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THE GEOPRESSURED-GEOTHERMAL PROGRAM: ENERGY CONVERSION
STATUS AND FUTURE POSSIBILITIES

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ABSTRACT

The Geopressured-Geothermal Program, sponsored by the Department of Energy (DOE) began in 1976 with the Wells of Opportunity. This early research concentrated on resource characterization at several locations in Texas and Louisiana. More recently, the program has included well operations and supporting university research in geoscience and engineering. Long term flow testing, reinjection of brine, and scale prevention were accomplished at the Gladys McCall Well. The Pleasant Bayou Well provided additional data for modeling and predicting geopressured reservoir behavior. This year a hybrid power system (HPS) was constructed at Pleasant Bayou in cooperation with the Electric Power Research Institute (EPRI). This is the first conversion of the geopressured-geothermal resource to electricity. An economic review of geopressured-geothermal resource development concludes that using off-the-shelf technology, electricity can be produced for \$0.125/kWh from a Gladys McCall type resource (40,000 bpd brine production, 27 scf methane/bbl, 288°F brine, and 10-year resource life). The Pleasant Bayou type resource can produce electricity for \$0.32/kWh. Advanced technology could reduce the cost to \$0.16/kWh.

A review and status of the HPS is presented with future possibilities for the program, including 1) recovery of medium and heavy oil with hot geopressured brine, 2) direct use, especially aquaculture, and 3) development and use of advanced technology for conversion at the Hulin Well, the deepest, hottest well in the program. The estimated improvement in efficiencies with advanced conversion technology range from 100 to 160%. This would greatly reduce the cost to produce electricity.

Introduction

The Geopressured-Geothermal Program, under the sponsorship of the Department of Energy, has constructed a hybrid power system at the Pleasant Bayou Well in Brazoria County, Texas and has initiated testing.

Geopressured resources, with simultaneous production of methane and hot brine, provide a natural application for a hybrid power cycle. In such a system, methane separated from the brine fuels a gas engine or gas turbine to produce electricity. Heat from the engine exhaust is transferred to the brine, which is then run through a conventional binary cycle system. Additional heat is supplied by the thermal energy in the brine. Additional power is available by utilizing the hydraulic energy in the fluid at the wellhead (typical flowing wellhead pressures are in the range of 800 to 3000 psi).

The Wells of Opportunity earlier in the Geopressured-Geothermal Program verified the availability of a large resource of gas, thermal, and hydraulic energy. The gas resource in the Gulf Coast area is estimated to be 5,700 trillion cubic feet (1 trillion scf = 1 quad); the thermal energy is estimated to be about 11,000 quad (Wallace et al., 1977). Additionally, it was learned early in the program that the hot brine could be disposed of by reinjection into relatively shallow aquifers without induced seismicity or other environmental effects. Long term flow testing and control of scale formation have demonstrated that the brine could be reliably produced at rates of 15,000 to 20,000 bpd without frequent shutdowns because of scaling. However, the predictability of reservoir behavior remains a challenging and ongoing research focus.

In March of this year EPRI joined the DOE in the construction of a hybrid power system at Pleasant Bayou. The purpose of the Pleasant Bayou conversion project is to determine the increase in efficiency obtained by using the waste heat from the high temperature exhaust gas in the power cycle. This will be the first time that conversion of the thermal energy in geopressured brine to electricity has been undertaken.

Testing of the hybrid cycle facility, which began this summer, is scheduled to last for one year. The first three months will be a period of start-up, shakedown, and testing. The

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remaining nine months will be for continuous operation at the design process flow rate of 10,000 bbl/day. Much of the equipment for the HPS is reused from previous projects and in some instances this fact places a constraint on the system, e.g., pressure ratings.

Geological Setting

The Pleasant Bayou Well penetrates the Andrau sand in the Frio 'C' stratigraphic interval at 14,684 to 14,716 feet. The top of this sand is interpreted to be a distributary channel; the lower and major portion of the interval is interpreted to be a distributary mouth bar (Tyler and Hamlin, 1986). An interpretation of the high constructive deltaic depositional system in which these types of sands are found is shown in Fig. 1. A structure map on the top of the 'T-5' marker in the Frio formation is shown in Fig. 2. Major down-to-the-basin growth faults trend NE-SW and bound the Chocolate Bayou East Field. Pleasant Bayou Well #2 is located downdip at -14,000 feet, 2,000 feet below the top of the Chocolate Bayou domal structure. The reservoir boundary to the south is unknown. A net sandstone thickness map of the C zone in the Andrau sand is shown in Fig. 3. This is the zone of interest to the Geopressured-Geothermal Program. The sand thickness is 125 feet in the Pleasant Bayou Well, showing a thickening of 65 feet from the area to the northeast higher on structure. The paleogeography configuration and lithology of the sand support the interpretation of a distributary channel mouth bar. A SW-NE cross section shows the relationship of Pleasant Bayou Well #2 to the major structure (Fig. 4).

Porosity from core analysis is 19%; permeability is 200 md. The total reservoir pore volume modelled by the University of Texas is about 8.7 billion barrels.

Well and Brine Characteristics

The Pleasant Bayou Well was reworked in 1986, but because of inadequate funding, the well was shut in. Production equipment was installed in late 1987 and early 1988. In May 1988 the well was placed on production. Since then, the well has flowed continuously about 20,000 barrels of brine per day from a perforation interval of -14,644 ft to -14,704 ft. The brine temperature is about 278°F (compared with a formation temperature of 301°F). The brine contains 70,000 mg/L chlorides and 127,000 mg/L total dissolved solids (Table 1).

Severe calcium carbonate scaling was treated with a phosphonate scale inhibitor squeeze. Subsequent coupon monitoring with the addition of scale inhibitor has assisted in controlling the scale formation.

Excessive sand production occurred at flow rates greater than 22,000 bpd. By reducing the brine flow rate, the sand production has been controlled. The produced sand has been identified as coming from the brine reservoir by the University of Texas. The flow rate has been maintained at about 20,000 bpd. When the HPS is in operation, the flow will be split to take 10,000 bpd to the conversion system.

The initial daily fluid analysis showed a gas/water ratio of 29 scf/bbl; recent analyses show 22 scf/bbl. The original 85.5% methane content has declined to about 82%; original 10.5% CO₂ content has increased to about 13%. Little or no sulfate is shown in the brine analysis (Table 1).

The brine gas analysis shows that ethane at 2.6%, is the dominant minor hydrocarbon component. Only 2% of the gas is made up of nitrogen (0.44%) and hydrocarbon components other than methane and ethane (Table 1).

The aromatic hydrocarbons dominate the analysis of hydrocarbons condensed from the gas stream. The occurrence of benzene is interesting to note because of earlier work by Gulf Research Lab in Harmorsville, PA (Zarrella et al., 1967). The concentration of benzene in ppm was recorded with the distance to known oil and gas occurrence in the same reservoir. A plot of these data shows an apparent correlation of increasing benzene content with proximity to known reservoir oil and gas in the same formation. The content of benzene at Pleasant Bayou, when added to this plot, suggests close proximity to hydrocarbon accumulation (Fig. 5). This correlation could possibly be utilized by the oil and gas industry in calculating the distance by which a brine well missed the desired hydrocarbon reservoir.

The Hybrid Power System

The goal of the initial test period is to operate the HPS over a wide range of operating situations, including off-design conditions, to obtain data helpful for the design of future commercial operations. A period of operation with maximum power output will follow. This longer period of operation will constitute an evaluation of the reliability of the HPS and will provide the opportunity to develop and document those features of design, operation, and maintenance that are important to achieving high reliability.

The objectives of the project are to demonstrate the hybrid cycle concept for electricity generation and to obtain data regarding operation over time of a power plant using a geopressured resource. Electricity will be produced from a gas engine burning methane and from a binary cycle operating on heat from the engine exhaust and from the geopressured brine.

Demonstration of the hybrid concept on a geopressured well has the benefit of testing current technology available to produce electricity from geopressured resources. During the year of operation, much is expected to be learned about potential problems such as scaling, corrosion, flow instabilities, and gas engine life with the impure wellhead gas.

The specific objectives of the HPS test program are as follows:

1. Evaluate the potential of a combustion/geothermal hybrid power cycle for use in the development of geopressured and low-temperature hydrothermal resources.
2. Demonstrate the technical feasibility of the HPS for use with a geopressured resource.
3. Evaluate the role of combustion thermal energy in geopressured resource development economics.
4. Establish a precedent and procedures for the permitting of a HPS utilizing a geopressured resource.
5. Identify the need and direction for future research and development, with the ultimate goal of commercial application (HPS Test Plan, 1989).

Prior to construction of the HPS the dissolved methane in the geopressured brine was separated from the brine and piped to a sales gas line. With the HPS, approximately half of the methane (200 mcf/day) will be used to feed a gas fired engine/generator. The electricity produced by this generator will feed directly into the Houston Power and Light grid. The design electricity production is 650 kW (gross), which represents about 55% of the gross power output of the HPS. Two Caterpillar 398 engines were selected for use in this project. The design called for the engines to be skid-mounted with all necessary controls and auxiliary equipment for industry application. For industry application consideration should be given for additional gas engines to utilize the entire gas production for conversion to electricity because of favorable economics.

A portion of the hot brine (about 50%) at 278°F will be passed through heat exchangers to heat the fluid in the binary system (isobutane) to approximately 210°F. The cooled brine, at approximately 164°F, will be mixed with the unused brine and pumped into the disposal well.

Exhaust gas from the gas engine at 1130°F is used to boil about 14% of the isobutane in the exhaust gas-to-isobutane boiler. The remainder of the isobutane is boiled in the

brine-to-isobutane heater. The brine, which leaves the separator at 278°F is cooled to 210°F in the brine-to-isobutane boiler. The brine from the boiler then enters the brine-to-isobutane preheater. The pressure-enthalpy diagram for isobutane with the binary cycle portion of the HPS design process path is presented in Fig. 6 (Gas Processors Supp. Assoc., 1987). A simplified process flow diagram of the hybrid cycle power plant is shown in Fig. 7.

The hybrid power cycle gives an advantage in conversion through the utilization of the exhaust heat from the combustion engine. This increase in efficiency obtained by using the waste heat from the high temperature exhaust gas in the power cycle to heat the evaporator will be calculated during test operations.

Isobutane is not the optimum working fluid for a standard binary cycle on a resource with a temperature as low as at Pleasant Bayou (278°F). Propane could be used instead of isobutane to generate more power. However, propane has a higher vapor pressure than isobutane, exceeding the pressure ratings of most of the reused equipment.

A comparison was made by EPRI of the difference in power production between propane and isobutane at Pleasant Bayou. Propane would yield approximately 5% more net power than isobutane. This relatively small advantage was not enough to justify the purchase of all new equipment and will not compromise the primary goals of the HPS.

Parasitic Loads

Power production and parasitic loads at the HPS design condition are summarized in Table 2.

TABLE 2. SUMMARY OF POWER PRODUCTION AND PARASITIC LOADS

Power Production:

Gas Engine	650 kW
Binary Cycle Turbine	541 kW
Gross Power Production	1191 kW

Parasitic Loads:

Condensers	75 kW
Circulating Pump	74 kW
Miscellaneous	60 kW
Total Load	209 kW
Net Power Production	982 kW

The parasitic load labeled "condensers" includes four water pumps, one for each Baltimore Aircoil Condenser unit, and eight fan motors. Fans are approximately 85% of the 75 kW

condenser parasitic load. The load labeled "circulating pump" is the isobutane pump used to pump the condensed isobutane liquid into the high-pressure heat exchangers. The miscellaneous loads total 60 kW and include the utility cooler, lube oil pumps, air conditioning, pressurizing air for the trailers, instrument air, control power and lighting. These parasitic loads are a higher percentage of generator output than would be expected for a commercial power plant.

Process Equipment

Isobutane is pumped to a pressure of 330 psia by the isobutane circulating pump, a multi-stage vertical turbine pump. Isobutane is heated to its bubble point by warm brine in the brine-to-isobutane preheater, a shell-and-tube heat exchanger with counter-current flow. After leaving the brine-to-isobutane preheater, the isobutane flow splits with some of the isobutane being boiled by exhaust gas from the engine and the remainder boiled by the hot brine.

Isobutane vapor from the brine-to-isobutane boiler and exhaust gas-to-isobutane boiler is combined, passed through an entrainment separator, and expanded through a turbine to generate electricity. Exhaust isobutane leaving the turbine is condensed in four Baltimore Aircoil condensers. Condensed isobutane enters the isobutane accumulator before being pumped back through the loop, thus completing the binary cycle.

Wellhead gas used in the power plant will be burned in a gas engine. The hybrid cycle design is based on the use of two Caterpillar 398 engines. These engines require jacket cooling which is generally done by circulating water. Jacket cooling can also be accomplished by putting water in the jacket where it boils to make steam. This second method of cooling is called ebullient cooling. Use of an ebullient-cooled engine is best for the hybrid cycle since the jacket heat is available at a higher temperature. However, ebullient-cooled engines were not available, so the current design was based on engines with water-cooled jackets.

Thermal Effects

Several areas of concern have been addressed in design reviews, including 1) thermal effects, 2) mechanical integrity, and 3) corrosion. The temperature associated with the combustion engine exhaust gases has given rise to concerns about the decomposition of isobutane. Isobutane tends to "crack" or thermally decompose at temperatures above 550°F. Analyses made by INEL verify the adequacy of the design to maintain the temperature of all surfaces in contact with the isobutane below this value.

The hottest surface in contact with isobutane is the portion of the tube bundle where the exhaust gases first enter. Here the exhaust gas temperature is near its design inlet value of 1130°F, but an excellent boiling heat transfer coefficient on the isobutane side, combined with a low convective heat transfer coefficient on the gas side combine to keep the outside (isobutane side) of the tube at an estimated 246°F, well below the critical temperature of 550°F. The heat flux at the tube entrance is estimated to be 15,500 Btu/hr-ft², over 2-1/2 times the average for the whole heat exchanger. The heat exchanger is designed to minimize vapor blanketing in this region by locating the isobutane inlet here and utilizing several baffles which created high velocities over the tubes.

Although a safety control is provided to divert the exhaust gas directly to the atmosphere if the liquid level in the boiler drops below a specified value, we investigated the case of a tube exposed to vapor over one half of its length. It was assumed that the bottom half of the tube (where the hot exhaust gas enters) was liquid covered. The exhaust gas temperature at the tube midpoint was calculated to be at 498°F, and the tube outside surface temperature at the point was calculated to be 292°F. These calculations conservatively neglect tube wetting from splashing by the boiling going on below the liquid surface, which would further lower the tube surface temperature. It can therefore be concluded that thermal degradation of the isobutane due to contact with hot surfaces in the heat exchanger will not be a problem (Lawford, 1988).

Mechanical Integrity

The fact that the tubes stay quite cool has been discussed. A maximum tube sheet temperature of 256°F was calculated which should not induce excessive thermal stresses (Texas Metal Fabrications, 1988). The exhaust gas inlet chamber (head) would be expected to see temperatures near the inlet gas temperature of 1130°F. However, this temperature will be fairly uniform over the entire chamber, and the chamber is bolted, not welded, to the much cooler tube sheet. Thus, stresses between the chamber and tube sheet should not be excessive.

The entire gas side of this heat exchanger has such a low design pressure (5 psig) that it is not considered a pressure vessel. Also there are minimal complications from minor leakage from the gas side to the atmosphere.

The shell (isobutane) side is designed to the ASME Section VIII Division I Pressure Vessels Code and the TEMA-R standard. The ASME code requires that stress calculations be made to back up the design, and that thermal stresses must be considered in those calculations. The

shell side has also been hydrotested at 1-1/2 times the design pressure of 350 psig, although this test was probably made at room temperature.

The juncture of the tubes and the tubesheet are both rolled and sealwelded. Rolling is a process where the tube ends are expanded mechanically from the inside to an interference fit with the tube sheet. Thus, leakage of high pressure isobutane into the low pressure exhaust gas would require a failure of one or more of the seal welds, which is considered highly unlikely. Furthermore a leakage of isobutane into the outlet (cold) chamber would merely result in a discharge of isobutane to the atmosphere, as the 300°F discharge temperature is below the ignition temperature of isobutane. A leakage of isobutane to the 1130°F inlet chamber would be expected to combust upon contact with the hot gas. However, the combustion engine manufacturer predicts that the (unreacted) oxygen content of the exhaust gas will be only 2%. Thus, the magnitude of the possible combustion would be significantly limited, and temperature increases inside the heat exchanger would not be expected to be excessive.

Isobutane leakage greater than that usable for combustion with the limited oxygen would be expected to pass up the stack to the atmosphere, but it will be below the autoignition temperature when it reaches the atmosphere.

The most likely location for an isobutane leak is the heat exchanger joint between the shell and tubesheet. This is a bolted flanged joint, which sees the full operating pressure of the isobutane (266 psig). Such joints are common practice for many heat exchangers. A scenario could be created that thermal distortion of the tube sheet (unlikely) would create an isobutane leak which would ignite on the hot surface (under insulation) of the exhaust gas inlet chamber or piping. The potential damage from ignition of such a leak is difficult to assess, because it would depend upon the quantity of leaked isobutane which had accumulated in the area of the heat exchanger before ignition, which would in turn depend upon the magnitude and direction of breezes at the HPS site. Within the unlikely event that such a leak would develop and be ignited, the most likely situation is that a steady state flame would be established, emanating from the leak. Metal temperatures adjacent to the flame will be limited by water deluge from the fire protection system. The isobutane supply to the heat exchanger would be limited by closing inlet and discharge valves, and the fire will burn itself out by exhausting the isobutane available to the leak. This potential accident is one which should be evaluated in the safety report. (Lawford, 1988).

Corrosion

Corrosion of the heat exchanger during operation is not expected to present a problem with respect to the integrity of the heat exchanger. It may, however, prove necessary to develop a lay-up procedure for shutdowns.

Sulfides are present in the engine fuel gas to the extent of 22 ppm. These would be expected to be converted to $(SO)_x$ in the engine. The engine also forms $(NO)_x$ from the air it ingests, amounting to about 0.3% of the exhaust gas stream. In an aqueous solution, these two components would form sulfuric and nitric acid respectively. This problem has been avoided during operation by using the standard boiler practice of maintaining the outlet temperature above 300°F, which keeps all of the H_2O in the exhaust in the vapor state. During shutdown, however, the small amount of water vapor present in the heat exchanger would be expected to condense, and small quantities of acid would be formed. If it is deemed necessary, this could be avoided by a simple air purge of the heat exchanger tube side immediately following shutdown of the engine.

All of the heat exchanger parts which contact the exhaust gas are made of 304 stainless steel. This includes the tubes, tube sheet, and inlet and outlet chambers (heads). Thus corrosion in general would not be expected to be a significant problem. The temperature at which significant scaling would take place is listed at 1650°F, which is significantly above the gas inlet temperature of 1130°F. Only the inlet chamber will see the 1130°F temperature. The inlet side of the tubesheet, the second hottest piece, will see a maximum temperature of about 256°F. Corrosion is therefore not expected to present a significant problem (Lawford, 1988).

Status

At the writing of this paper the HPS is under construction. By the time this paper will be presented the HPS should have been completed and testing initiated. The Eaton Operating Company (EOC) is the operating company under contract to DOE at the Pleasant Bayou Well. The Institute of Gas Technology is under contract to EOC to operate the production surface facilities, and the Ben Holt Company is under contract to EOC to construct and operate the HPS.

Preliminary Economics of Pleasant Bayou Conversion

A recent review of economics of energy forms from the geopressed resource suggests the following comparison of costs to produce

electrical energy from a Pleasant Bayou type resource (Negus-de Wys et al., 1989).

Form	Method	Cost to Produce \$/kWh
Gas	Gas Engine	0.07
Thermal	HPS or-off-the shelf technology	0.32

The costs to produce electrical energy from both the gas and hydraulic energy fall within the range set as the Geopressured Program goal, 6-10 cents/kWh (levelized 1986 constant dollars). However, the conversion of geopressured thermal energy to electricity is high. Increased efficiency and lower cost for technology are needed to meet the Program's objective.

With advanced technology (assuming an increased efficiency of 100%) the cost to produce electricity from thermal energy in a Pleasant Bayou type resource can conceivably be reduced to 16 cents/kWh. This estimate is predicated on a flow rate of 20,000 barrels per day, 23 scf/bbl methane content, 278°F brine wellhead temperature, a 970 kW plant, and a 10-year plant and reservoir life (Negus-de Wys, et al., 1989).

When gas, hydraulic and thermal are considered as an energy package, the overall cost to produce becomes about 15 cents/kWh. Thus, the capital cost and efficiency of thermal conversion remain an anchor on the economic viability of geopressured thermal conversion. Direct use of the thermal energy could enhance the economic viability in using this energy form.

CONCLUSIONS

It is anticipated that the Pleasant Bayou HPS will have been constructed and be in the testing phase at the time of this presentation. This is the first actual conversion of geopressured-geothermal energy to electricity. The Pleasant Bayou HPS will provide measurements of the increase in efficiency obtained by using the waste heat from the high temperature exhaust gas in the power cycle to heat the evaporator.

An economics review concludes that both geopressured gas and hydraulic energy conversion to electricity are within the program's desired cost to produce range (6 to 10 cents/kWh). However, the thermal conversion for a Pleasant Bayou type resource with off-the-shelf technology falls well above the goal (32 cents/kWh), but could be brought closer with advanced technology (16 cents/kWh).

Taken as an energy package, the gas, hydraulic, and thermal energy from a Pleasant Bayou type resource results in an estimated

average cost to produce of about 15 cents/kWh with off the shelf technology (Negus-de Wys, et al., 1989).

The future possibilities for the geopressured-geothermal resource could include the following:

1. Conversion of geopressured gas to electricity through use of a gas engine, resulting in a cost-to-produce of about 7 cents/kWh. This may be of interest to independent oil and gas operators.
2. Conversion of geopressured hydraulic energy to electricity through use of a hydraulic engine, resulting in a cost-to-produce of about 8 to 10 cents/kWh.
3. Research on advanced technology to increase efficiency and reduce cost to convert geopressured thermal energy to electricity.
4. Direct use projects for cascading utilization of geopressured thermal energy tailored to regional markets and needs. The concept of total energy use makes the geopressured-geothermal resource more economically viable.
5. Other direct uses of geopressured thermal energy such as the recovery of medium to heavy oil.

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Figure 1. The location of Pleasant Bayou in the Frio depositional systems

Figure 2. Structure Map on the *Anomalina bilateralis* zone with Pleasant Bayou location (UTA-BEG)

Figure 3. Net sandstone map with Pleasant Bayou location (UTA-BEG)

Figure 4. Structural cross-section referenced to the top of C zone (UTA-BEG)

Figure 5. The Pleasant Bayou site showing the HPS location

Figure 6

Figure 7