LOW TEMPERATURE GEOTHERMAL WASTE-HEAT-TO-POWER

An Undergraduate Research Scholars Thesis

by

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Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
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May 2015

Major: Petroleum Engineering

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ABSTRACT

Low Temperature Geothermal Waste-Heat-To-Power. (May 2015)

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Texas and other states currently have a large demand for emergency and supplemental power to remote regions with little infrastructure. In Texas, many of these remote areas have significant oil and gas operations currently in place which have a high demand for onsite power during the various operations and life of a well. Most wells in Texas also produce significant amounts water and most wells are abandoned due to high water cuts. Much of this produced water is hot enough, due to reservoir depth, to be considered as a Low Temperature Geothermal (LTG) resource, meaning capable of electricity generation. This hot fluid combination of hydrocarbons and water can be run through an Organic Rankine Power Cycle (ORC) for effective Waste-Heat-to-Power generation to mitigate the cost of producing and/or disposal of produced fluids. This provides values to otherwise worthless hot water which can potentially prolong productive well life.

NOMENCLATURE

BBL: Barrel

DPSGE: Deep Permeable Strata Geothermal Energy

ESP: Electric Submersible Pump

GPM: Gallons Per Minutes

HDR: Hot Dry Rock

kWh: Kilowatt Hour

LTG: Low Temperature Geothermal

mW: Mega Watt

NPV: Net Present Value

ORC: Organic Rankine Cycle

TVD: Total Vertical Depth

CHAPTER I

INTRODUCTION

Low Temperature Geothermal: A Renewable Resource

The interest in Low Temperature Geothermal power generation in Texas stems from the huge number of existing oil and gas wells. Most of these wells produce large amounts of water as well as hydrocarbons. Due to the shear massive number of wells in Texas there is also a huge number of wells that have been abandoned as oil and gas wells but still produced significant amounts of hot water suitable for electricity generation. For these wells the largest hurdle of any geothermal project has already been overcome, the drilling of the wellbore itself, affording these projects with very little overhead and expenditure cost.

The main advantage of geothermal power over other alternative energy sources is the availability of power. Unlike wind or solar power the energy inside the Earth is constant and independent of surface conditions. This provides a secure and reliable source of power year round that requires little infrastructure when combined with existing wells. Geothermal energy is also considerably cheaper than other alternative energies, for as little as $0.10 per kWh. While this cannot compete with oil and gas in a large scale power plant for grid power, geothermal energy can provide solutions for off-the-grid power to remote locations.

Introduction to Geothermal Resources

Currently there are 3 broad categories for geothermal energy use: ground source or geothermal heat pumps, direct use and electrical power generation. The viability of these applications is largely dependent on the classification of the thermal resource. Thermal resources are categorized as low (<194F), moderate (194-302F) and high (>302F) according to the Geo-Heat Center at the Oregon Institute of Technology. The scope of this project in only concerned with geothermal resources capable of electricity generation. Figure 1 illustrates the various applications of geothermal energy for a range of temperatures.

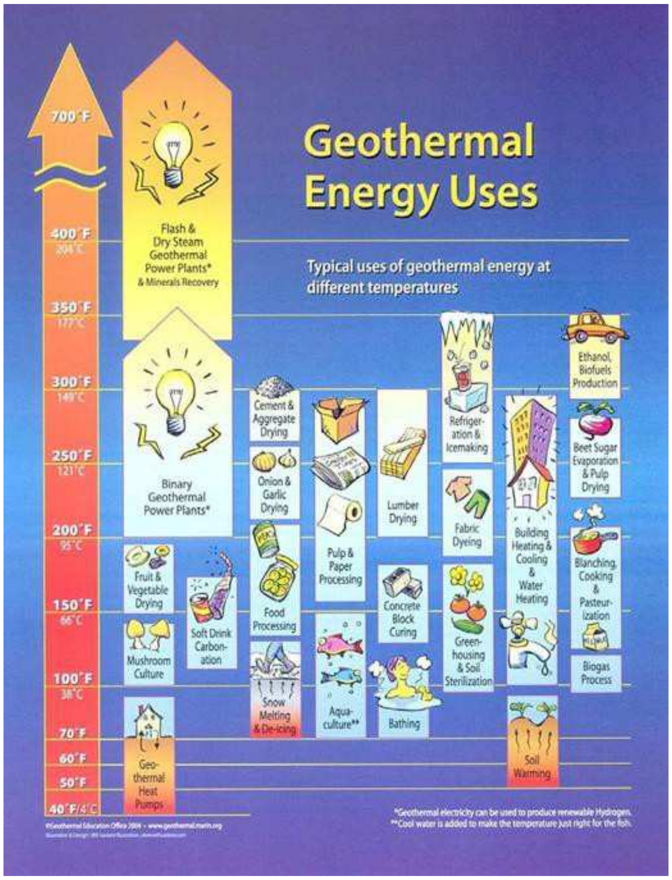


Figure 1: Geothermal Energy uses at various Temperature

In the past, electrical generation was only done via large power plants utilizing the hottest and highest production resources. These types of resources can generate upward of hundreds of mW and are concentrated to tectonic regions of Western United States. This project will focus on lower temperature resources capable of small scale electricity generation, with our key target to be repurposed oil and gas wells. The geothermal reservoirs capable of electrical power generation fall into 5 categories: hydrothermal, geopressured, hot dry rock, magma and 'Deep Permeable Strata Geothermal Energy' [4]. However in Texas, only geopressured, hot dry rock and 'Deep Permeable Strata Geothermal Energy' are present.

Hydrothermal resources are considered the conventional geothermal resource. The source of heat for these aquifers comes from hot igneous rock intrusions, generally near highly tectonic regions. This is seen in the already well developed geothermal power plants in the Western United States, especially California. However, these conventional hydrothermal resources are not present in Texas with to the exception of the Trans-Pecos region of far West Texas.

Geopressured resources are large deep aquifers consisting of hot brine and generally methane. These reservoirs have significantly higher pressure then typically expected due to the rapid burial of sediments and the water trapped within. Due to the high pressure these aquifers flow very readily and if the temperature requirements are met they can make very economic reservoirs. The Gulf Coast region is currently the largest known geopressured resource in the United States. A few of the reservoirs in the Gulf Coast region are: the Lower Frio, the Lower/Upper Claiborne, Vicksburg-Jackson, and the Lower/Upper Carrizo-Wilcox.

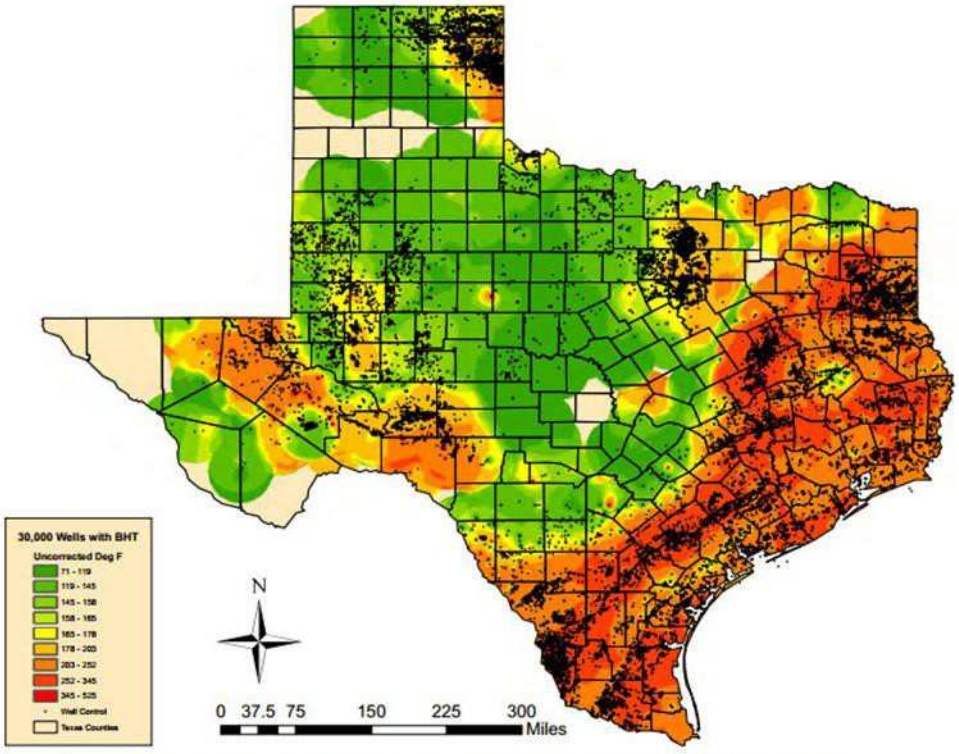
Hot Dry Rock (HDR) is the most abundant resource, however as the name suggests the issue with this resource is lack of water due to the absence of aquifers or fracture for water transportation. Enhanced Geothermal Systems have been developed for this type of resource that use induced fracture paths to inject and simultaneously produce water after it has traveled through the reservoir gaining heat. The abundance of HDR is massive compared to hydrothermal; however HDR has much greater startup costs due to the need for multiple wells and fractures. HDR is very prominent in Northeast Texas; however the economics of a HDR project are currently unfeasible due to large initial capital and expenditure costs.

In 2009 researchers in Iceland discovered a shallow magma chamber which was used to operate a geothermal power plant. Magma resources are everywhere in the world, however highly tectonic regions are currently the only place where the magma is shallow enough to utilize for electricity production.

Deep Permeable Strata Geothermal Energy is very similar to hydrothermal resources, with the exception that the heat is simply from the sufficient geothermal gradient, i.e. depth, rather than an intrusion of hot igneous rock. Thus these resources are considerably deeper. DPSGE is also generally associated with oil and gas production so geothermal fluid can be co-produced from existing wells eliminating the largest cost of geothermal projects, therefore much of Texas's resources fall into the DPSGE category.

Texas Geothermal Trend

Texas has several regions of geothermal interest: Trans Pecos, the Delaware-Val Verde Basin, Anadarko Basin, along and east of Interstate 35 corridor and the Gulf Coast Region. The region with the highest temperatures is along the southern I-35 corridor, meaning a large portion of the Southern Eagle Ford shale is within this region (Webb, Duval, McMullen, Live Oak, Bee, Goliad and DeWitt counties) as seen in Figure 1. The high number of gas wells in this region is potentially attractive for small scale geothermal operations due to the large amount of hot flow back and produced water (200-300°F) as well as the significant geopressure due to the average well depth in this region (~13,000-15,000 ft.).



This temperature gradient map, based on bottom hole temperatures from 30,000 existing wells in Texas, shows large regions with geothermal potential. The reported temperatures are typically lower than the true temperature of surrounding material because they are taken shortly after drilling fluid has stopped circulating in the borehole. Future maps will correct these temperatures upward accordingly. Data: IGOR Database and Texas Railroad Commission. Map: Colgan Smith, Adam Stater and Andrew Setchko.

Figure 2: Geothermal Trend of Texas from Bottom Hole Temperatures

The Gulf Coast region has already been considered many times for geothermal applications and in late 1970s the United States Department of Energy sponsored an extensive studying of the Gulf Coast for geothermal viability. This involved studying wells sponsored by industry partners in addition to drilling new wells. The Pleasant Bayou #2 well in Brazoria county, Texas was the first successful demonstration of a hybrid binary cycle electricity generation from a deep well in a sedimentary basin; drilling into the Lower Frio formation (Hidalgo, Armstrong, Corpus Christi, Matagorda and Brazoria counties). The well produced a minimum of 20,000 bbls/day of geothermal brine with 22 scf gas/bbl. The power plant on site utilized only 10,000 bbls/day (292 gpm) at a maximum temperature of 309° F. generating average 1.191MW gross power for the 121 days the plant was run in 1989-1990, however only 542 kW was generated from the geothermal binary cycle and 650 from a gas engine onsite. There was an additional -209 kW parasitic load on the system resulting in a net production of about 982 kW [4]. The major issues during operation of the facility were impurities in gas, corrosive brine and scaling within the heat exchanger.

In addition to the Lower Frio, the Gulf Coast also contains the Lower/Upper Claiborne, Vicksburg-Jackson, and the Lower/Upper Wilcox. Each of these reservoirs have potential for development, however the Lower Frio is the only reservoir that has seen actual development (Pleasant Bayou #2). Dr. David Blackwell with the SMU geothermal team has described "...the entire Gulf Coast area is considered geothermal-geopressured at various depths, Bebout et al., (1982; 1983) described specific 'geothermal fairways' having the most prospective reservoirs." … "By 9,000ft. the majority of Texas east of I-35 is at or above 200°F" [1]. Blackwell goes further to mention that the Lower Wilcox (Zapata, Duval, Live Oak, DeWitt, Colorado and Harris counties) has the highest temperatures at specific depths of all the Gulf Coast region.

Emergency Power

Geothermal energy is so consistent that it provides an excellent option for emergency power use. This type of electric supply is critical for services such as hospitals, especially in rural communities. Geothermal energy is extremely well suited to the Gulf Coast region of Texas due to the highly geopressured/geothermal tendencies of the region and due to the lack of infrastructure. Additionally, this region encounters frequent power outages from tropical storms sweeping from the Gulf to the south. For example, in 2008 a series of storms, concluding with Hurricane Ike knocked out power for an estimated 4.5 million people, some for as long as two weeks. Readily available emergency power is crucial in situations like this as there will be no doubt injuries will occur, which will require medical services.

West Texas is also exceptionally rural; a blackout at a medical facility could mean no emergency medical attention is available for hundreds of people. Geothermal energy is particularly well suited for ranchers of this region, who generally own hundreds, if not thousands, of acres. With the implementation of multiple on-site wells it is very feasible for a rancher’s power needs to be run self-sustained.

CHAPTER II

METHODS

Heat Recovery from LTG: The Organic Rankine Cycle Process

A Binary Rankine Cycle or also known as an Organic Rankine Cycle (ORC) is somewhat of a new process that enables us to extract heat from lower temperature resources. The ORC power plant is used where the geothermal resource is not hot enough to efficiently produce steam (170^{o}F–240^{o}F), or where too many chemical impurities are contained within the hot water to allow flashing. In this process, the geothermal fluid is brought to the surface and passed through a heat exchanger (**Figure 2**). The secondary fluid in the heat exchange system is a fluid with a lower boiling point that water, such as isobutane, pentane, or ammonia. This secondary fluid is vaporized, and passed through the turbine to generate electricity. The working fluid is condensed and recycled for another pass through the heat exchanger. The geothermal fluid can then be processed and treated for surface disposal or reinjected into the aquifer. The use of two separate fluids for power generation gives the name ‘binary’ to this type of power plant.

ORC geothermal power generation is particularly strong suited for horizontal wells that are reaching or have reached their economic limit within the oil and gas industry. The added benefit of electricity production mitigates the cost of produced water and allows more hydrocarbon resources to be extracted.

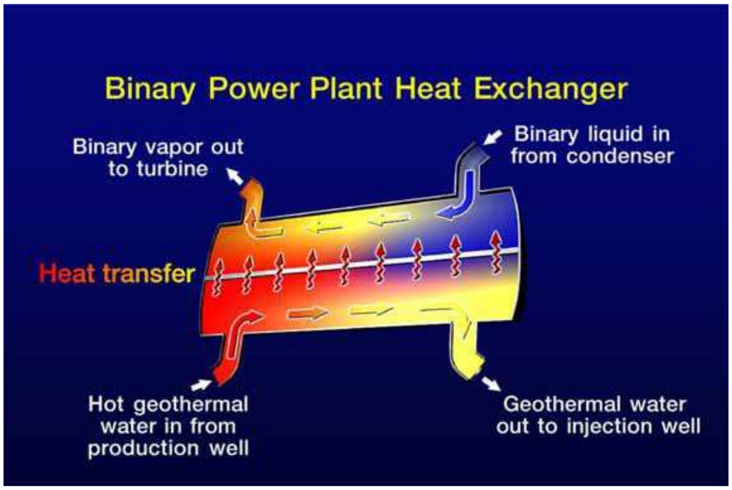


Figure 1: General process of Binary Heat Exchange

Horizontal wells are particularly good heat exchangers due to the long lateral section as temperature within the formation of the lateral section will be constant at any particular depth. As geothermal fluids are produced the reservoir will temperature will drop, and this is especially true in vertical or circulating systems. However due to the lengthy lateral the temperature drop in the reservoir can be considered negligible. This fact makes the South Texas shale wells extremely well suited for electrical generation and many shale wells are nearing economic limit for gas production.

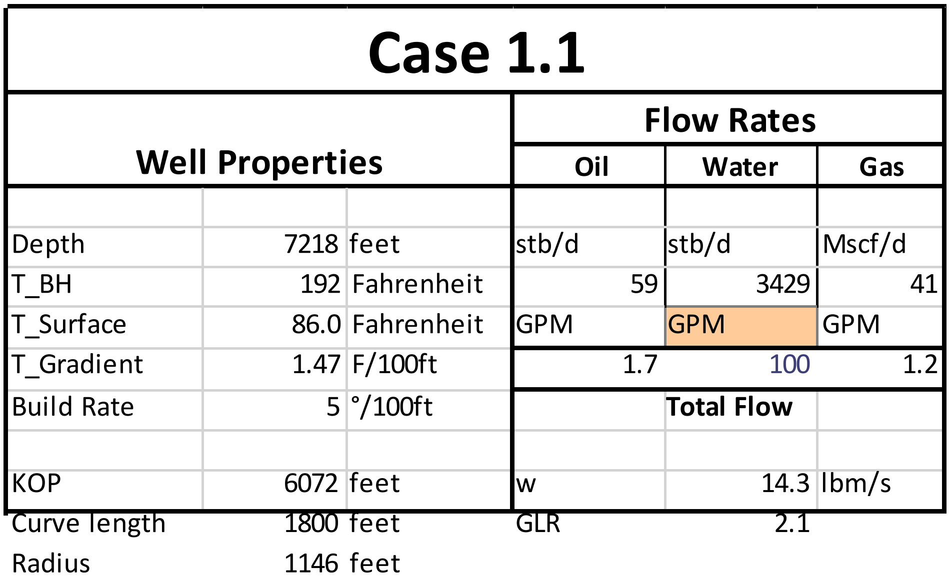
One major distinction must be made in the configuration of LTG wells. For much of the Gulf Coast large high-pressure aquifers exist with ample hot water for electricity generation. For these systems the water is simply produced and disposed of accordingly, through treatment or injection. However in shale wells, the water produced is largely frac flow back and not from the reservoir itself. Due to this fact, for shale wells it may be advantageous for a circulating system to be put into place. Water, or preferably a fluid with lower boiling point, will be injected down the annulus and produced through the tubing. This setup can be run autonomously with minimal intervention as there will be no water to dispose of.

Parameters affecting flowing surface temperature

It can be considered that there are near infinite parameters affecting the efficiency of heat transfer from bottomhole fluids to surface heat capture equipment. A few of these parameters are: Heat conductivity of the Earth and tubing/insulation, fluid and formation density, wellhead pressure and surface temperature. Time also affects the heat transfer however this is only early in production where significant affect is seen. Gas rate also significantly affect temperature profile, however due our interest in abandoned or low gas production wells it is minor. Tubing insulation maybe considered for use, however due to our conversion of existing wells this may be uneconomic. During modeling of wellbore heat transfer it became evident two main parameters affected temperatures more than the others: bottomhole temperatures and fluid production rate. Of the two bottomhole temperature could be considered more important due to some control on the variability of flow rate.

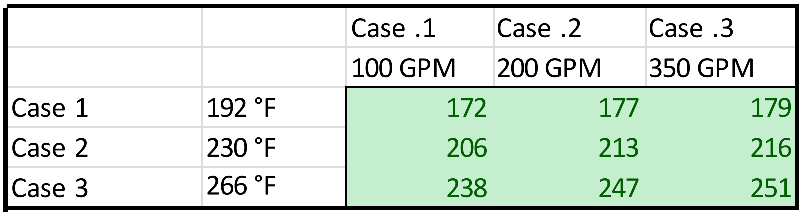
To illustrate the variability of surface fluid temperature three bottomhole temperatures at three different fluid production rates were compared using a wellbore temperature developed by A.R. Hasan and C.S. Kasir [5] from a 10,000 ft. well with a TVD approximately 7,250 ft. **Table 1** consists of the well and fluid properties that were used in the model. Each Case 1, 2 and 3 bottomhole temperature was held constant at 192, 230 and 266° Fahrenheit respectively. Each case was analyzed at three water flow rates of 100, 200 and 350 gallons per minute (GPM). The resulting surface temperatures (three for each case) are tabulated in **Table 2.** For each case a graph was constructed to illustrate the wellbore fluid profile for varying flow rates (**Graphs 1-3)**.

***Table 1**: General Well and Fluid properties*



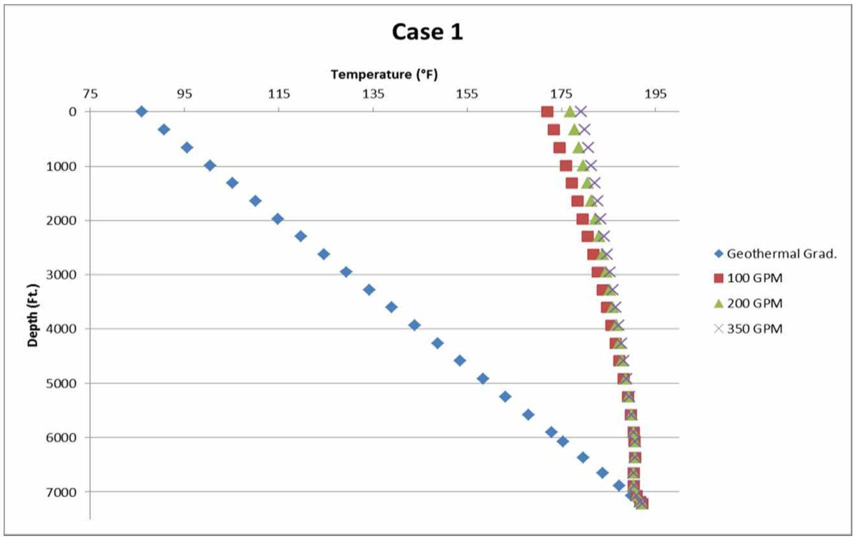
Case 1.1					
Well Properties			**Flow Rates**		
			Oil	**Water**	**Gas**
Depth	7218	feet	stb/d	stb/d	Mscf/d
T_BH	192	Fahrenheit	59	3429	41
T_Surface	86.0	Fahrenheit	GPM	GPM	GPM
T_Gradient	1.47	F/100ft	1.7	100	1.2
Build Rate	5	°/100ft		**Total Flow**	
KOP	6072	feet	w	14.3	lbm/s
Curve length	1800	feet	GLR	2.1	
Radius	1146	feet			

***Table 2**: Calculated surface temperatures in Fahrenheit*

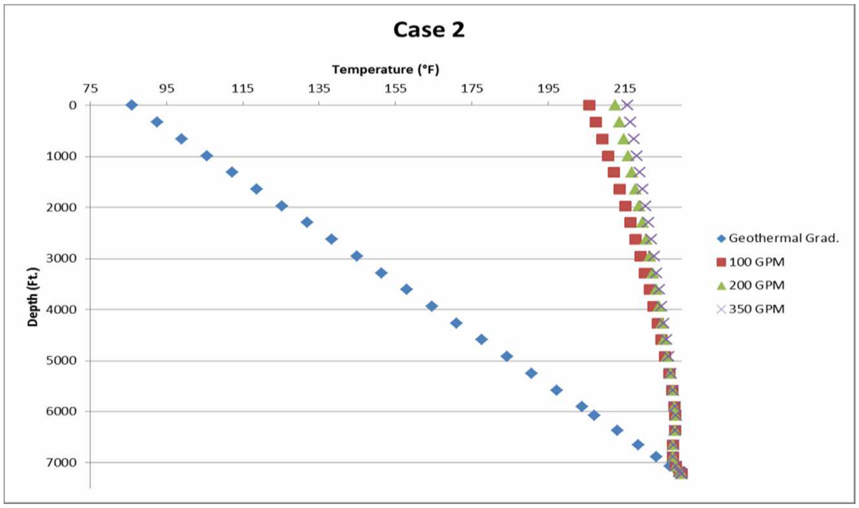


		Case .1	Case .2	Case .3
		100 GPM	200 GPM	350 GPM
Case 1	192 °F	172	177	179
Case 2	230 °F	206	213	216
Case 3	266 °F	238	247	251

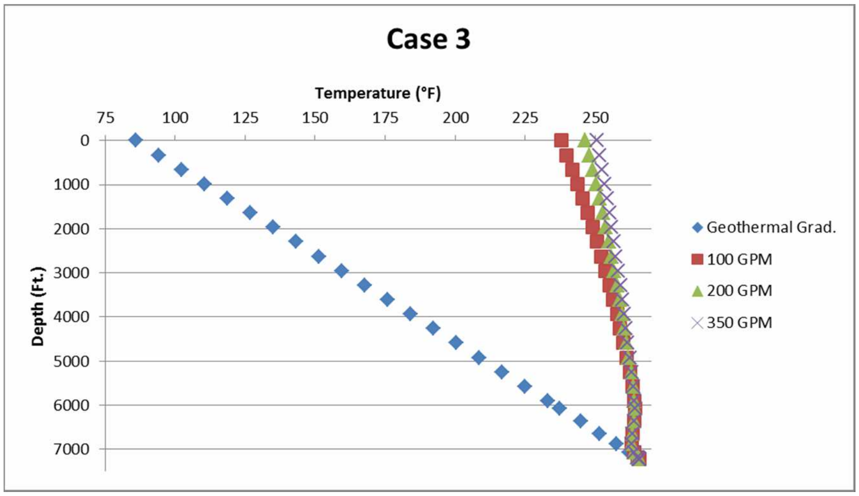
From the graphs and Table 2 it can be concluded that bottomhole temperature has a much more significant of an impact. In each case a significant jump in surface temperature can be seen between the 100 GPM and 200 GPM case however it is considerably less pronounced between 200 GPM and 350 GPM. 200 GPM could be considered the ideal flow rate we wish to achieve because this will maximize surface temperature with minimum energy needed for pumping costs.



Graph 1: Wellbore temperature profile for Case 1 (192 °F)



Graph 2: Wellbore temperature profile for Case 2 (230 °F)



Graph 3: Wellbore Temperature profile for Case 3 (266 °F)

CHAPTER III

RESULTS

Cost Analysis

This section will detail the economics of the Green Machine 6500 Organic Rankine Cycle electricity generator invented and manufactured by ElectraTherm out of Reno, Nevada and cost roughly $290,000. The cost analysis compares power generated, profit per hour and per barrel of fluid, and the payback period and year 20 profit (estimated machine lifetime). **Figure 4** was used to estimate gross power output vs. fluid flow rate for various temperatures.

Similar to previous graphs, it can be seen in Figure 3 that the power output curve begins to taper off around 200 to 250 GPM so it can be assumed the highest efficiencies for heat transfer are within this range. This is due to the fact that at higher flow rates heat transfer is less per unit of volume due to the higher velocity of the fluid, although it is less pronounced in the higher temperatures.

According to DieselServiceAndSupply.com, a distributor of many industrial diesel generators, a diesel generator will consume about 7 gallons/hours of diesel fuel to output 100kW. Considering diesel price to be $3.00 a gallon, it will cost 21 $/hr or 21 ¢/kWh to generate 100kWh. It is also very important to note that these economics are considering selling power to the grid for 19.5 ¢/hour. This is price of generating electricity using diesel minus the parasitic load (1.5 ¢/kWh) that is required to operate the machine.

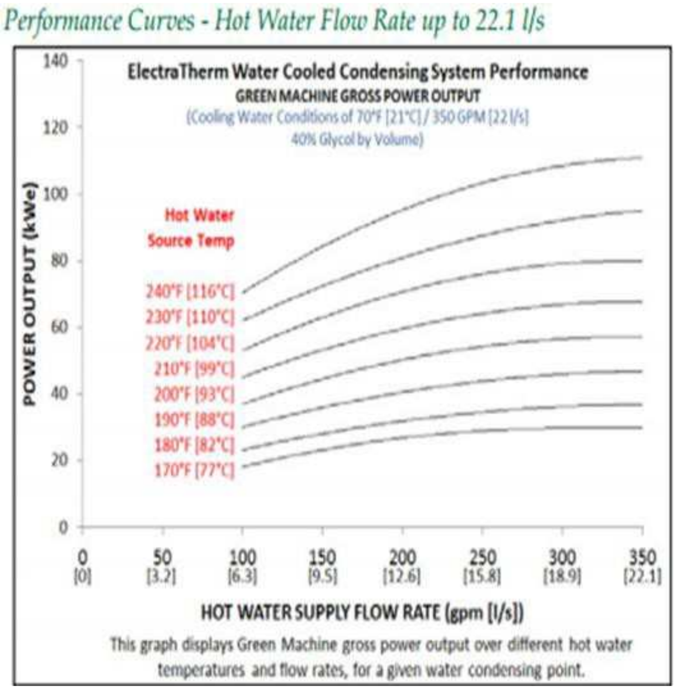


Figure 2: Power output vs. Hot water flow rate at various temperatures [2]

In **Table 3** it is shown profits per hour, profits per barrel, payback period and year 20 profits. It should be noted that again it is seen that for higher velocities less heat (thus money generated) is utilized per unit volume. This means that the ideal economic zone is somewhere within 150-250 GPM. With subsequent increasing flow rates, we see minimal decrease in payback period but considerable lower profit per barrel of fluid processed.

This table proves the viability of this machine. At 226 GPM and 240 °F, the Greenmachine essentially generated the same amount of energy as the diesel generator for free, meaning a savings of $19.50 per hour. However, we must also remember that higher flow rates will most likely be achieved with artificial lift, such an ESP, and in this case the power generation will go to offsetting the pump.

Because the machines offset of the energy cost is determined by the cost of the next cheapest option it will be easily feasible in remote locations where the cost of electricity is high, or where artificial lift is not required.

		170F			*Payback*		*profit, year 20*
GPM	GPH	*kWe*	*$/hour*	*¢/bbl*	*time, days*	*Years*	*$*
100	6000	18	$3.54	2	3407	9.3	$ 331,050
150	9000	23	$4.40	0.02	2742	7.5	$ 481,710
200	12000	26	$5.05	0.02	2387	6.5	$ 596,475
250	15000	28	$5.50	0.02	2191	6.0	$ 675,344
300	18000	29	$5.75	0.01	2098	5.7	$ 718,317
350	21000	30	$5.79	0.01	2083	5.7	$ 725,393
		210F			*Payback*		*profit, year 20*
GPM	GPH	*kWe*	*$/hour*	*¢/bbl*	*time, days*	*Years*	*$*
100	6000	44	$8.67	6	1391	3.8	$ 1,230,414
150	9000	53	$10.38	5	1162	3.2	$ 1,529,547
200	12000	60	$11.75	4	1026	2.8	$ 1,770,564
250	15000	66	$12.79	4	943	2.6	$ 1,953,462
300	18000	69	$13.51	3	893	2.4	$ 2,078,244
350	21000	71	$13.89	3	869	2.4	$ 2,144,908
		240F			*Payback*		*profit, year 20*
GPM	GPH	*kWe*	*$/hour*	*¢/bbl*	*time, days*	*Years*	*$*
100	6000	72	$14.03	10	860	2.4	$ 2,169,825
150	9000	85	$16.58	8	727	2.0	$ 2,617,432
200	12000	96	$18.64	7	647	1.8	$ 2,977,862
226	13542	100	$19.50	5	618	1.7	$ 3,129,241
250	15000	104	$20.20	6	597	1.6	$ 3,251,116
300	18000	109	$21.26	5	567	1.6	$ 3,437,195
350	21000	112	$21.82	4	553	1.5	$ 3,536,097

Table 3: Cost analysis for Waste-Heat-to-Power

Case Study

The Hasan and Kabir fluid temperature model was analyzed on two wells from different regions of Texas. All production and reservoir temperature log information was gathered from info.DrillingInfo.com. The first well was API number: 42-239-02764; originally a Hillcorp well drilled in Jackson County in South Texas. The reservoir had average water production of 216 GPM and a bottomhole temperature of 366° Fahrenheit. As shown in **Figure 5** this makes estimated average surface temperature to be 300°; which is even over the working temperature of the Greenmachine. This could be mediated with a working fluid with a higher boiling point. Predictions for electricity generation cannot be made, however it can be assumed that it will be substantial due to the large heat flow.

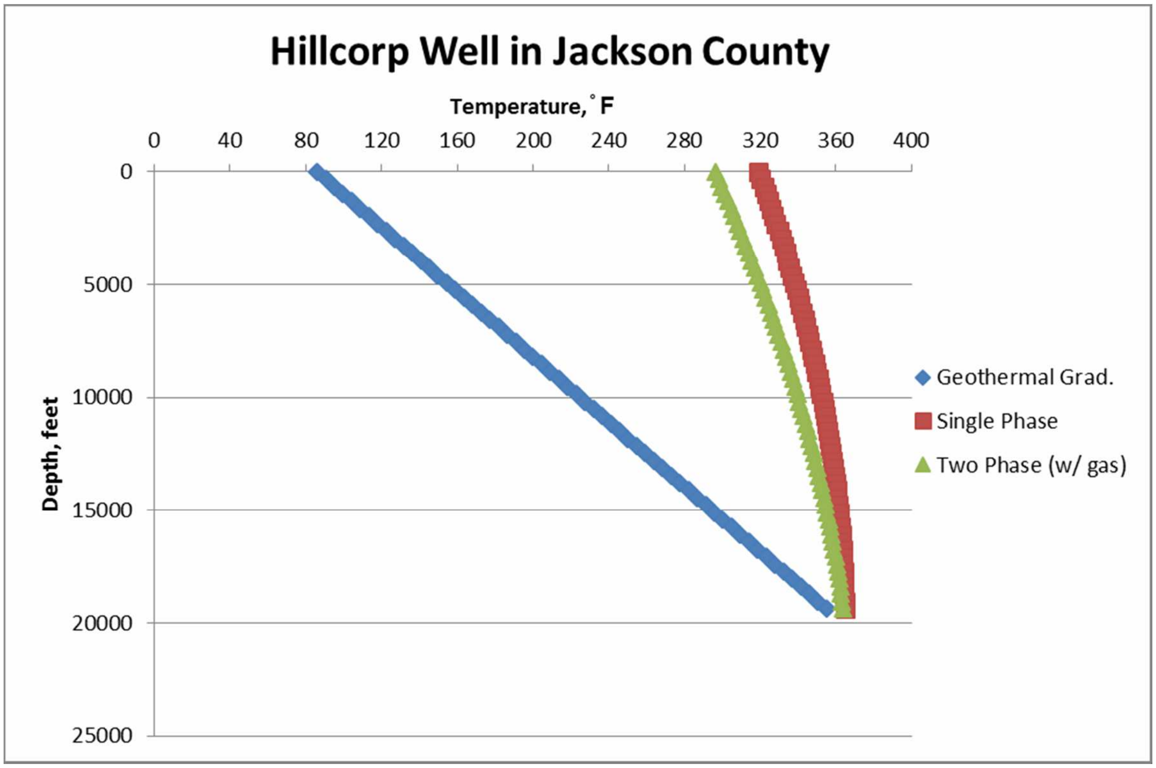


Figure 3: Geothermal gradient and temperature prediction of a South Texas well

The second well was API Number 42-227-81495; a Conoco well drilled southwest of Midland. This reservoir had a bottomhole temperature of 338 °F with an average of 150 GPM. This means surface temperatures of around 260° Fahrenheit, as shown in **Figure 6**. It can be estimated that the Greenmachine will generate roughly 100kW with these conditions. Which at 21 ¢/kWh, means the machine would payback for itself in 1.7 years.

From this analysis we can see that LTG Waste-Heat-to-Power power generation in coproduction with oil and gas is an option that is very much available to be taken advantage of in the right scenarios.

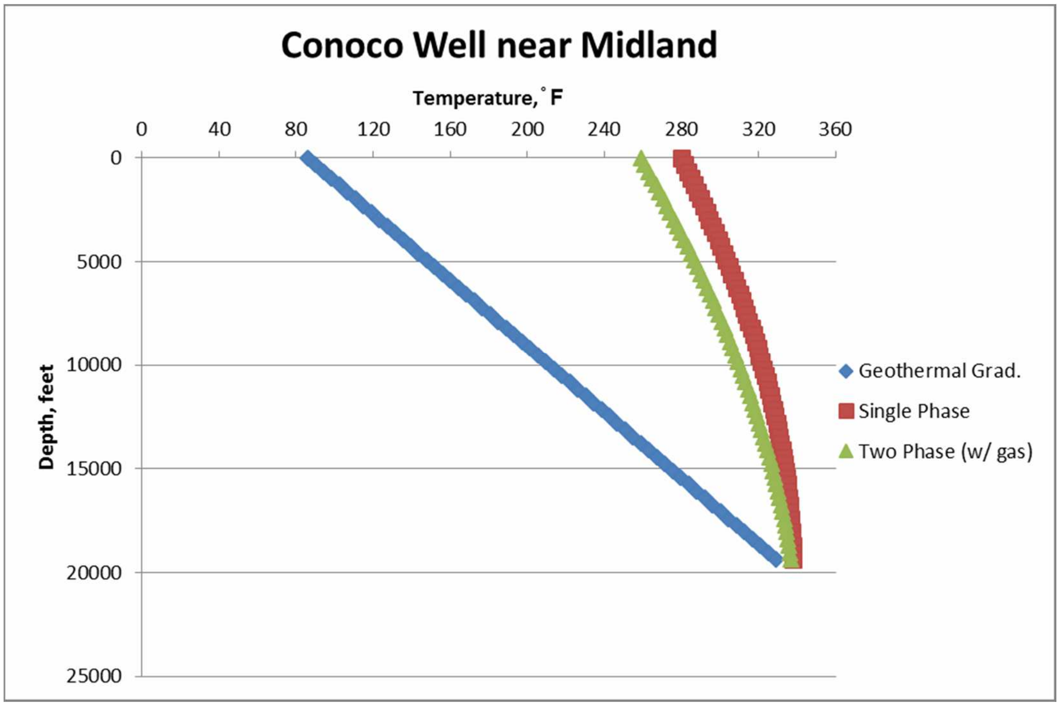


Figure 4: Geothermal gradient and temperature prediction of a West Texas well

Circulating Scenario

A.R. Hasan and C.S. Kasir in Fluid Flow and Heat Transfer in Wellbores also developed a model for predicting surface temperatures in a fluid circulating scenario. Using this prediction model, the previous wells were analyzed for Waste-Heat-to-Power electricity generation. In this model the fluid is injected in the annulus and produced up the tubing for a vertical wellbore.

For circulating fluid cases we see a much lower surface temperature then for the production of reservoir fluids. Circulating time in addition to fluid rate also plays an important factor to the slope of the fluid temperatures. For late circulating times and high flow rates we see a very flat temperature profile, due to the surface and bottomhole temperature reaching equilibrium. Tubing insulation is much more critical to fluid circulation cases, however it was not accounted for in this scenario.

For the Hillcorp well, the flow rate was again assumed to be 216 GPM with 366 degrees Fahrenheit bottomhole. The fluid was circulated for 1000 hours and the injection temperature was assumed to be the same at the produced temperature (i.e. closed circulating loop). The fluid temperature with depth is shown in **Figure 7** and it was found that for this formation the maximum surface flowing temperature that could be obtained was approximately 190 degrees Fahrenheit. This puts the electrical production at roughly 50kW, meaning the machine would payback for itself in roughly 3.2 years at 21 ¢/kWh.

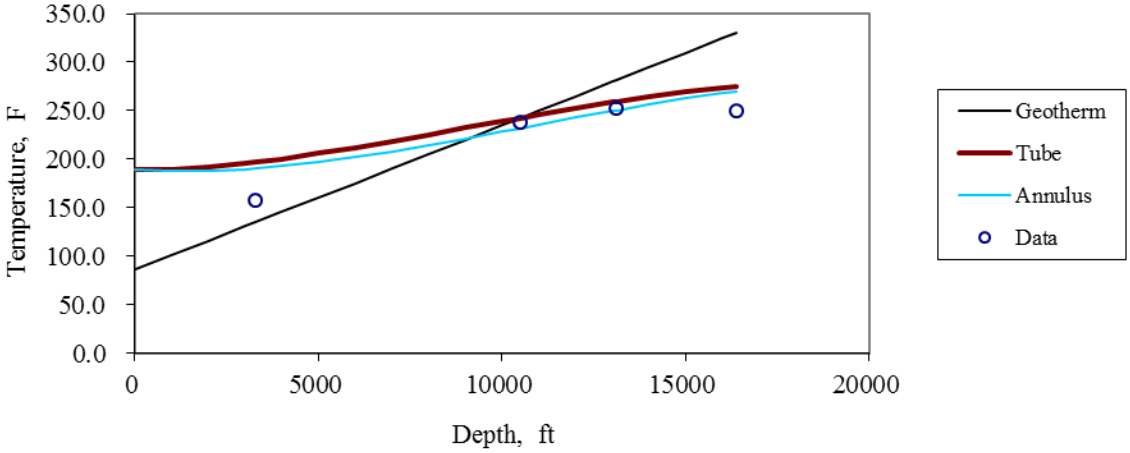


Figure 5: Temperature prediction of circulating fluid in a South Texas well

The Conoco was assumed to have the flow rate of 212 GPM and a bottomhole temperature of 338° Fahrenheit. Just as the previous example, the fluid was circulated for 1000 hours and the injection temperature was assumed to be the same at the produced temperature (i.e. closed circulating loop). This produced a surface tubing temperature of 160° Fahrenheit, which equates to roughly 20 kW for the flow rate of 212 GPM. Considering the price of electricity to be 21 ¢/kWh, the Greenmachine will pay for itself in roughly 8.5 years.

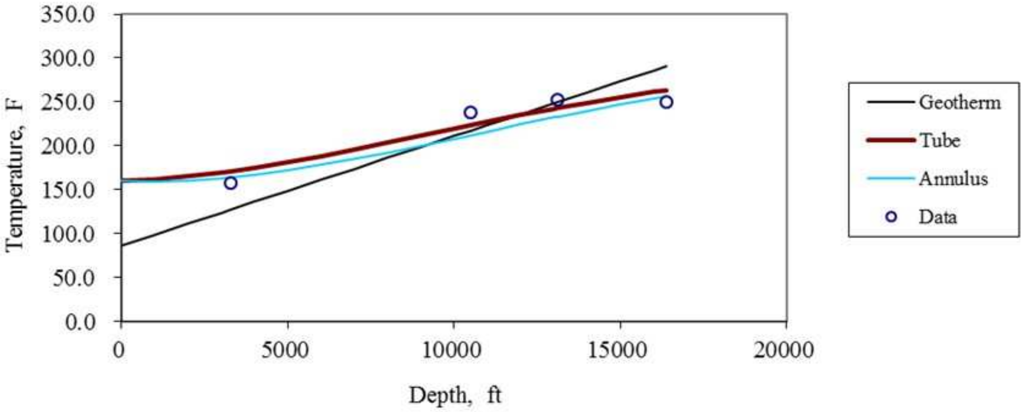


Figure 6: Temperature prediction of circulating fluid in a well near Midland

For the fluid circulation cases the wellbore was considered to be vertical, however it can be assumed that for horizontal wells there will be a big temperature jump, with respect to total depth. The fluid will accept heat from the surrounding formation and depending on the length of the lateral will be considerably higher temperatures then for vertical wells. Again, we must consider that for longer laterals the pumping costs will be higher.

The prospect for Waste-Heat-to-Power generation for circulating cases opens an entirely new realm of opportunity for the Greenmachine. The machine could be adapted to accept drilling mud and associated cuttings in high temperature wells, which would be particularly advantageous is extended reach lateral wells. For a closed loop system the circulating wellbore fluid could be adapted so that it has a very low boiling point, meaning the fluid could vaporize downhole so the cost of pumping is greatly decreased.

Denbury Field Trial

In the summer of 2011, Electratherm worked with Denbury Resources to install a demonstration Greenmachine on an oil and gas well. This was the first Greenmachine to be used for the purpose of Waste-Heat-to-Power generation with the co-production of oil and gas. The test well was in Laurel, Mississippi which is approximately 100 miles from the Gulf Coast.

Figure 7: Greenmachine at Laurel, MS test site

During the field trial the well produced fluid at an average rate of 120 GPM and 204° F. This netted an average production of 19-22kWe, depending on the ambient temperature (day or night) which can be seen in **Figure 10**. Even with less than favorable conditions this setup was able to offset more than 20% of the down-hole pump tied to the well.

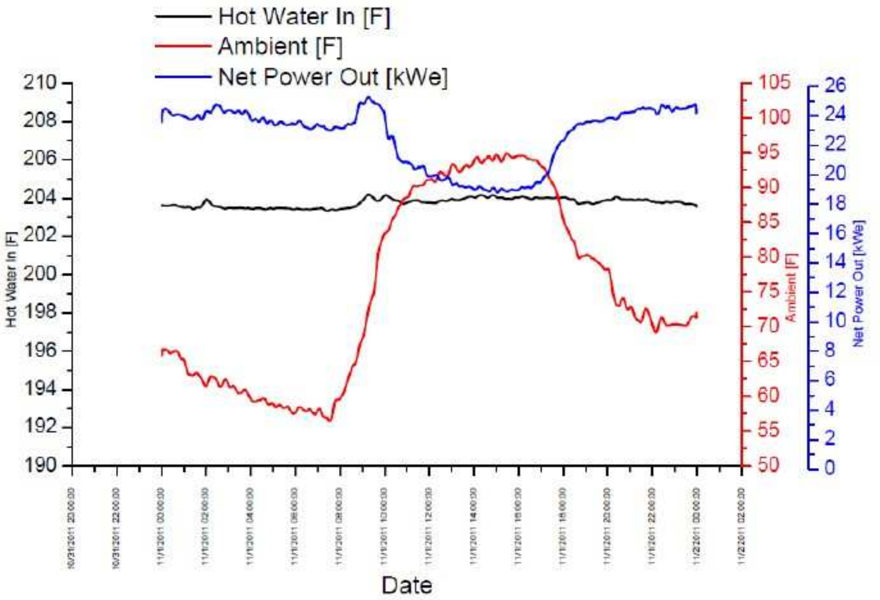


Figure 8: 24-hour power generation for the Greenmachine during November 2011

The major take away from this trial is that Waste-Heat-to-Power generation with co-production of reservoir fluids is without a doubt possible and very effective at reducing the onsite power requirement. We can see that the Hot Water input is nearly constant, which proves how consistent this energy source is. However, Electratherm concluded that most wells do not have sufficient temperature and/or flow rates to reach the Greenmachine's optimal zone. The solution to this would be to target very high temperature wells with moderate to high flow rates and well pads with several deviated wells within close proximity.

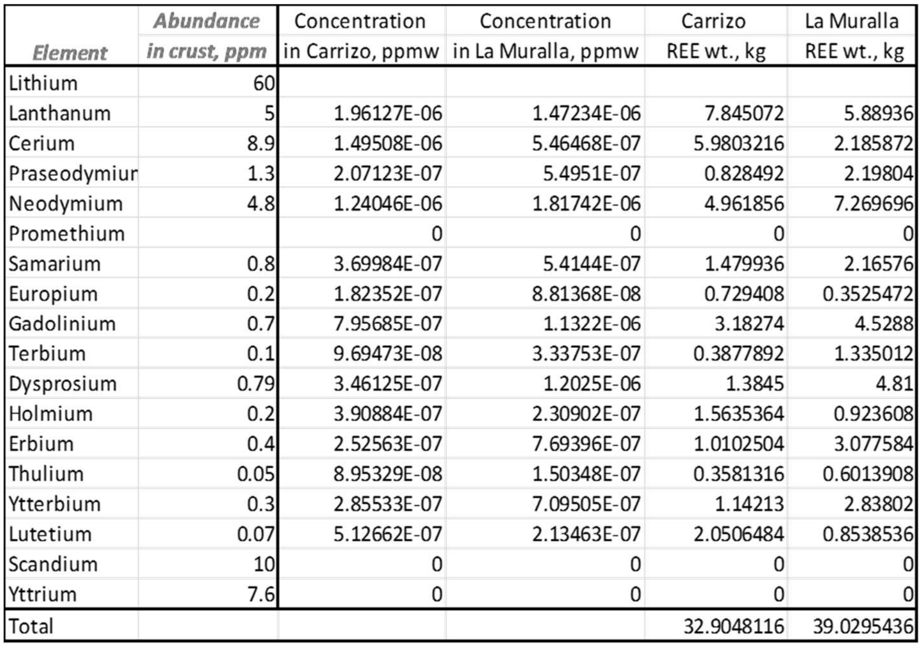
The ambient temperature also plays a twofold challenge due to the binary power cycle. The high average ambient temperature of 94°F means the energy transfer from the produced fluids to the working fluid via the heat exchanger is limited. In addition, the high ambient temperature means it requires more energy to condense the working fluid within the Greenmachine thus increasing the parasitic load of the system.

An additional consideration is that hydrocarbon fluids have a lower heat capacity then water, which could have been a cause of the less than expected power generation.

Future Development

Strategic Materials Recovery

Generally speaking, produced water from high temperature formations contains higher dissolved solids content then lower temperature formations. In some instances, these produced waters can contain trace minerals of economic importance, such as Lithium and a series of metals known as Rare Earth Elements (REEs). These materials have had a huge increase in demand with the development of new technologies such as touch screen phones and high-end electronics which use these materials in their components. Additionally, REEs are not found in large ore deposits such as Gold or Silver. Minerals which contain REEs are the main source of these elements and are only formed under very specific conditions. Currently, roughly 90% of the world's REE supply comes from China, with nearly 45% coming from Bayan Obo in Northern China which is the largest deposit of Rare Earth Minerals. Due to this fact, the supply and demand of REEs is extremely volatile and in the past the Chinese government has limited exports, leading to market panics. It is very evident that with the ever increasing demand and use of high-end electronics in our society that the U.S. will need a reliable supply for our needs.



Element	*Abundance in crust, ppm*	Concentration in Carrizo, ppmw	Concentration in La Muralla, ppmw	Carrizo REE wt., kg	La Muralla REE wt., kg
Lithium	60				
Lanthanum	5	1.96127E-06	1.47234E-06	7.845072	5.88936
Cerium	8.9	1.49508E-06	5.46468E-07	5.9803216	2.185872
Praseodymiur	1.3	2.07123E-07	5.4951E-07	0.828492	2.19804
Neodymium	4.8	1.24046E-06	1.81742E-06	4.961856	7.269696
Promethium		0	0	0	0
Samarium	0.8	3.69984E-07	5.4144E-07	1.479936	2.16576
Europium	0.2	1.82352E-07	8.81368E-08	0.729408	0.3525472
Gadolinium	0.7	7.95685E-07	1.1322E-06	3.18274	4.5288
Terbium	0.1	9.69473E-08	3.33753E-07	0.3877892	1.335012
Dysprosium	0.79	3.46125E-07	1.2025E-06	1.3845	4.81
Holmium	0.2	3.90884E-07	2.30902E-07	1.5635364	0.923608
Erbium	0.4	2.52563E-07	7.69396E-07	1.0102504	3.077584
Thulium	0.05	8.95329E-08	1.50348E-07	0.3581316	0.6013908
Ytterbium	0.3	2.85533E-07	7.09505E-07	1.14213	2.83802
Lutetium	0.07	5.12662E-07	2.13463E-07	2.0506484	0.8538536
Scandium	10	0	0	0	0
Yttrium	7.6	0	0	0	0
Total				32.9048116	39.0295436

Table 3: Rare earth concentration in crust, Carrizo and La Muralla Aquifers, with estimates of recoverable materials in 1 million gallons of water

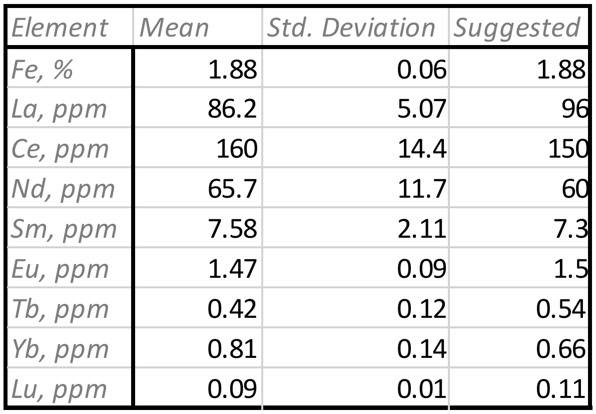
A potential source for REEs is from produced water from oil and gas wells. **Table 3** comprises of geochemical data of REE concentrations for the Carrizo aquifer in South Texas (9. Tang et. al) and the La Muralla aquifer in central Mexico (Johannesson et. al). This table also contains estimates for weight of each element dissolved in one millions gallons of water. While this may seem like an insignificant amount, the selling price for these materials can range from $500 to $2,000 per kg, with certain elements jumping as higher as $10,000 per kg in times of market panic.

The challenge of this is the ability to filter the produced fluids. In times past, to filter out these types of particles required nano-filtration or reverse osmosis which would require high pressure and high cost of filtration. The Global Petroleum Research Institute is currently working with researching at Rice University to create a flocculant that will which will bond to the chosen elements so that they can be separated using microfiltration.

According to a GPRI field study of Ultra-high salinity brine in the Marcellus shale, the cost of micro-filtration is roughly $0.04 per barrel (2. Burnett et. al). Considering that favorable REE concentration are in high temperature reservoirs, the Greenmachine could be used to power microfiltration on site autonomous of off-site power. This would solve a two-fold problem: it would reduce the cost of producing water (by giving the water value) as well as the filtered water could be reused for other oil and gas operations onsite, eliminating trucking costs and disposal.

Subsea waste heat to power generation

Subsea conditions are extremely ideal for waste-heat-to-power electricity generation. Offshore wells generally have much higher production then onshore, as well as very high temperatures of produced fluid from the subsurface. However, the big advantage that subsea WHP holds over onshore is the huge temperature difference between the sea-floor and the produced fluids. According to the Laws of Thermodynamics this allows for much more effective power generation when using an Organic Rankine cycle. Additionally, the cold sea water provides an excellent heat sink for the working fluid.



Element	*Mean*	*Std. Deviation*	*Suggested*
Fe, %	1.88	0.06	1.88
La, ppm	86.2	5.07	96
Ce, ppm	160	14.4	150
Nd, ppm	65.7	11.7	60
Sm, ppm	7.58	2.11	7.3
Eu, ppm	1.47	0.09	1.5
Tb, ppm	0.42	0.12	0.54
Yb, ppm	0.81	0.14	0.66
Lu, ppm	0.09	0.01	0.11

Table 4: Selected Geochemistry from East Pacific Rise hydrothermal vent

Another application where small scale WHP would excel is in the heat extraction of hydrothermal vents on the seafloor. Hydrothermal vents have been found to have temperatures as high as 850 °F, which is a massive temperature difference when compared to the surrounding sea floor at near freezing temperatures. Additionally, hydrothermal vents have considerably higher concentrations of REEs and trace metals. **Table 4** shows average geochemical data for a hydrothermal vent on the western side of the East Pacific Rise. It is obvious that in addition to Waste-Heat-to-Power, strategic materials capture could be very economical.

CHAPTER IV

CONCLUSIONS

Through the course of this study, I believe that the juxtaposition of a high geothermal gradient, ample opportunity to use the existing infrastructure of oil and gas wells, and the need for a non-interruptible alternative energy source make LTG particularly attractive, especially in recent light of poor oil prices. For Texas, the zone of optimal geothermal quality is the Gulf Coast region following south along I-35 to Laredo. This is has a high geothermal gradient and extensive existing well infrastructure. Additionally, this area has numerous horizontal wells with long laterals meaning more exposure to the geothermal reservoir and potentially an increase in heat flow. For the unit that was analyzed, the temperature of the fluid played a much more key role then the flow rates for efficiency of energy produced from the heat flow. The Greenmachine actually saw a significant decrease in thermodynamic efficiency after approximately 200 GPM, meaning that the flow rates of oil and gas wells will actually be an optimal condition in terms of efficiency. In conclusion, LTG energy capture operations on producing and near-abandoned oil and gas wells can in some cases significantly increase the productive operating life of the well by generation electricity on site which the profits of which can be used to offset the cost of water production.

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