Geothermal Resources Council *Transactions*, Vol. 21, September/October 1997

Geothermal Energy From Hot Salt Domes

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ABSTRACT

Numerous salt domes are sufficiently hot to provide geothermal energy. This paper describes how existing technology can be used to drill wells into hot salt and transport the heat to the surface for use in direct geothermal application or to generate electricity. This heat source, like other geothermal sources, can provide a clean, renewable energy. This paper also describes how these hot salt geothermal wells will differ from other geothermal technology, such as hot water wells and dry hot rock wells. The hot salt energy technology described includes insulating gas blankets between tubing and casing strings that allow a superheated fluid to retain its bottom hole temperature while being circulated to the surface. The hot fluid can then be used for direct heating or to generate electricity. Deep hot salt wells, from seven to twelve thousand feet, can be reliably drilled and operated with today's technology.

Introduction

Existing oil field technology can be used to drill wells into hot salt formations, to extract the heat from these formations and make it available for direct use or to generate electricity. The thermal gradient observed in most salt domes is 1.5 to 2.7°F per 100 feet of depth or 25 to 50°C per km. By drilling wells to 12,000 feet (or 4 km) salt temperatures of 345-400°F (or 127-227°C) can be reached. The hotter of these wells can provide 275°F of useable temperature difference. The heat available per well will depend on the geometry of the salt cavern that is leached when the well is drilled. Each salt cavern will be a closed system that can be used to superheat a fluid. At the surface this fluid can be used in a heat exchanger to heat another fluid or it can be used for direct heat or electric generation.

This paper describes methods developed to drill and complete geothermal wells in salt domes and presents some of the trade-offs that will be made at each well. Several of these methods have been patented (5,370,182-1994) by the authors for the successful extraction of heat from deep salt wells.

Geothermal Technology

Most geothermal projects use water or steam directly; however, to generate electric power usually requires heat exchangers to transfer the geothermal heat to a fluid that can flash and drive a turbine. These heat exchangers are a source of heat loss in a process that strives toward thermal efficiencies of 10 to 20%. A hot salt well can be a single fluid geothermal system that will not have the expense or heat loss of a binary fluid system. A salt well is a closed system; all the fluid that is circulated through the well returns to the surface where the heat can be used before the fluid is returned to the well. The single fluid used in a hot salt well must not dissolve or react with salt or brine. For example, propane or isobutane can be circulated through a hot salt well and used directly in a turbine to generate electricity. After the generation and cooling process the propane or isobutane is returned to the well to be heated again.

Temperature Gradients of Salt Domes

Salt domes that are still connected to a deeper salt layer, such as along the Gulf of Mexico, exhibit temperature anomalies higher than surrounding formations. A brine well on the Clay Creek dome in Washington County, Texas has an actual recorded temperature of 160°F at 3,800 ft. The gradient is 2.4°F per 100 feet of depth (160-70{ambient}=90/38). Present data suggests the stalk of the dome transports heat from great depths, creating an elevated temperature gradient in the upper reaches of the dome (above 12,000 ft.) and a depressed (or at least not elevated) temperature gradient in the lower part of the dome. The temperature gradient in and around salt domes could be viewed three different ways; 1) the clearly elevated gradient from the surface to the upper portion of the dome; 2) the flatter gradient within the dome itself; 3) the horizontal gradient wherein the core of the dome exhibits temperatures higher than the periphery. Ground water, faults, dome size, geopressures and other factors will affect individual dome temperatures.

Drilling and Completion

The search for hydrocarbons under the overhang of salt domes and beneath bedded salt has led to the successful development of methods to drill and complete wells through long, deep salt intervals. Oil based, heated brine, or under-saturated brine drilling fluids are normally used. A gauge hole is preferred to assure the proper cementing of casing strings. Recent developments in a Jet Leacher drilling system has reduced the drilling time and cost of completing deep wells in salt. The cost of drilling and completing a salt well is much less than drilling and hydro-fracturing required in hot dry rock goethermal wells. J.W.Barker, "Drilling Long Salt Sections Along the U.S. Gulf Coast," SPE Drilling and Completion, 1994, describes drilling in salt and K.G. Pierce, "An Estimate of the cost of Electricity Production from Hot-Dry Rock," GRC *Bulletin*, September 1993, describes the cost of drilling and fracturing hot dry rock.

A hot salt geothermal well will be drilled and cased to a depth where the salt temperature is sufficient. Two strings of tubing are placed in the single well system (side-by-side or concentrically) or a single tubing per well in the dual well design. High pressure nitrogen gas is then injected between tubing strings or between the tubing and casing of the wells to insulate the hot fluid on its journey to the surface.

Nitrogen at 3,000 psi and 300°F has a thermal conductivity, k = .035 Btu/h.ft.R, (Ahlberg, *AGA Gas Handbook*) and is not a very good insulator. Table 1 illustrates the heat that can be lost through conductivity. Natural convection and radiation will increase this loss. In this example the casing size is 8 inches, the liner 5 inches and the tubing 2.5 inches. A dual well configuration, one injection well and one heat extraction well, will reduce the heat loss by increasing the distance between the tubing and the casing. The rows labeled dual well in Table 1 are two well configurations. Also the heat loss will decrease as the rock behind the casing heats over time. The experiance at Fenton Hill Dry Hot rock well is that this heating takes several months. The 2.5 in the liner column is a two-string configuration. One string for cool fluid into the well and one string for hot fluid exiting the well. The flow is 112 gallons per minute of oil at 6.6 lbm/gal and Cp=.6. The bottom temperature is the temperature of the fluid before it starts up the tubing, and the top temperature is the fluid as it exits from the well. The Top Temp + 50% column is the heat loss after the casing heats up by 50%.

The fluid between the tubing and the casing is forced out into the cavern. Figure 1 illustrates the basic hot salt well design. The hot fluid production pipe will be equipped with low-heat conducting centralizers to reduce heat loss through contact with the cool fluid injection pipe or well casing. Such centralizers are commonly used in oil wells to electrically isolate tubing strings. Other gases may be used for insulation, but nitrogen is inexpensive, readily available, dry, and will not support oxidation. To prevent the absorption of the nitrogen into the brine that remains in the cavern, a blanket of oil may be injected into the well, forming a floating barrier between the nitrogen/brine interface.

Table 1. Heat Loss in Geothermal Salt Well

Liner	Tubing	Bottom Temp. °F	Top Temp °F	Top Temp °F +50%
5 liner	2.5	400	331	364
5	2.5	300	252	278
2.5 tubing	2.5	300	255	279
8 dual well	2.5	400	377	388
8 dual well	2.5	300	284	293

Casing and tubing sizes will be dictated by good engineering practices. Once a temperature gradient is known (or at least estimated), then the proposed well depth will be known. Sizing the casings and tubing will then be decided based on the following:

1. Surface casing requirements: usually required by the well permitting agency to protect fresh water zones;
2. Depth and formations between ground surface and salt: one string of casing between the surface casing and total depth would save drilling cost, but problem formations, voids in the caprock, and casing strength (tensile, collapse, and burst) may prohibit a single string;
3. Liquid circulation rates; size the tubing to minimize friction pressure losses;
4. Insulating gas pressure requirements: the necessary gas pressure is a product of overall well depth, the depth to which insulation is necessary, and the friction pressure losses of the returning fluid. For a 10,000 ft. well, the insulation gas pressure would vary between 2,000 and 4,600 psig, depending on insulation requirements. These pressures may seem ex-

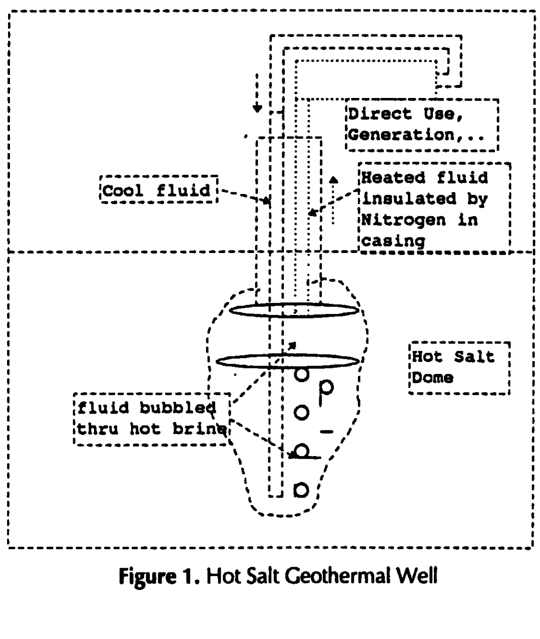

Figure 1. Hot Salt Geothermal Well

traordinarily high, but are common and ordinary in oil and gas production.

A single well system will require more pressure to insulate the cool injection fluid from the hot returning fluid at a deep, near cavern level. In a two-well system the production pipe will only need to be insulated from the cooler, shallower overburden, thus requiring less nitrogen gas pressure. Water bearing formations will become heat sinks, and must be insulated behind the gas blanket.

Heat Available in a Salt Cavern

Salt domes come in a wide range of shapes and sizes. They are several miles across and several miles deep. A single dome containing a cubic mile of salt between 10,000 and 15,000 feet deep can theoretically contain 1.4 billion dollars worth of useful heat. Cooling the salt from 370°F to 200°F provides 7E+15 Btus of heat. This is the equivalent heat of 7E+9 mcf (million cubic feet) of natural gas which sells at current price ($2/mcf) 14 billion dollars. However, the latest gas turbine generator can achieve an efficiency of over 50% compared to only 10-20% possible with the lower temperature geothermal energy.

The heat flow from the salt into a cylinder shaped salt cavern can be estimated as follows:

$$Q = (L*k*\Pi*(Tc-Ts))/ \ln(rs/rc)$$

where:

Q is heat flow in BTUs per hour

L is the length of the cavern in feet

K is the thermal conductivity of salt (varies from 3.0 BTU/hr*ft2*F at 200°F to 2.2 at 400°F.)

Π is 3.1416

Tc is the temperature of the fluid

Ts is the temperature of the salt

rs is the radius of the cool salt around the cavern

rc is the radius of the cavern full of fluid

These variables are not independent. The greater the flow the lower the cavern temperature and the greater the heat flow, and the faster the 'cool' front around the cavern *(rs)* also grows. The 'cool' salt around the cavern appears to be the limiting factor in this heat flow calculation. On the plus side, the lower the temperature of the salt around the cavern, the greater its thermal conductivity *(k)*.

Our experience with salt wells indicates that periodic maintenance can provide steady heat flow and indefinite well life. Circulating water to remove some cool salt each year or two will keep the well open (see creep closure discussion below) and will help keep the well's heat flow constant. Our initial estimate of heat available from a cavern are included in Table 2, Heat from Hot Salt Wells. Millions of Btus per hour .vs. years of production are included for 2000, 3000 and 4000 ft tall caverns.

Table 2. Heat Available from Hot Salt Well
(Million Btus per Hour)
Production years
.vs.
Cavern hight and temperature delta

Years	2000/ 100°F	2000/ 200°F	3000/ 100°F	3000/ 200°F	4000/ 100°F	4000/ 200°F
1	1.8	3.9	2.5	5.8	3.3	7.8
2	1.6	3.4	2.2	5.1	2.9	6.8
4	1.5	3.1	2.1	4.6	2.7	6.1
8	1.4	2.9	2.0	4.3	2.5	5.7
16	1.4	2.7	1.9	4.1	2.5	5.5
32	1.3	2.7	1.9	4.0	2.4	5.3

Note that the temperature difference between the hot salt and the cavern liquid is the largest contributor to heat flow, and that after four years of production the heat flow gets flat. There is not significant reduction in heat flow at 8, 16 and 32 years due to the geometric increase cool area as it moves through the salt.

Creep Closure

Hydrostatic pressure from the liquid (.5 psi/ft for brine) is less than the lithostatic overburden pressure (1 psi/ft); consequently a 10,000 foot deep cavern could have a pressure imbalance of 5,000 psi. A salt cavern will close at a rate exponential to the pressure imbalance. The rate of closure is described in Sandia Report SAND85-0830, by James Todd. To keep a deep salt cavern open additional pressure must be used and occasionally additional salt must be mined from the well. The cost of this additional pressure will be heavier pipes and pumps and parasitic energy cost. Equipment that can operate at 5000 psi pressure is readily available today in the oil field. Additional energy will be required to pressurize the liquid entering the well, and some of this energy can be reclaimed with the liquid as it leaves the well. Additional energy will also be used to periodically remove additional salt from the well. No workover rig is required because water is circulated in the bottom of the cavern in the existing tubing and brine is removed from the top. Cavern leaching requires eight bbls of water to wash a single bbl of salt cavern and in our experience, the energy cost is approximately one dollar per bbl of cavern. The cost to remove 10,000 cubic ft. of salt would be 10,000 /5.61 ft3/bbl = $1,800 per well per year. In many locations this salt can be sold for $1 per bbl to offset the leaching cost. An additional cost is the downtime of the well due to the leaching operation. This down time can be several weeks.

Cost of a Well

Drilling and completing the first geothermal salt well on a salt dome should cost between $ 1,000,000 and $ 1,500,000. Subsequent wells will cost less, $ 700,000 to $ 1,000,000. The wide range of variables that affect drilling costs (depth, location, permitting, overburden, lost circulation, caprock thickness, hole size, casing program, etc.) cannot be addressed in a paper of this scope. Site specific cost estimates can be reliably calculated by experienced engineers familiar with drilling in salt. Maintenence cost will depend on the creep closure rate, but could be $1,800 per well per year.

Cost of Electric Generation

Two basic designs are available for electric generation from hot salt wells; a binary design that circulates one fluid in the well and generates electricity with another fluid; and, a single fluid design that circulates through the salt cavern and generates electricity with a single fluid. The cost estimates here are the more conservative, binary electric generation. Additional engineering work is required to estimate the efficiency and cost of a single fluid generation plant. The plant cost and efficiencies used in this binary design are from K.G. Pierce, "An Extimate for the Cost of Electricity Production for Hot-Dry Rock".

Estmates for the binary example include the following: 1) 11 hot salt wells with cavern height of 12,000 to 15,000 ft and a cavern diameter of 6 feet; 2) an oil working fluid with Cp=.6 and 6.6 lbm/gal; 3) a 2 MW binary generation plant.

The salt dome is 500°F and the cavern temperature is maintained at 300°F. This will produce 5.8 Million Btus/hr or 1.7 MW of heat (see Table 2). A flow rate of 113 gpm will maintain the 300°F cavern temperature the first year and the flow rate can be decreased to keep a 300°F temperature over time. By the thirty-second year the flow rate will be 77 gpm. The heat loss of the oil on the way to the surface should be less than 10% (see Table 1) with an 8 inch casing and 2.5 inch tubing. This results in 1.5 MW of heat per well at the end of the first year; therefore, only eight wells will be required initially to provide 12 MW of heat. Using 17% efficiency for the binary plant will produce 2 MW of electricity. A 90% plant availability results in an operation and maintenance of 2.7¢/kW.hr for both the well field and plant. Table 3 summarizes the plant and well cost and the operation and maintenance cost. Many geothermal plants operate well above 90% availability and the number of salt wells results in high field availability. By the end of the second year the ninth well will be required and after four years the tenth well. The eleventh well will provide availability and additional heat past eight years. Each salt well will be out of service several weeks a year for cavern washing and maintenance.

Table 3. Cost Example for a Binary Hot Salt Electric Generation Plant (2MW)

Capital Cost		O&M	
2MW Plant	$ 3.0M	Plant $.3M/yr	1.9¢/kW.hr
11 Salt Wells	$ 9.2M	Wells $.120/yr	.8¢/kW.hr
Water wells	$ 0.2M	($1800/well/yr+$100k)	
Dosposal well	$ 0.1M	Total $.420/yr	2.7¢/kW.hr
Total $12.5M	($6,250	/kW Installed)	

The salt well maintenance estimate is $1,800 per well per year plus $100,000 for well field maintenance. The $1,800 is to maintain the cavern by leaching out 10,000 cubic feet of salt each year. The $300,000 plant maintenance assumes a highly automated geothermal plant that does not require an operator 24 hours per day.

The capital recovery cost for a hot salt electic generation plant is included in Table 4.

Table 4. Capital Recovery for $12.5M over 30 years.

Discount Rate	$/yr	¢/kWhr
4.6%	.82M/yr	5.2 ¢/kWhr
10%	1.4 M/yr	8.8 ¢/kWhr
15%	2.0 M/yr	12.7 ¢/kWhr

Conclusions

Deep wells are expensive. Hot salt wells are much less expensive than hot-dry rock wells, but many more hot salt wells are required to provide sufficient heat to generate electricity over 30 years. The engineering estimates presented in this paper are conservative estimates based on current technology. There are several areas of study that could reduce the cost estimates and increase the heat available from hot salt well models. A single fluid design looks like the most promising to increase overall efficiency and a dual salt well design is a good candidate to increase the heat available from hot salt wells. The temperature, depth and location of hot salt domes are the most important factors in well cost and efficiency.

Areas for Further Study

A. Fluid selection for hot salt wells. The fluid cannot dissolve or react with salt, should be as heavy as possible to maintain hydrostatic pressure and have good thermodynamic properties in the 70 to 400 degree F range and from 50 to 5000 psi.

B. Survey of the thermal properties of salt domes along the Gulf of Mexico.

C. Downhole engineering study to provide more detailed drilling, finishing and well maintenance processes.

D. Comparison of drilling cost of salt wells to other geothermal wells.

E. Above ground engineering study to develop cost estimates for a standard electric generator that could be used with each group of geothermal wells.

F. Prototype well and geothermal installation.

Acknowledgments

The authors deepest gratitude to James Linn, Sandia Labs, and all the others whose studies and labors we have used. A special thanks to our mentor and father, A. L. Hickerson, Founder of Permian Brine Sales.

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