Evaluation of the Effect of Gravity on the Total-Flow Geothermal Cycle

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Abstract

Linear Power Ltd. employs a semi-closed cycle gas-lift total flow geothermal process that has the potential to generate more than double the amount of power than is produced by current geothermal cycle technology. The increased power is a thermodynamic result of vaporizing a liquid phase working fluid to a low mass high pressure vapor within a high mass hot water column via direct heat exchange deep within a well bore. High mass water is displaced with low mass gases and the density of the water column is made much lower. Substantial additional power is gained as a result of the change in density of the column of water by the process that lowers its gravitation pull. The force of the pressure at the base of the well exerted by the reservoir is in opposition to the weight of the water. Lowering the water's density (weight) while the earth's force is unchanged produces an extremely powerful water pumping force powered by gravity. This gravitational effect is a separate side effect of the thermodynamic process and totally independent from the thermodynamic process, although the result could not occur absent of the thermodynamic process. The total flow of accelerated high mass water and gases produced by the process drives a prime mover with much greater Kinetic energy force than can be attained by conventional geothermal processes that create low density gases via indirect heat exchange to produce power. The energy to pump the liquid phase working fluid to depth into the well does not change to a substantial degree from that of a conventional Rankine cycle performed on the surface as the liquid must be pumped into the high pressure boiler at the surface, which is at approximately the same pressure as the hydrostatic pressure of the water within the well. Engineering proves that the gas-lift total process described herein typically generates more than double the amount of power from the same geothermal heat resource.

Introduction

This document describes a total flow geothermal power cycle that closely parallels the geothermal power generation cited in the technical paper “The Total Flow Concept for the Recovery of Energy from Geothermal Hot, Brine Deposits” by A. L. Austin. The total flow power cycle may be summarized as a process by which the total flow of two-phase mixtures of liquids and gases are accelerated through a nozzle to high velocity having enhanced kinetic

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energy levels due to the drive force of the expanding gas that accelerates the high mass water to high velocities. The water column of the well described in the paper while at equilibrium remained below surface level and water did not free flow to the surface. A water pump was placed on the well and it was then pumped creating suction, which resulted in lowering the pressure within the well that allowed vaporization of a portion of the liquid water to a low-density gas (steam produced by water flashing to vapor in response to lower pressure). The steam displaced high density water causing the overall water column to be less dense (lighter in weight) that resulted in a wellhead pressurized free-flow of water having over 300 psi pressure and the pump was no longer necessary. While at equilibrium the water's hydrostatic pressure and the reservoir pressure were the same. The hydrostatic pressure changed but the reservoir pressure remained the same resulting in the gas-lift total flow of pressurized water and gases from the well that were capable of producing power via harnessing their kinetic energy potential.

Stathis Michaelides, Ph.D., at the University of Texas concluded in a written report concerning the Total Flow Paper, "The bottom line is that it is an interesting concept but we do not have the engine/turbine to do it. This is what happens: The authors have gotten the properties of the brine and have based their analysis for the power on the 'availability' or 'exergy' concept. This gives the maximum work / power one may extract from a resource, but it does not tell you how to get it and what type of engine you can use. Their numbers are correct, in the sense that this is the maximum we can get from the well. But, there is no such engine as the "total flow engine" (no-one markets it nor has anyone produced / designed it). In the report the authors dance around this issue by implying that an isentropic turbine will do this job, but they are incorrect. There are no such isentropic turbines that would expand the two phase fluid."

The Total Flow Concept paper provides clear mathematical evidence that there is greater power potential within geothermal wells and within oil and gas wells that may be converted to long-life geothermal power plants than is currently believed by using the kinetic energy potential of accelerated high mass liquids as part of the total flow of pressurized gases and liquids discharged from the well. This process also carries with it the additional benefit of providing the service of pumping water from the well, while producing greater net power generation instead of using power to drive a water pump as a parasitic power loss as is currently the case in conventional geothermal power cycles used today; thereby, providing additional power by two separate means.

Gas-Lift Method and Free-Piston Engine Linear Equipment Used to Generate Power

Linear Power, Ltd. has engineered a gas-lift method to perform the total flow concept, using equipment with significant improvement over the devices presented in the older April 3, 1973 paper. Linear Power, Ltd.'s proprietary closed cycle described herein employs a gas-lift direct well bore heat exchange process developed by Robert D. Hunt to harness power from geothermal wells and from oil and gas wells, using a modified variant of the total flow concept but being a different method of operation and equipment than that suggested in the total flow paper. Linear Power, Ltd.'s proprietary long stroke, free-piston engine can successfully operate to harness the power under the harsh operating conditions, which include the extreme working fluid pressures and velocities of the dual phase flow from the well, described in the Total Flow Concept paper.

Power can be generated from the kinetic energy of geopressure resource wells. However, there are a very limited number of such pressurized free flowing wells. Gas-lift can be used in association with these rare wells having geopressure to produce even greater water production volume, higher velocity, and greater pressure. But most importantly, the total flow concept that can gas-lift a pressurized flow of water and gases from geothermal or oil and gas wells that do not have geopressure, which opens the potential for a much larger number of wells to produce power via their kinetic energy.

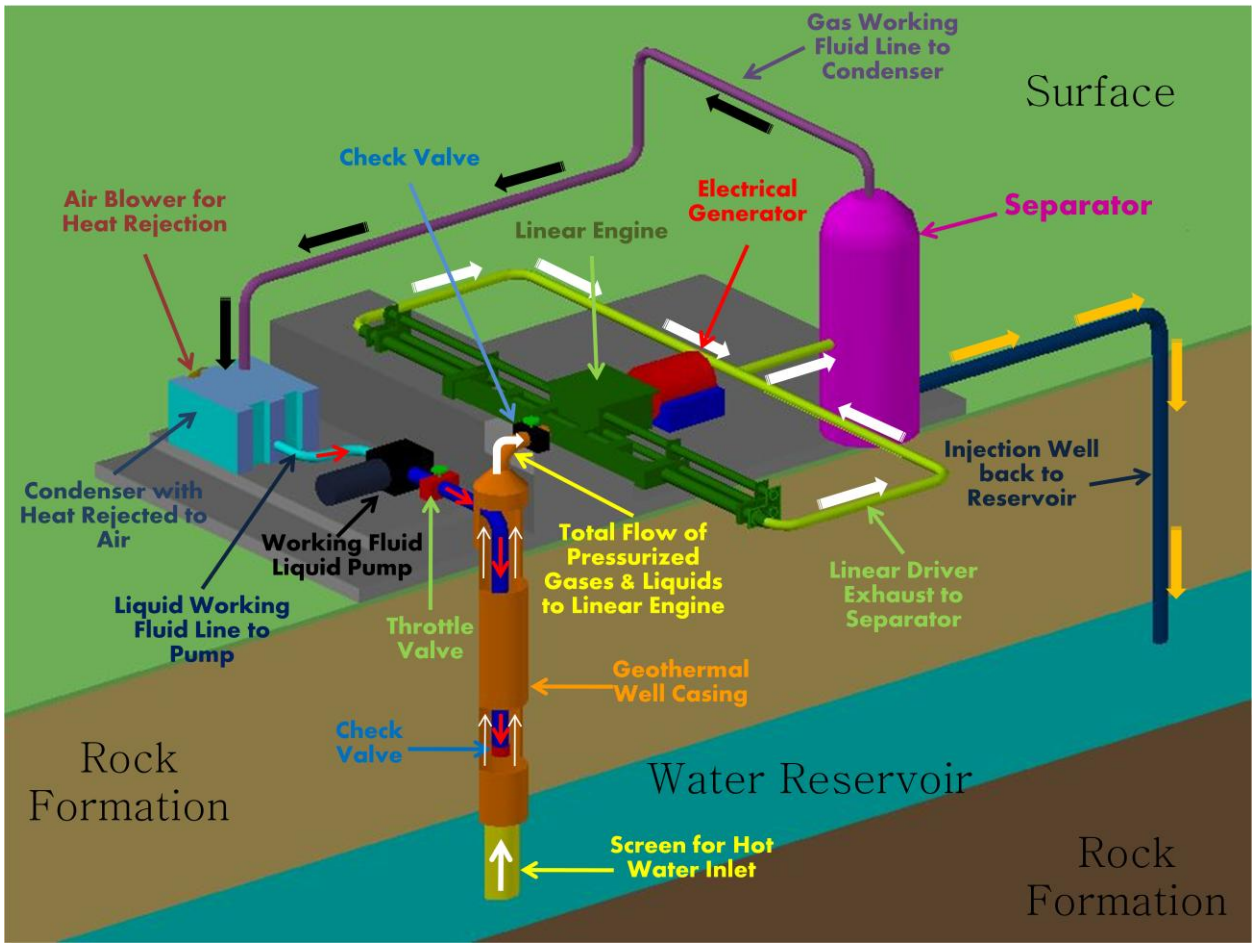

Figure 1. Represents the Linear Power, Ltd. Gas-Lift Total Flow Power Cycle Schematic

The Linear Power technology continuously injects liquid phase working fluids for a closed Total Flow Power Cycle being a Rankine power cycle whereby gaseous working fluid is cooled by heat rejection to air to the liquid phase that is then pumped back directly into the well bore to maintain a continuous flow rate; however, the flow will be greater as the working fluids used have high vapor pressure that allow them to be injected on the order of ten thousand feet into the wells for higher temperature wells, resulting in greater lightening of the water column that will induce greater flow rates via gas-lift than those expressed in the paper. This process allows

kinetic energy to be attained from wells that are not geo-pressured, as the Linear Power process creates gas-lifted induced stimulated geopressure creation.

The Linear Power modified Rankine cycle total flow concept has a number of notable exceptions, such as it is not a fully closed system as the working fluid must be separated from the produced water that may result in some loss of working fluid and the well bore acts as the hot side heat exchanger that saves on equipment costs and maintenance. And, direct heat exchange is far more efficient in the transfer of thermal energy to the working fluid; and, as the name implies, the total flow of gases and liquids drive the Linear Power free-piston linear engine.

The Total Flow Concept paper shows that more power with the lower capital costs can be gained using this concept. The simplest explanation of the process is that rather than bringing up hot water to the surface using a conventional water pump that uses power and then using surface heat exchangers that are costly and are subject to severe fouling due to the nature of the brine's corrosive properties and buildup of minerals, heat exchange is conducted in the well bore in order to boil a liquid working fluid to the gaseous phase to create gas-lift by making the water column lighter that results in the pressurized flow of liquids and gases being discharged from the well. The water is slightly cooled by the process before it comes to the surface with the heat energy being converted into high pressure gas within the well bore that acts to gas-lift the water by reducing its hydrostatic weight.

Then the total flow of high mass water and the resultant gas produced within the well bore are accelerated to high velocity through a nozzle at the surface that causes acceleration of the dual phase fluids which the free-piston engine to produce power. The water is only slightly cooled in the well bore vaporizing the working fluid to a gas; and, there is sufficient thermal energy remaining in the water to run a conventional surface thermal power cycle. The Linear Power, Ltd. gas-lift cycle generates power via kinetic energy can act as a power producing water pump for conventional geothermal power cycles in order to increase the total amount of power generated.

Figure 2. Linear Power, Ltd.'s Free-Piston Engine Being Driven by a Dual-Phase Mixture of Pressurized Gas and Water to Simulate the Effect of Gas-Lift Pumping of a Geothermal Well in order to Harness Its Kinetic Energy

Linear Power, Ltd.'s improved engine design, free-piston engine, achieves improvements to engine power density, engine weight, and to engine mechanical efficiency. In patent literature the free-piston engine is defined as an engine not having a crankshaft. The engine is capable of megawatts of power output, limited only by the pressure and volume of the input energy source. It is capable of operating on any pressure source, such as compressed air, the pressure of natural gas and or water from the earth, hydrostatic pressure from a dam to produce hydro-electric power.

In conventional engines that use a crankshaft upwards of fifty percent of the piston power is lost in converting linear motion to rotary motion due to poor vector angles applied by the cranks. In the Linear Power engine, a Sprague gear transmission converts linear motion to rotary motion while always maintaining a ninety-degree vector angle for maximum power transfer.

A great deal of attention is currently directed to the tremendous potential of free-piston engines with advantages that include: (1) the high mechanical efficiency of a piston with reduced frictional losses, (2) elimination of the heavy crankshaft that increases engine weight and friction, which also produces poor vector angles that cause inefficient power conversion of linear power to rotary motion; and, (3) elimination of the need to compress air on the upstroke of the piston with the associated power losses; and, (4) lower initial and lifetime costs and maintenance (5) flexibility to harness the power of any kinetic energy resource without the need of a heat resource, such as the kinetic energy of natural gas wells, geo-pressurized water wells, the hydrostatic pressure of water to produce conventional or run-of-the-river hydro-electric power, etc. (6) may be constructed to provide durability under high pressures and to work in harsh environments for improved operational flexibility, (7) produces a longer stroke length that increases the power output potential; and, (8) high-power-to-weight ratio provides high output

power within a small area comparable to that of turbine engines; and, (9) low noise and vibration.

The improved engine design is capable of handling the high pressure corrosive nature of the resultant dual phase mixture used by the total flow concept, which has high pressure and extreme velocity; and, is capable of expanding the gaseous phase of the two-phase flow due to the long six to ten feet stroke of the free-piston engine.

The Effect of Gravity on the Total Flow Gas-Lift Process that Generates Additional Power

The effect of gravity upon the total flow gas-lift geothermal process presented herein is modeled as a comparison of the results of an identical thermodynamic process performed on the surface as a conventional power cycle as compared to the total flow gas-lift geothermal process performed within a well bore at substantial depth within the earth. The total flow gas-lift model describes the added effect of gravity (totally aside from the thermodynamic calculations in the model) on the energy calculations in order to provide a true representation of the fluid dynamics that occur in this gas-lift process.

The model uses a column of pure water that is 10,000 feet in height and the thermodynamic side of the model allows liquid phase CO2 to be injected into the bottom of that column with sufficient temperature that the liquid will boil to a vapor. Assuming that the water column is hydrostatically balanced, it will not be over pressured or under pressured such that the water rises to the surface exactly and will not flow out from the well or fall below the surface. These conditions mean that the water column is in equilibrium. The downward force of the water's hydrostatic pressure is exactly equal to the pressure of the reservoir.

The hydrostatic pressure of the 10,000 feet high water column at its base is 4,333 psi (calculated as the weight of a cubic foot of water being 62 lbs divided by its base of 12" X 12" of 144 sq inches with a result of .4333 psi times 10,000 feet of depth, being solely derived from the weight of the water as a result of the gravitational pull of the earth) and given that the earth's opposing pressure is also 4,333 psi in order for the column to rise exactly to the surface -- thus equilibrium of the two forces of hydrostatic pressure of the weight of the water opposing the push from the earth thereby being equal.

Then if the weight of the water column is altered by either making it heavier or lighter, the status of equilibrium will be disturbed. If an additive is placed in the water to make it heavier, the water column's height will fall below surface. Basically this is what drillers do with heavy drilling mud in order to stop over-pressured water flow from a well. But if the column is made lighter, then flow will be initiated.

The model scenario assumes that the temperature is such that a high vapor pressure working fluid, such as CO2, is capable of being vaporized into a gas at the bottom hole pressure of 4,333 psi. Using the Yellig & Metcalf formula (See Figure 3.) to determine the vapor pressure of the CO2, the temperature must be greater than 410 deg. F. The effects of a flow of CO2 into the bottom of the wellbore can be modeled. Due to the high pressure at the base of the well, the gas bubbles will be relatively small but as they rise and the pressure drops they will significantly

increase in volume. Even though the initial bubbles are small in size, enough volume of working fluid is pumped to the bottom of the well that a significant amount of water volume is displaced.

The bubbles continue to grow as they rise to lower pressure and by the time the mixture of gases and water reach the surface, the gas is modeled to occupy one half of the total volume of the water column. One-half the total volume of water in the water column is displaced by vapor – less per cubic foot near the bottom with an ever increasing portion of gas per cubic foot of volume closer to the surface. If for simplicity you assume that the density of the lightweight gas is negated, the water column is only one-half as heavy as it originally was when it was all liquid.

The result of the effect of gravity is that the hydrostatic pressure at the base of the water column is only 2,166.5 psi. However since the push from the earth is unchanged it remains 4,333 psi. The net result is that a pumping action having a force of 2,166.5 psi is produced at the inlet to the well by the pressure of the reservoir, being the differential of forces after the water column's weight has been reduced by 50%. If the thermodynamic conditions were not such that the liquid working fluid could vaporize into a gas at that depth, this result could not be accomplished, but the conditions are such that it can vaporize. And as a result of the vaporization, the weight of the water column is altered and a significant and powerful gas-lift pumping force of 2,166.5 psi is created due to the effect of gravitation effect of altering the density of the mass of the water column.

The thermodynamic effect of vaporizing the liquid phase working fluid to a gas results in occurrence of the gas-lift pumping action by resulting in lowering the density of the water column by fifty percent (50%), but does not directly power the gas-lift pumping process. Because the temperature of the water is only slightly changed by the vaporization gas-lift process, it only takes away a small amount of the thermal power generation potential via the use of a conventional geothermal power cycle. The pumping force is powered by the gravitational effect solely and is separate and apart from the thermodynamic effect and it stands on its own.

The gravitational effect and the thermodynamic process each stand on its own. This gravitational effect is a separate side effect of the thermodynamic process and totally independent from the thermodynamic process. It just occurs because the process that takes place changes the density of the water column and the gravitational effect itself is the result of the change in the gravitational pull of the column of water that is thereby reduced due to its decrease in density – yet the opposing push from the earth is unchanged by the process.

In regard to the energy to pump the working fluid to depth into the well that is a common concern of the gas-lift process, the input power does not change to a substantial degree from that of a conventional Rankine cycle performed on the surface. The liquid phase working fluid must be pumped into the pressurized boiler in a conventional ORC. In the model the boiler is at the same temperature as the bottom of the well of 410 deg. F. Therefore, the vapor pressure within the boiler is also 4,333 psi, being equivalent to the hydrostatic pressure at the bottom of the well. In fact it may take less effort to pump the liquid to the bottom of the well as compared to pumping it into the boiler as the working fluid has a positive hydrostatic pressure and the line running to the bottom of the well is 10,000 of height so almost half of the pumping pressure is

produced by the weight (hydrostatic pressure) of the working fluid (liquid CO2 being about half the weight of water) taking into consideration frictional losses and other factors.

The total flow concept that can gas-lift a pressurized flow of water and gases from geothermal wells or oil and gas wells that do not have geopressure opens the potential for a much larger number of wells to produce power via their kinetic energy.

Any high vapor pressure working fluid will perform adequately and most of the best working fluids are already produced by oil and gas wells. Working fluids with higher vapor pressure produce more power because they have greater capability to overcome the hydrostatic pressure of the water at greater depth and thereby more gas-lift pumping of the well is created. Carbon dioxide gas has the highest vapor pressure of all of vapors, Ethane is next and Propane is also adequate. All of these fluids are readily liquefied at the surface which is necessary to perform the Organic Rankine cycle. Then in a closed loop, the liquid phase working fluid is pumped back deep into the well-bore.

Table 1 below represents the results produced by a Calculator prepared by Dr. Michaelides. In the table he refers to the effect of gravity on the gas-lift process as "pressure power".

Water Flow (gal/min)	CO_2 Flow (gal/min)	Well Depth (feet)	a. Pressure Power (kW)	b. Thermal Power (kW)	c. Total Power (kW)
1500	150	10000	1148	1364	2513
1500	300	10000	2239	1120	3359
1200	120	10000	926	1082	2013
1200	240	10000	1780	890	2690
1000	100	12000	809	1591	2400
1000	200	12000	1560	1396	2957

Table 1. Selection of Results Produced by Dr. Michaelides Calculator

Michaelides' written notes regarding the Calculator from his Report: The output of the calculator is the maximum power (in kilowatts) that may be produced from the well flow by an ideal thermal or pressure engine. In the following Table, I have listed a few examples of such calculations with carbon dioxide as the injected fluid. The geothermal gradient in all the calculations is 1.6 deg. F. per one hundred feet and the maximum power that may be produced is given as: (a) power from the pressure of the fluid alone; (b) power from the temperature difference; and (c) total maximum power, which is the sum of (a) and (b). Each set of data is illustrative of the maximum potential of geothermal wells with injected fluids to produce power.

Correlation of the Relationship between Temperature, Well Depth, and Selection of Working Fluid

The effect of gravity on the gas-lift pumping process for a geothermal well is the generation of gravity induced pumping force herein termed "pressure power" that is created as a result of making the water column lighter by displacing high mass liquid water with low mass vapor. The force is depth dependent and increases in a straight line with depth. For example, assume a first geothermal well in which the water rises exactly to the surface being in equilibrium with the reservoir pressure having temperature of 300 deg. F., and the well is 1,000 feet deep, and liquid phase CO2 working fluid is injected to the bottom of the well and is boiled to vapor displacing one-half of the liquid water volume, then the resultant gravity induced pumping pressure power is 216.5 pounds per square inch. The pressure power is the force of the reservoir that is unchanged by the gas-lift process, which reduces the hydrostatic weight of the water and a differential of pressure is created between the hydrostatic pressure of the water and the pressure of the reservoir that results in a pressurized positive flow of water from the well.

Now assume a second geothermal well in which the water rises exactly to the surface being in equilibrium with the reservoir pressure having temperature of 300 deg. F., and the well is 8,000 feet deep, and CO2 liquid-phase working fluid is injected to the bottom of the well and is boiled to vapor displacing one-half of the liquid water volume, then the resultant gravity induced pumping pressure power is an extremely powerful 1,830 psi. Over eight times more pumping pressure power is produced by the deeper well.

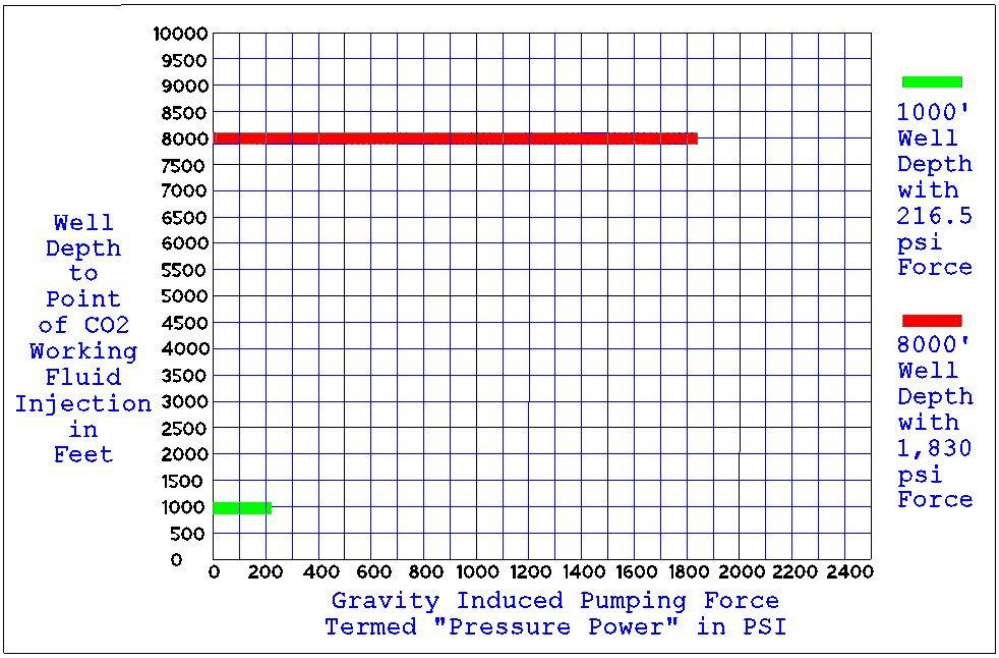

Table 2. Results of Comparison of "Pressure Power" of Two Wells having Identical Temperature of 300 deg. F. with Varying Depths of CO2 Working Fluid Injection

The vapor pressure of working fluids can vary considerably. Carbon dioxide has the highest vapor pressure of the available working fluids currently available. In the example wells above, a number of working fluids would produce vapor at the stated temperature of 300 deg. F. with sufficient vapor pressure to overcome the hydrostatic pressure of the water column of well one of only 433.3 psi in order to displace high mass water with low mass gases. However, the second well is much deeper being 8,000 feet deep and thereby has a much greater hydrostatic pressure at the bottom of the well that must be overcome by the vapor pressure of the working fluid and the available working fluids that can reach the bottom of the well are very limited. In fact only CO2 is known to have sufficient vapor pressure to displace water at the bottom of the well.

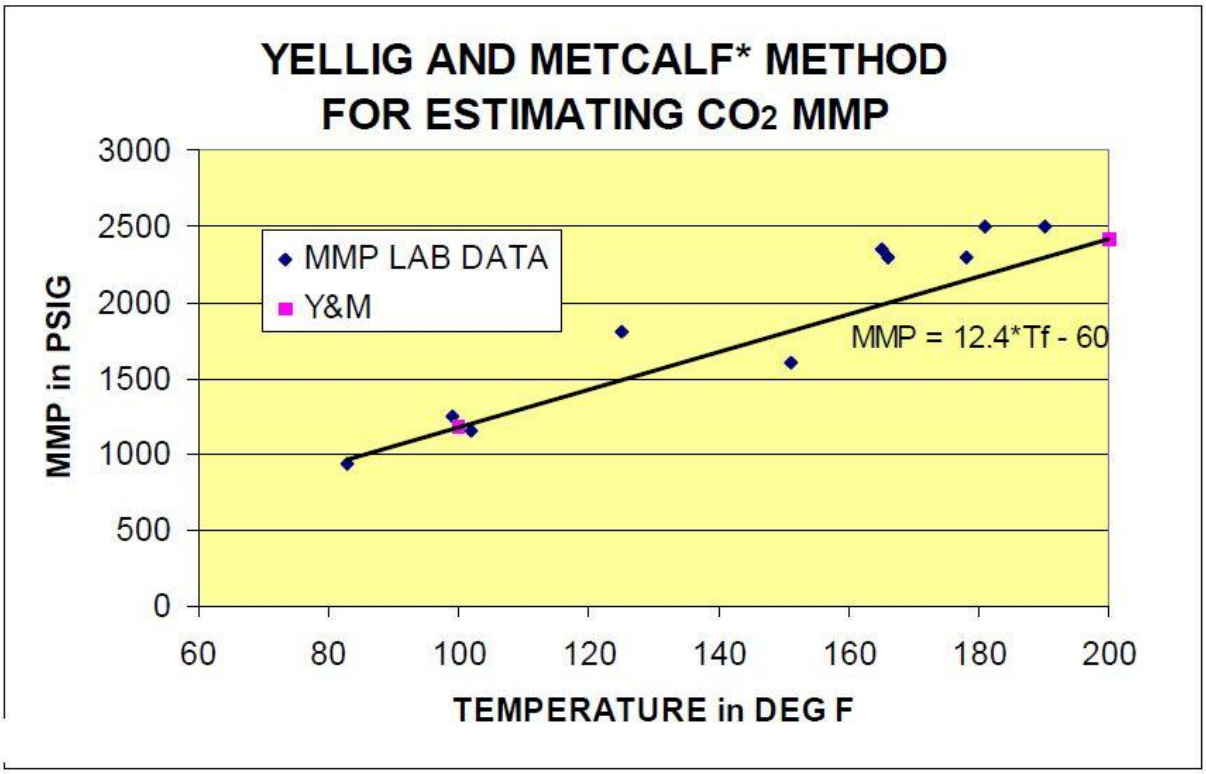

Figure 3. Yellig and Metcalf Method of Calculation of Carbon Dioxide's Temperature / Vapor Pressure Regime

Using the Yellig and Metcalf vapor pressure estimate method, 300 deg. F. multiplied by 12.4 equals 3,720 less 60 equals 3,660 psi vapor pressure at 300 deg. F. The hydrostatic pressure of water is .4333 psi per foot. Each psi of pressure can extend 2.3 feet of depth into a column of pure water; thereby, vapor having a pressure of 3,660 psi can displace water to a depth of approximately 8,452 feet deep into the water column within a well bore at the stated conditions. Other factors such as friction losses, effect of well casing sizing, effect of temperature gradients, weight of the vapor, etc. have been ignored for simplicity in the above comparison of the two

wells. The amount of pressure power that can be produced by the technology is thereby significantly depth dependent and the technology favors the use of wells having substantial depth and with sufficient temperature to vaporize the working fluid to a high vapor pressure gas deep within these wells.

Summary

The result of the evaluation of the effect of gravity on Linear Power, Ltd.'s proprietary gas-lift total flow concept that harnesses the kinetic energy of a flow of pressurized liquids and gases clearly indicates that more power can be gained using the Total Flow Concept in association with gas-lift technology than from any other possible geothermal means that are currently available.

The Linear Power, Ltd. gas-lift cycle that generates power via kinetic energy acts as a kinetic energy power producing thermal cycle water pump for conventional geothermal power cycles and the device increases the total amount of power generated. Typically, the water is only slightly cooled in the well bore vaporizing the working fluid to a gas; and, there is sufficient thermal energy remaining in the water to run a conventional surface thermal power cycle. The net result is that the total flow gas-lift process adds kinetic energy generated power to the cycle and beneficially pumps hot water from the geothermal well. The results show that more power is generated by the gas-lift process within the well than if the thermodynamic process is performed only on the surface; and, it is shown that the positive effects of gravity provide additional pressure power to the gas-lift process that increases its power output by the sub gravitational effect of lightening the water column.

High mass water is displaced with low mass gases and the density of the water column is lowered. Additional power is gained as a result of the change in density of the column of water by the process that lowers its gravitation pull. The force of the pressure at the base of the well exerted by the reservoir is in opposition to the weight of the water. Lowering the water's density (weight) while the earth's force is unchanged produces an improved water pumping force powered by gravity termed "pressure power". This gravitational effect is a separate side effect of the thermodynamic process and totally independent from the thermodynamic process, although the result could not occur absent of the thermodynamic process.

Additional power is gained as a result of the "effect of gravity" on the gas-lift cycle that creates pressure power. Engineering produced by Dr. Michaelides proves that the gas-lift total process described herein typically generates more than double the amount of power output from the same geothermal heat resource than any other known geothermal power cycle.

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Stathis Michaelides, Ph.D., P.E., Professor and Chair, Mechanical Engineering University of Texas at San Antonio, Texas written report concerning verification of the accuracy of mathematics within the Total Flow Concept Paper cited above; and, the preparation for Linear Power, Ltd. of an interactive spreadsheet Calculator that models the effects of gravity on the Modified ORC Total Flow Concept Geothermal Power Cycle described herein.

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The Author would like to thank Dr. Stathis Michaelides for his assistance in preparing the Calculator used to determine the power generated by the thermal cycle and by the effect of gravity (pressure power) on the gas-lift total flow power cycle.

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