter.

In July 1999, David Goldberg, Alex Meltser and their team from the Lamont-Doherty Observatory took measurements of temperature and pressure inside of a monitoring well just 20 meters away from the future geothermal wells. Their goal was to explore the geology and hydrology of the site. Measurements of pressure (psi) and temperature (°C) were taken every second of during lowering of the instrument into the well. The lowering rate was 5.3 m/min. As a result, the geologists obtained a log of pressure and temperature vs. time within the upper 140 meters of the ground. I make the assumption that the geothermal gradient of the old well is the same as of the geothermal boreholes since they are located only 20 meters apart and share the same lithology. Therefore, I can use the well data to infer the temperature gradient of the geothermal boreholes.

A geothermal gradient is the change of temperature with depth. If I plot the recorded temperature vs. depth, the slope of the graph gives me the geothermal gradient of the test well. Because the instruments did not record the depth values directly, I have to deduce the depth profile from the pressure data. The following graph shows the recorded pressure measurements.



Graph 1: Pressure vs. Time.

On the 922nd second of lowering, the pressure begins to increase rapidly. This indicates that the logging tool hits the ground water table, which is located 52.2 meters beneath the surface of the earth. Pressure is hydrostatically related to the depth of the water column: it starts mounting as the logger penetrates deeper into the water column. In fresh water, pressure changes at a rate of 1.47 psi/m. Pressure reaches its maximum value (107 psi) at the bottom of the aquifer and stays constant while the instrument remains on the bottom for approximately 7 minutes. After that the logging tool returns on the surface. The logger leaves the water on the 2726th second of drilling.

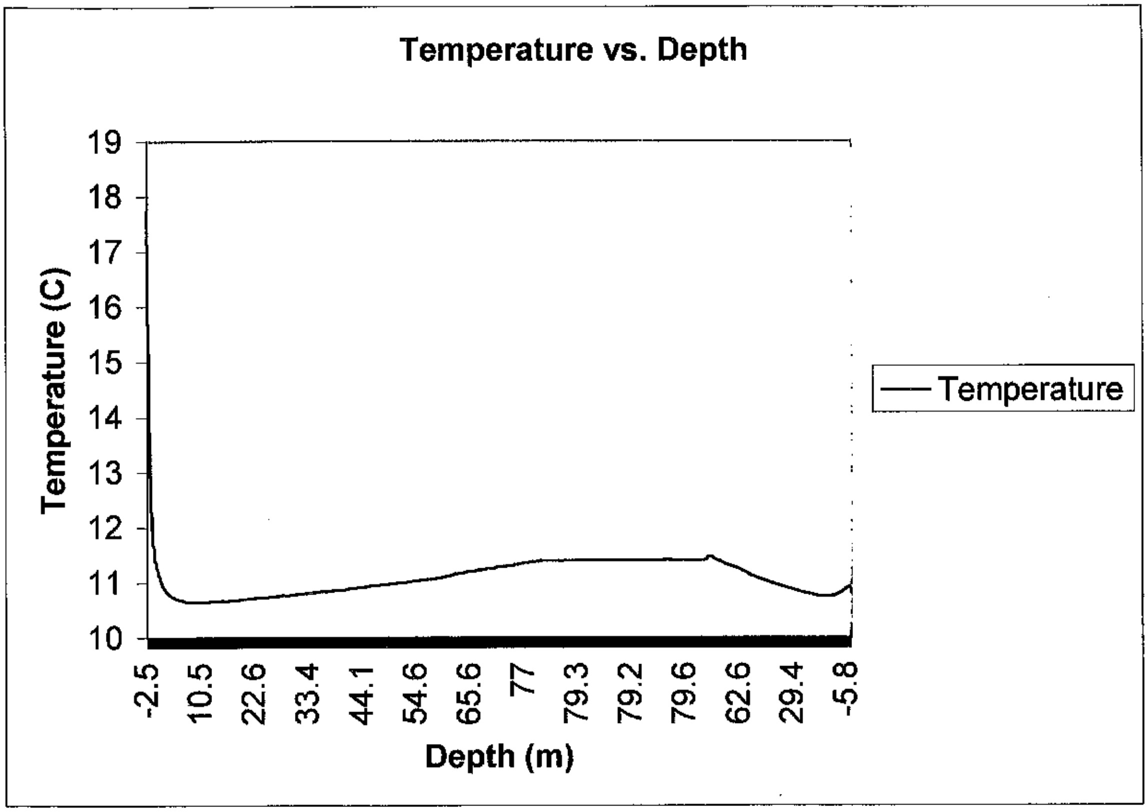
The graph clearly relates that for the purposes of reconstruction the depth profile from pressure data, I should use the data recorded while the log was descending to the bottom of the aquifer. But before plugging in a conversion factor, the recorded pressure should be corrected for the pressure transducer offset, which at the beginning of drilling amounts to 13 psi and grows linearly with time until it reaches 28 psi at the end of drilling. The formula that I used to correct the transducer offset factor is as follows:

Corrected Pressure = Recorded Pressure + 13.2222 +

(row#) x (24.4444 – (initial transducer offset + (28-13)/3331))/(2726 – 922)

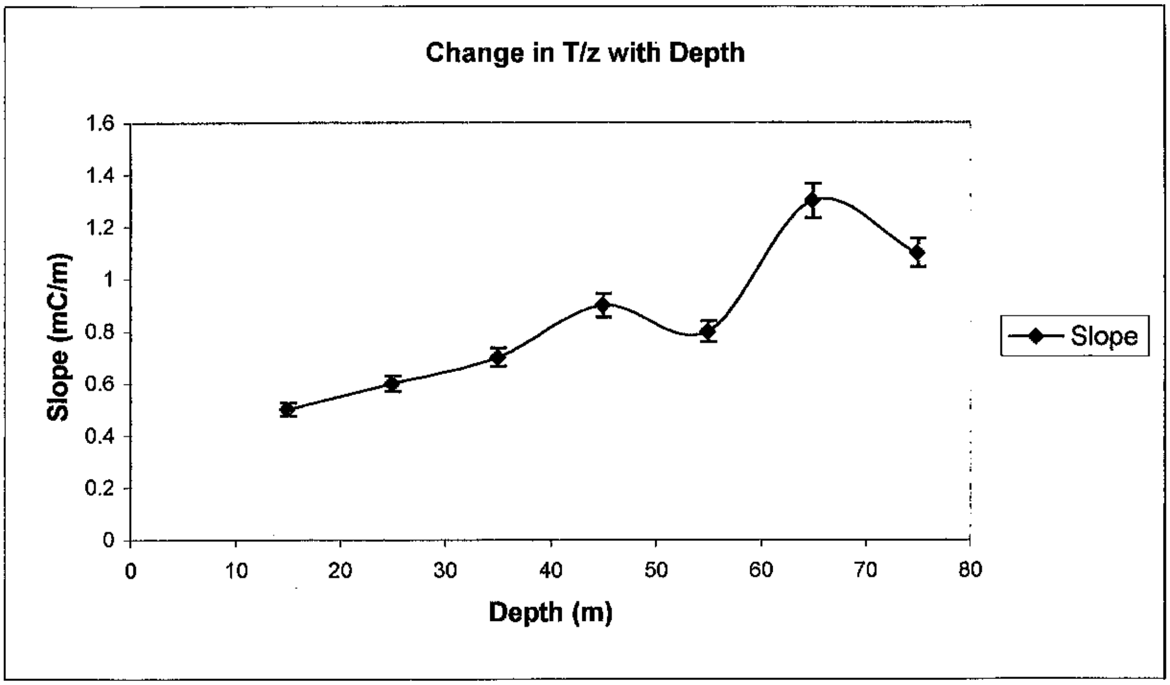
After I obtained the correct pressure values, I divided them by the conversion factor of 1.47 psi/m, which generated the corresponding depth data.

Next, I plot the temperature vs. depth to predict temperature profile of the borehole.



Graph 2: Temperature vs. Depth.

The plot suggests that the slope of the temperature graph, which corresponds to the geothermal gradient of the borehole, is not linear as expected but curved. The temperature of the surface layer of water drops precipitously from 16.5 °C to 10.6 °C in a span of the first 10 meters. Further down the hole, the water temperature gradually reaches 11.4 °C at the bottom of the aquifer. But even this gradual rise in temperature is not uniform everywhere. To portray it better, I make a series of plots of temperature vs. depth for every ten-meter segment of the borehole and determine the slope and its error value for each of them. Then I plot the slopes vs. depth to see if they increase linearly.



Graph 3: Change in Geothermal Gradient with Depth (every data point is given with its error value).

As the graph shows, the slope increases irregularly, which means that geothermal heat is not evenly distributed over the water column. This pattern of temperature distribution suggests that water is flowing down the hole and transfers heat from the upper warm layer to the bottom, and by doing so distorts the natural geothermal profile. "The drilling process itself introduces temporary disturbances, both by the friction of drilling and by heat exchange of the rock wall with drilling fluid." (Jessop, p.22) It is well known that movement of the ground water disturbs the Earth heat flux. Therefore, the geothermal gradient cannot be calculated from the temperature vs. depth plot, but should employ a special equation that accounts for this phenomenon (Bredehoeft and Papadopulos, 1965):

$$\partial^2T/\partial x^2 + \partial^2T/\partial y^2 + \partial^2T/\partial z^2 - c_o\rho_o/k\,[\partial(v_xT)/\partial x + \partial(v_xT)/\partial y + \partial(v_zT)/\partial z] = c\rho\partial T/k\partial t$$

where

T - temperature at any point in time ***t***

t – time since flow started

c_o - specific heat of fluid

ρ_o - density of fluid

c – specific heat of solid-fluid complex

ρ – density of solid-fluid complex

k - thermal conductivity of solid-fluid complex

v_x, v_y, v_z – components of fluid velocity in **x**, **y**, and **z** direction

x, y, z – Cartesian coordinates

Because the flow of the heat and fluid is one-dimensional (vertical) and steady in my problem, the differential equation reduces to:

$$(\partial^2T_z/\partial z^2) - (c_o\rho_o v_z/k)\,(\partial T_z/\partial z) = 0$$

To solve this equation, I have to apply the boundary conditions:

$$T_z = T_0 \quad \text{at} \quad z = 0$$

$$T_z = T_L \quad \text{at} \quad z = L$$

where

T_z – temperature measurement at any depth **z**

T_0 – uppermost temperature measurement

T_L – lowermost temperature measurement

L – length of vertical section over which temperature measurements extend (vertical distance between **T_0** and **T_L**)

Using this equation, Pr. Abbott designed a computer program that analyzed the data and produced a real geothermal gradient of the borehole.

Results

The computer program reveals that the geothermal gradient of the borehole is equal to 0.017472 °C /m or 17.472 °C/km. This means that with every kilometer of descent into the Earth, the temperature of the crust rises by ~17.5 °C. Now that the thermal gradient of the borehole is known, I can calculate the heat floe of the geothermal wells:

$$\mathbf{Q = K\, \Delta T/\Delta z}$$

where

Q – heat flow

K – thermal conductivity

ΔT/Δz – geothermal gradient

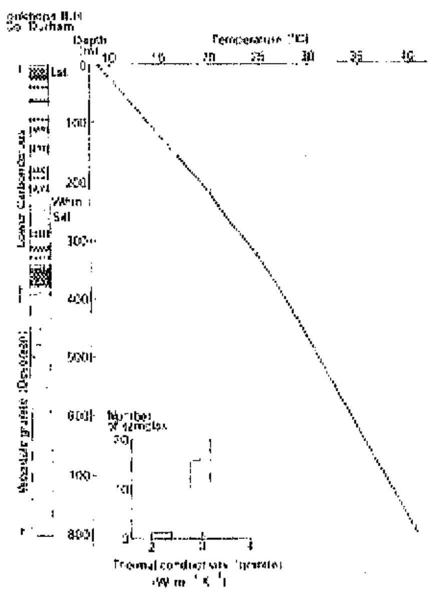
The lithology has some variations but is mostly dominated by granite and gneiss. The thermal conductivity of granite at temperatures between 0-50 °C is 3.02 Kcal/m^2 or 3.5099 J/s m °C. Using the above formula of the heat flow, I obtain the value of 61.32 mW/m^2. The magnitude of the mean continental heat flow in the Eastern United States is thought to be 57 mW/m^2. (Bott, p.292) The heat flow value is necessary in order to estimate the geothermal potential of the site. The productive area of the site includes the area in direct contact with the pipes inside the wells. To simplify the calculations, I consider a well as a cylinder with a height of 152.4 meters and a radius of 0.0762 meters. The surface area of a cylinder is defined as:

$$\mathbf{S = 2\pi Rh}$$

Therefore, the surface area of one geothermal well is equal to 73 m^2. Since the site employs 6 wells, the total productive area comes to 438 m^2.

The product of the heat flow and the productive area gives a solution to the main question of the project: How much energy per unit time is available for the pump to withdraw? The answer is 26.86 W or 26.86 J/s.

Discussion



After the pressure data was converted into the equivalent depth values, it became possible to plot the recorded temperature vs. depth. One of the surprising outcomes of the graph is that the temperature-depth relationship does not behave linearly as expected. Except for transient changes in the thermal gradient in upper 10-20 meters of the earth attributed to the climatic effects of the outside weather, temperature in the solid lithosphere of a uniform composition should increase linearly with depth.

Figure 7: Temperature-depth profile obtained at the Rookhope borehole, Stanhope, north England.

The heat from the deep interior is transferred to the overlying rocks of the crust by conduction, therefore the rocks that are closer to the surface show smaller temperatures than deeper rocks. For this reason the temperature is increasing almost linearly with depth. (Bott, p.267) The other component of the continental heat flow is the radioactive heat from the decay of the radioactive isotopes concentrated in crustal rocks. It accounts for 40-50% of the total heat flow and is the source of the local variability of the geothermal gradient. (Bott, p.280)

Coming back to my case study, the first explanation for the observed deviations from the linear increase of temperature with depth was the disturbance of the outside climate. But after I plotted temperature for every 10 meter segment of the borehole, the graph showed that the temperature did not behave linearly even at the depths of 60, 70, or 80 meters where perturbations due to the outside weather changes should be absent. Instead, the temperature at the bottom of the monitor well grew and fell irregularly, which suggests that some other phenomenon caused the disturbance of the temperature profile.

Bredehoeft and Papadopulos say that "geophysicists have long recognized that moving ground water can affect the flux of heat within the Earth. Van Orstrand [1934, p.996] indicated that the transfer of heat by migrating water could cause variations of temperature gradients within the Earth." (Bredehoeft and Papadopulos) In this case, the water that flows down the hole is the drilling fluid. Because water has a high heat capacity, it effectively absorbs geothermal heat from rocks while in contact with the walls of the borehole. Consequently, it transfers the heat from the surface, flowing down the hole and in doing so, it obscures the real thermal gradient. As soon as this problem was recognized, it became apparent that the recorded temperature profile should be corrected for the heat transferred by the drilling fluid. That was done by a specially designed computer program, which produced a temperature gradient equal to 17.472 °C/km. This thermal gradient appears too small when compared to 30 °C/km, which is accepted as an average geothermal gradient. (GRTUS, p.3) The calculated gradient gives a heat flow value of 61.32 mW/m^2, which is very close to the generally considered heat flow of 60.6 mW/m^2 for the North American continent. (Jessop, p.155) Therefore, I assume that the calculations of the geothermal gradient and heat flow are correct and accurate.

The resulting flow of energy across the geothermal wells is 26.86 W. One way to check if this were a reasonable value would be to calculate the amount of heat gained while the carrier fluid circulates in the underground pipes. The difference between the inlet and outlet temperatures would tell how much heat the fluid gained for the time spent underground. Unfortunately, right now it is impossible to make such a check because the data on the temperature of the carrier fluid is not available. But as soon as the administration of the Center installs the necessary sensors, such a proof check will become possible.

Conclusion

This research project has produced some valuable results and marked the outlines for the future research projects in the subject of geothermal energy exploitation on the example of the geothermal heat pump at the Center for Science and Education at the Black Rock Forest. One apparent conclusion that stands out is that the flow of energy across the wells is very small, only 26.86 W. What remains unclear is how long this energy flow can support the operation of the heat pump. Clearly the energy content of this geothermal reservoir is poor, and the pump withdraws the stored energy much faster that the reservoir is recharged. This suggests that the heat pump is going to have a limited lifetime depending on the availability of the resource. Boyle says that " particularly in low-enthalpy applications, heat is being removed faster that it is replaced and the concept of 'heat mining' is appropriate. Although geothermal resources are non-renewable on the scale of human lifetimes,... they are included [into this book] because they share many features with the true 'renewable' resources.... At one time, it was thought that many high-enthalpy resources were indeed renewable, in the sense that they could be exploited indefinitely, but the experience of declining temperatures in producing steam fields and simple calculations of heat supply and demand show that heat is being mined on a non-sustainable basis." (Boyle, p.357)

Nevertheless, some other phenomenon contributes to the heat content of the reservoir in Black Rock Forest: Since the pump also works in a cooling mode during the hot months of the year, it dumps the excess heat from the building into the ground and by doing so it recharges the reservoir. Although it is unknown whether this dumping of heat in summer can balance the withdrawal of the heat in winter, this additional heat source from the outside offsets the depletion of the geothermal heat reservoir. This topic would require a separate research project that could reveal very interesting results.

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