PROCEEDINGS, Thirtieth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31-February 2, 2005
SGP-TR-176

A REEVALUATION OF GEOPRESSURED-GEOTHERMAL AQUIFERS AS AN ENERGY SOURCE

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ABSTRACT

The search for more efficient and economical forms of energy is a continual process. Natural gas production and electricity generation from geopressured-geothermal aquifers is an unconventional hydrocarbon source that has long been unproductive due to its economic constraints and lack of technical certainty. Given current economic constraints and considering the application of modern potential technologies, geopressured-geothermal energy maintains a potential future as an alternative domestic energy source. This paper presents a range of conditions where the production of geopressured-geothermal aquifers offers an economically viable solution.

INTRODUCTION

During the energy crisis of the 1970's, the United States began to explore for potentially significant amounts of hydrocarbons stored in unconventional resources. Oil shales, oil sands, methane hydrates, coalbed-methane and geothermal-geopressured aquifers were given research priority due to large quantities of potentially recoverable energy. Industry and governmental financial support were given to projects that evaluated the economic viability and level of technological competency required to develop these unconventional sources of oil and natural gas. Due to government deregulation of the natural gas market and the ensuing price collapse, the economic incentive to commercially develop most unconventional sources of natural gas was not present. The commercial development of geothermal-geopressured aquifers was considered marginally economic in only special circumstances and considered a long-term alternative hydrocarbon source.

Once again, the United States is poised to enter an energy crisis. The oil and natural gas price crash of the 1980's, and the lack of energy value price parity between oil and natural gas, has motivated many power generation, industrial, residential and municipal users to transition to natural gas as a primary energy and heating source during the past 15 years. The International Energy Administration (IEA) forecasts that this trend will continue and that world natural gas demand will increase by over 100% or 30 Tcfy by the year 2030 (Oil & Gas Journal, December 1, 2003). This transition and the forecasted increase in demand places a greater burden on the ability of energy companies to meet the world market demand of natural gas. As supply tightens, natural gas imports to the U.S. have risen, and plans to reactivate or build liquefied natural gas (LNG) trains at several U.S. ports have been announced.

To meet the forecasted increase in domestic U.S. and world energy demand, the IEA stated that global spending on hydrocarbon exploration and production must exceed $5.3 trillion dollars by 2030. Resources are again being dedicated to develop alternative domestic energy sources. Research currently focuses on economic methods to produce oil sands and oil shales, and the U.S. Department of Energy (DOE) has announced plans to fund a ten-year clean coal technology (coal gasification) pilot program (Department of Energy briefing, February 27, 2003).

Attention may return to geopressured-geothermal aquifers as an unconventional hydrocarbon resource. But, continued research should be justified by demonstrating that there is potential for sustainable, economic production of geopressured brines. The geopressured-geothermal resource base for the northern Gulf of Mexico could exceed 1,000 TCF of recoverable natural gas (Wrighton, 1981). This resource base is not insignificant; in 1995 the United State Geological Survey estimated that U.S. technically recoverable volumes of conventional and unconventional gas, excluding geopressured brines and clathrate structure-gas hydrates, was 1,073 Tcf (Petzet, 1995).

New technologies may allow more efficient extraction of methane and thermal energy from the geopressured brine. The use of binary-cycle power plants may improve thermal recovery efficiencies to economically sustainable levels. The injection of paraffinic hydrocarbons into the produced fluid stream could improve methane recovery efficiencies while reducing the amount of surface equipment necessary for handling geopressured brines.

This paper presents a historical overview of research into geopressured-geothermal aquifers, discusses the range of reservoir properties encountered during experimental field developments, and discusses a range of economic and physical constraints that may enable the sustainable, economic development of geopressured-geothermal aquifers as an energy source.

BACKGROUND

Estimating the Geopressured Resource

Geopressured-geothermal aquifers are a subset of geopressured reservoirs. As a potential resource, energy contained in the geopressured-geothermal aquifer takes three forms: mechanical energy as excess pressure at the wellhead, thermal energy, and methane dissolved in the aquifer pore water. Geopressured aquifers are commonly defined to have a pore pressure in excess of 0.675psi/ft (13.0ppg) and a geothermal gradient of 1.8°F/100ft or higher. Total aquifer bulk volumes can be in excess of 3 cubic miles, but individual reservoirs may be smaller (Bassiouni, 1980). Fig. 1 presents the geographic range of the geopressured zone in the northern Gulf of Mexico (Bebout, 1981). Fig. 2 shows the major depocenters during the Upper Cretaceous and Tertiary along the northern Gulf of Mexico (Bebout, 1981).

Estimates of the amount of geopressured-geothermal energy available in the northern Gulf of Mexico vary widely. Papadopulos et al (1975) estimated the resource total for onshore Texas and Louisiana to be 46,000EJ [1 EJ ≅ 1.04 Tcf] of thermal energy, 25,000EJ of methane, and 2,300EJ of mechanical energy. Based on the occurrence of geopressured aquifers in the studied area, offshore and other onshore sediments not included in the study were estimated to be 1.5 to 2.5 times the amount estimated in the study. Papadopulos also estimated absolute recovery efficiencies to be between 0.5% and 3.5% of the resource in place (Wallace, 1979). Jones (1976) estimated the total methane content to be 49,000Tcf, of which 17,000Tcf was offshore. He estimated that between 246 to 1,145Tcf of methane could be recovered. Brown (1976) went on to state that recovery efficiency "probably lies in the range of 4 to 50% of the methane within reservoirs which are eventually developed." Hise (1976) estimated the total in place methane to be only 3000Tcf; and that perhaps 28Tcf of natural gas could be recovered

Bassiouni (1980) published a report that ranked the sixty-three most promising geopressured-geothermal prospects in the state of Louisiana according to estimates of the total recoverable energy available in each prospect. The report detailed reservoir properties of the six highest ranking prospects and the Tuscaloosa trend; recommending three of these prospects, Grand Lake, Lake Theriot and Bayou Hebert, as suitable test sites. The Table 1 presents a summary of aquifer properties for the six highest-ranking prospects.

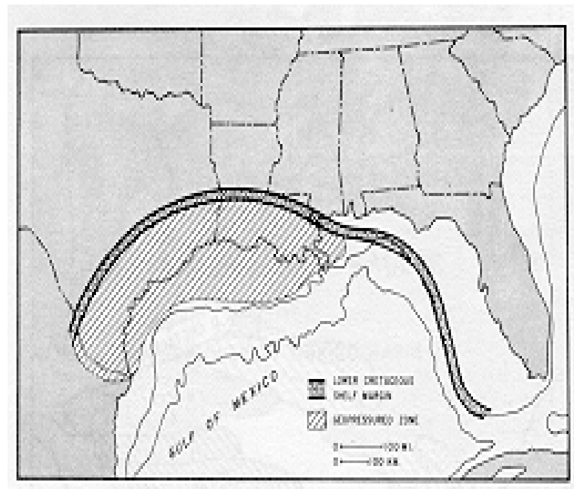

Fig.1. Range of occurrence of geopressure in the Northern Gulf of Mexico Basin. (Bebout, 1981). (Note: not to scale).

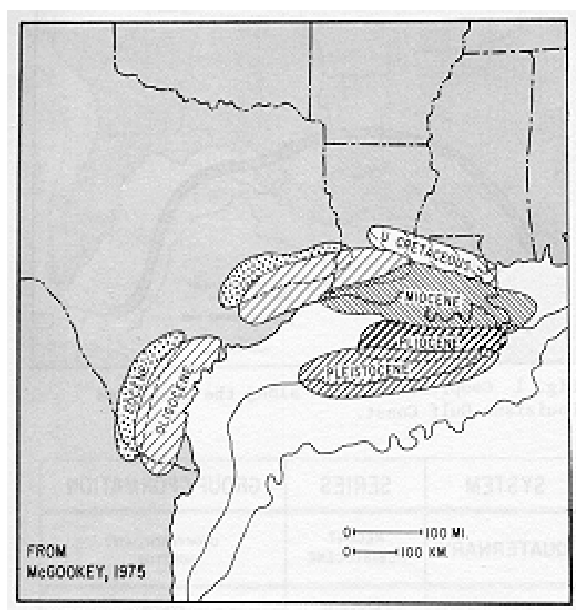

Fig. 2. Major depocenters during the Upper Cretaceous and Tertiary along the northern Gulf of Mexico. (Bebout, 1981). (Not: not to scale).

Prospect	Physio-graphy	Top of Geo-pressure (ft.)	Bulk Rock Volume (ft^3 x 10^9)	k (md)	ϕ (%)	In-Place Water (bbl x 10^9)	Avg. Pressure (psia)	Avg. Temp. (°F)	Avg. Water Salinity (ppm)	Gas Solub. (scf/bbl)	In-Place Dissolved Gas (Tcf)
Grand Lake	Marsh	13,600	657	21	18	21	12,600	240	100,000	28	0.6
Lake Theriot	Marsh	12,600	1,738	103	28	87	11,620	232	46,000	32	2.8
Bayou Hebert	Dry Land/ Marsh	13,000	543	45	16	15	11,600	230	87,000	26	0.4
Kaplan	Dry Land	12,000	312	273	23	13	12,770	259	57,000	37	0.5
South White Lake	Marsh	14,900	211	68	12	4	16,200	281	150,000	23	0.1
Solitude Point	Dry Land	19,000	1,914	5	9	30	15,000	328	60,000	58	1.7

Table 1. Louisiana geopressured aquifers. (Bassiouni, 1981).

Industry Experience with Geopressured Aquifers

In 1972 the National Science Foundation sponsored the Geothermal Resources Research Conference, which brought together scientists, engineers and environmentalists to discuss emerging geothermal technologies. In 1973, the conference report was published and geopressured water was recognized "as a significant and special type of geothermal energy, having in addition to thermal energy, natural gas and geohydraulic energy (Hickel, 1973; Hawkins)."

McMullan and Bassiouni (1981), recognizing that maximizing flowrate maximized NPV, presented an equation to predict brine flowrate given a constant tubing head pressure. Additionally, the results of the study showed that the location of the well in respect to the aquifer was relatively unimportant compared to the effect of tubing size, skin, and initial aquifer properties.

Isokari (1976) described a two-phase, two-dimensional reservoir simulation program for the modeling of a geopressured-geothermal aquifer. Knapp et al. (1977) included the effect of shale de-watering in the numerical simulation of geopressured aquifers. The results of the simulation's sensitivity analysis found that water influx from underlying and inter-bedded shales would play a more important role in aquifer pressure maintenance than water influx from laterally adjacent shales. They also found the depletion of geothermal geopressured aquifers can be approximated as an isothermal process. Doscher et al. (1979) found critical gas saturation to be an important parameter controlling ultimate recovery from a geopressured aquifer.

Economic studies of geopressured aquifers focused on determining the sensitivity of wellhead gas price to differing reservoir and completion parameters. Randolph (1977) varied the tubing diameter, porosity, permeability, rock compressibility, flowrate and aerial extent and found that the "reservoir criteria for natural gas production are much less stringent than for electricity generation from Gulf Coast geopressured aquifers."

The "Wells of Opportunity" and "Design Well" Programs

In 1975, the United States Energy Research and Development Administration (now DOE) began funding studies of the geopressured-geothermal resource that performed geologic assessments of the Gulf Coast geopressured-geothermal potential. The scope of the program was later expanded to include projects that sought 1) to physically verify the reservoir fluid and near wellbore petrophysical properties of geopressured aquifers, and 2) test the long-term producibility of geopressured aquifers. Completion of the goals was chartered under the Wells of Opportunity (WOO) and the Design Well (DW) programs, respectively. The purpose of the programs were "to determine whether or not the resource has potential… as an economic, reliable and environmentally acceptable energy source (Westhusing, 1981)."

The WOO program was designed to provide large amounts of quickly available information from a diverse geographic and geologic area without great expense to the DOE. Short-term tests allowed for the data collection on aquifer fluid characteristics, near-wellbore petrophysical properties, fluid behavior under flow and well deliverabilities, the evaluation of completion techniques, and scale and corrosion potential.

There were limitations to the success of the WOO program. Wells selected for completion were not located in structurally favorable locations. Even though permeability barriers were encountered in all of the test wells, the short-term pressure transient tests did not provide information on complete reservoir limits. Due to the nature of the WOO

	Girouard No.1	Koelemay No.1	Saldana No.2	Prairie Canal No.1	Crown Zellerbach No.1	Fairfax Sutter No.2
Parish (County)	Lafayette, LA	Jefferson, TX	Zapata, TX	Calcasieu, LA	Livingston, LA	St.Mary, LA
Shut-in Surface Pressure (psia)	6695	4373	2443	6420	2736	-
Max Flow Rate (BWPD)	15,000	3,200	1,950	7,100	2,832	7,700
Max Gas Rate (Mcfd)	600	1,017	105	390	93	-
Surface Flow Temp (F)	255	206	220	230	198	240
Produced Gas-Water Ratio (scf/bbl)	40	30-318*	47-54	43-55	33	22.5-30
Lab Gas-Water Ratio (scf/bbl)	44.5	35	41	43	-	22.8
Water Salinity-TDS (ppm)	23,500	15,000	12,800	42,600	32,000	190,000
Carbon Dioxide (Mole %)	6	7.2-2.7	26.4-16.4	9.6	22.6	7.8
Total Water Produced (bbls)	41,930	30,030	9,328	41,079	10,338	-
Formation	Frio - Marg. Tex No.1	Yegua - "Leger"	Upper Wilcox	Hackberry, Upper Frio	Tuscaloosa	-
Perforations (ft)	14,774-14,819	11,639-11,780	9,745-9,820	14,782-14,820	16,720-16,750	15,781-15,878
Gross Interval (ft)	107	139	90	25	36	-
Net Interval (ft)	91	77	79	14	35	58
Reservoir Pressure (psia)	13,203	9,450	6,627	12,942	10,075	12,203
Reservoir Temperature (F)	274	260	300	294	327	270
Porosity – Log (%)	26	20	16	28	17	19.3
Porositry – Core (%)	-	26	20	25	-	-
Permeability - Core (md)	-	85	20	-	-	-
Permeability - Test (md)	200-240	100-200	16.7	95	16.6	14.5
Radial Distance Explored (ft)	1,658	1,972	2,768	3,897	1,758	-

Table 2. Reservoir characteristics of selected Wells-of-Opportunity.

program, not all wells tested were in good condition: 11 wells were accepted to the WOO program, 8 wells were successfully re-completed in geopressured aquifers, and seven wells provided flow data (Swanson, 1986). Table 2 provides reservoir information for six of the WOO program wells (Klauzinski, 1981, McCoy, 1980).

In two wells, brine salinities were higher than expected and resulted in reduced methane solubilities. Carbon dioxide content of some wells was much higher than expected, resulting in reduced methane solubility in the brine. The Tuscaloosa sand test in Livingston Parish showed brine under-saturated with methane. The Lake Charles, LA and Laredo, TX wells produced gas at rates in excess of the methane solubility in brine. All other test wells showed methane content at or near saturation in the brine. Scaling and corrosion tendency depended on brine salinity and reservoir temperature. Bottom-hole temperatures were between 7% and 16% higher than log derived data (Klauzinski, 1981).

The Design Well program focused on long duration tests to extensively study reservoir fluid composition, reservoir characteristics, and drive mechanisms. These wells were located at optimum reservoir locations and designed to produce geopressured brines at high rates for periods to 2 years. The location of design wells were chosen to allow testing of the most favorable fairways and to provide testing of sand complexes that had yet to be produced. Selection guidelines for design well sites were similar to the WOO. Table 3 describes the reservoir characteristics and flow properties of the Design Wells.

The Pleasant Bayou No.2 test well was the first well drilled and completed in the DOE Design Well program. Testing of the well lasted from 1979 until

	Pleasant Bayou No.2	Gladys-McCall No.1		Amoco Fee No.1		L.R. Sweezy No.1
Parish (County)	Brazoria, TX	Cameron, LA		Cameron, LA		Vermillion, LA
Formation	Lower Miocene Oligoncene	Frio Oligocene		Miogypsinoides Sand Upper Oligocene		Upper Frio Oligoncene
Tested Zone	-	Zone 3	Zone 5	Zone 8	Zone 9	-
Max Flow Rate (BWPD)	28,900	6,604	36,500	36,500	4,400	10,700
Sustained Flow Rate (BWPD)	18,900	-	15,700	33,300	-	8,500
Produced Gas-Water Ratio (scf/bbl)	23	20.2-24.1	23	27-29.8	32	20.2
Total Water Produced (bbls)	15.4E6	27E6		1.1E6		2E6
Water-in-Place (bbls)	5E9	7.8E9		1.8E9		106E6
Water Salinity-TDS (ppm)	131,320	168,650	165,000	97,800	96,500	99,700 +/-240
Carbon Dioxide (mol %)	11.28	-	-	9.92		-
Gross Interval (ft)	60	34	32	338	128	73
Net Interval (ft)	53	24	27	333	114	57
Res. Pres. (psia)	11,168	11,887	12,082	12,799	12,911	11,410
Res. Temp. (F)	305	293	298	291	294	237
Porosity	18	20	22	16	16	27
Permeability	192	42-140	12-162	160	67	126

Table 3. Reservoir characteristics and flow properties of Design Wells.

late August 1990 and approximately 15.4MMbbls water and 330MMscf natural gas was produced. Initial testing of the aquifer was conducted from 1979 through 1983, when wellbore failure occurred. In 1988 the well was re-completed and testing of an experimental Hybrid Power System (HPS) occurred until 1990. The Pleasant Bayou No.2 was the only Design Well to utilize the HPS for the generation of electricity (Chacko, 1998).

The Gladys-McCall No.1, drilled and completed in 1981, provided a successful field test of a moderately sized geopressured aquifer. The well produced over 27MMbbls of water and 675MMscf between its initial production date in 1983 and shut-in in 1987. Scale production was controlled through the use of continuous inhibitor injection into the production stream and through the periodic injection of an inhibitor pill into the formation (Tomsor, 1986). This enabled the well to produce brine at rates in excess of 30,000 BWPD. Short- and long-term pressure transient tests estimated the primary aquifer volume at between 270 and 408MMbls. Long-term transient test estimated that an additional 7.5 billion barrels of water was partially connected to the primary volume. The additional volume was hypothesized to come from either shale water influx, additional volume connected through a partially-sealing fault, or a combination of both (Lee, 2000; Rogers, 1991). Core analysis from the Gladys-McCall No.1 showed that both reservoir compaction and formation creep could greatly contribute to the reservoir drive mechanism (Chacko, 1998, Kelkar, 1983).

EXPERIMENTAL METHOD

Studies to determine the commercial potential of geopressured-geothermal aquifers typically focused either on reservoir performance or financial viability of field development (Quitzau, 1981; Knapp, 1977). Unfortunately, no comprehensive studies to determine the commerciality of geopressured aquifers have been performed for almost twenty years. This study combines reservoir performance, facility efficiency and financial constraints to determine a range of potential outcomes for viable commercial development of geopressured-geothermal aquifers.

The reservoir performance model utilizes a commercial reservoir simulation program to predict the production rates from aquifers under constrained surface pressure. Sensitivities consider single- well and multi-well developments. Reservoir model components are varied to determine a wide range of aquifer productivities. Varied parameters include bulk volume, depth, reservoir dip angle, porosity/permeability, initial pressure and temperature gradient, salinity, formation compressibility, maximum allowable flowrate, wellbore radius, formation dip angle, and initial gas saturation. If variations of reservoir input parameters are considered using full factorial design, over 470,000 simulation runs would be needed to provide the results of all combinations. By using a mixed-array (MA) the full range of solutions for all simulation parameters can be defined while reducing the number of required simulation runs to 36. Additional models were created to gauge the effect of shale-water influx and formation compaction.

The facility model uses reservoir temperature and flowrate from the reservoir performance model to estimate the net electric output of the thermal recovery system. The facility model assumes that a Kalina-cycle binary power plant is utilized. The financial model computes the discounted cash flow of geopressured aquifer developments. Input parameters for the financial model are flowrate from the reservoir model, discount rate, natural gas price, net electric output, electricity price, capital and operational costs, severance taxes and net revenue interest. Output parameters include discounted cash flow, payout time, profitability index and the internal rate of return. A range of input parameters that yield a positive life-cycle cash flow are delineated by combining the results of the reservoir, facility, and financial models. The ranges can be applied to evaluate geopressured-geothermal resources and identify areas where additional research is warranted.

CONCLUSIONS

Economic viability can be broken into three performance groups: positive under all constraints, positive under a specific range of constraints (marginal), and never positive. For this study, negative performance is defined as having a negative ROR, marginal performance has a ROR below 30% and a positive NPV, and positive performance has a ROR above 30% and a positive NPV. Realized natural gas price, electricity price, capital cost, and operating expenses are the underlying constraints for this study. Table 4 and Fig. 3 rank the input parameters based on their effect on economic outcome.

Rank	
"Marginal or Economic"	"Economic"
V_b	D_w
S_{gi}	Phi/ k
Phi/ k	V_b
D_w	dP/dh
Salinity	Flowrate (q)
Aquifer height (h)	C_f
Flowrate (q)	Salinity
Depth	Sgi
dP/ dh	Dip Angle
C_f	Aquifer height (h)
Dip Angle	Depth
dT/ dh	dT/dh

Table 4. Rank of factors.

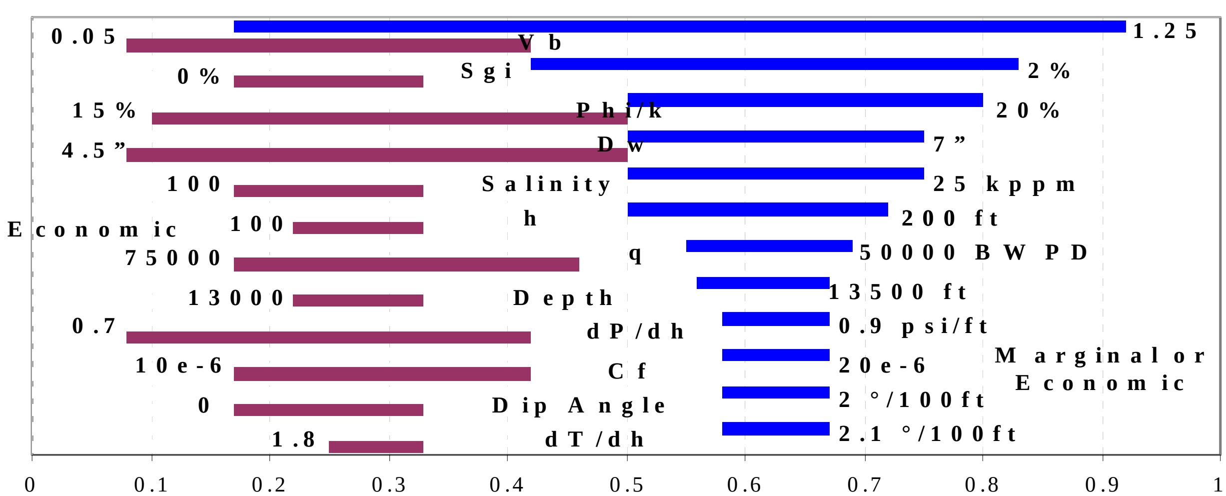

Fig. 3. Tornado diagram of results of sensitivity analysis for single-well developments with flowline length of 100 ft. Note that the x-axis represents the fraction of runs that exceed the requirement, not the probability that the requirement will be met.

Fig. 4 and Fig. 5 display the economic potential of a simulation case based on the interaction of two input variables. These "maps" were generated to determine the interaction of variables and the result on economic potential. Fig. 4 shows that low salinity/ large bulk volume aquifers have the largest potential for economic development. Salinity affects economic viability through methane solubility. Fig. 5 shows that greater economic potential exists for moderate flowrate/ large bulk volume systems than for high flowrate/ large bulk volume systems. This result can be explained through the incremental cost associated with transitioning from a moderate flowrate system to a high flowrate system.

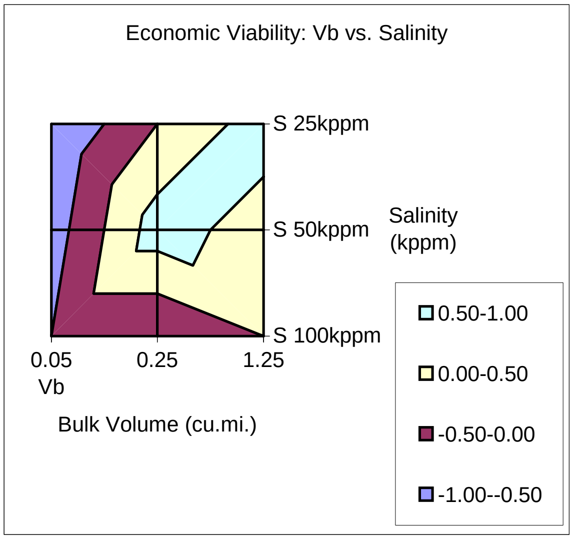

Fig. 4. Economic viability of a : V_b vs. pressure gradient.

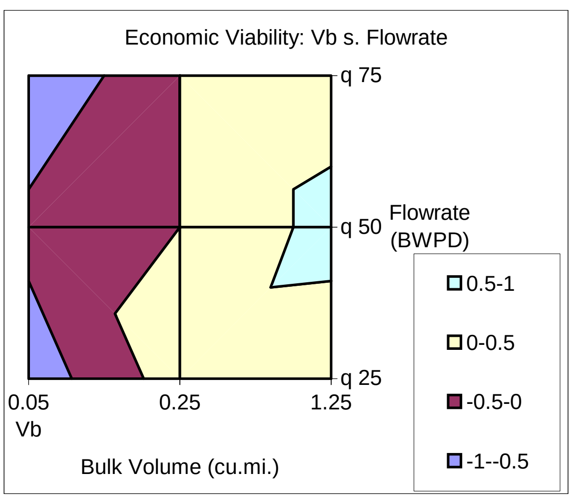

Fig. 5. Economic viability: V_b vs. flowrate (flowrate is divided as follows: ≤25,000 BWPD, ≤50,000 BWPD, and ≤75,000 BWPD).

The inclusion of the binary-cycle power plant dilutes the economic incentive to develop geopressured-geothermal aquifers. Table 5 displays the effect removing the thermal recovery unit has on Rate of Return of a simulation case. However, the values for temperature gradient and depth used in this study represent a limited range of those expected in northern Gulf of Mexico environments. The temperature gradients used in this study ranged from 1.8°F/100ft to 2.1°F/100ft. Aquifers tested in the WOO and DW programs varied in depth from 9,500 ft to 15,500 ft and with geothermal gradients between 1.5 °F/100ft and 2.5 °F/100ft.

Sensitivity Run	ROR (%)	
	$4.50 /Mscf $0.03 /kW-hr	$4.50 /Mscf No TRU
Case 09	31	32
Case 10	32	33
Case 11	5	6
Case 12	8	8
Case 21	27	31
Case 22	56	64
Case 23	11	23
Case 24	38	61
Case 33	27	29
Case 34	59	73
Case 35	35	36
Case 36	-	-

Table 5. Change in ROR for selected cases.

FUTURE WORK

The economic and technical constraints posed in this study determine a potential range of conditions where the development of geopressured aquifers may have commercial application. However, these factors also indicate that challenges remain before field development of geopressured aquifers can begin. Five groups emerge that warrant further investigation and could greatly enhance the value of the geopressured-geothermal resource:

1. Reservoir characterization and resource estimation. By refining estimates of rock compaction, shale-water influx, and diagenic history a more detailed analysis of aquifer drive mechanisms could be determined. The re-activiation of the Wells of Opportunity

program could refine estimates expected aquifer volumes and aid in quantitatively determining the effects of carbon dioxide and heavier hydrocarbons on methane solubility in brine.

2. Facility optimization and systems analysis. Detailed system analysis and facility optimization could decrease capital cost and operating expense while providing for more efficient extraction of methane. Accurate temperature, flowrate, and facility coupling could provide "fit-for-purpose" equipment and significantly reduce expense.
3. High efficiency binary-cycle power plants. Further investigation of Kalina-cycle power plants could provide for a cheap, yet highly efficient, means of extracting thermal energy from geopressured brine. Detailed evaluation on the implementation of a Hybrid Power System could further enable geopressured aquifers to provide a "micro-scale" power grid.
4. Detailed economic analysis. Accurate estimation of facility and power plant expense, along with more detailed estimates of drilling cost may provide a more economic opportunity. Commercial potential of geopressured aquifers could increase with the inclusion of dry-hole risk, well replacement cost, and the likely-hood of different development.
5. Legal and political difficulties. The aerial extent of potentially commercial geopressured aquifers is likely to be in excess of 10 sq. mi. and small acreage landowners could derail the development of this energy source. Mineral law case history is vague concerning the ownership of sub-surface brine. The renewal of federal tax credits and the implementation of severance tax relief and federal loan guarantees could provide significant economic incentive to develop geopressured aquifers.

ADDENDUM

This paper presents a summary of text originally written as a Master's thesis. The complete text of this study can be found at http://etd.lsu.edu/docs/available/etd-07082004-102126/ and is available for unrestricted viewing.

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