p.19 to 30

THE GEOPRESSURED-GEOTHERMAL RESEARCH PROGRAM: AN OVERVIEW

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NATURE OF THE RESOURCE:

The geopressured-geothermal resource consists of deeply buried
reservoirs of hot brine, under abnormally high pressures, that contain
dissolved methane. Geopressured brine reservoirs with pressures
approaching the lithostatic load are known to occur both onshore and
offshore beneath the Gulf of Mexico coast, along the Pacific west
coast, in Appalachia, as well as in deep sedimentary basins elsewhere
in the United States. The Department of Energy (DOE) has concentrated
its research on the northern Gulf of Mexico sedimentary basin (Figure
1) which consists largely of Tertiary interbedded sandstones and
shales deposited in alternating deltaic, fluvial, and marine
environments. Thorsen (1964) and Norwood and Holland (1974) describe
three generalized depositional facies in sedimentary beds of the Gulf
Coast Geosyncline (Figure 2):

- a massive sandstone facies in which sandstone constitutes
  50 percent or more of the sedimentary volume.

- an alternating sandstone and shale facies in which
  sandstone constitutes 15 to 35 percent of the sedimentary
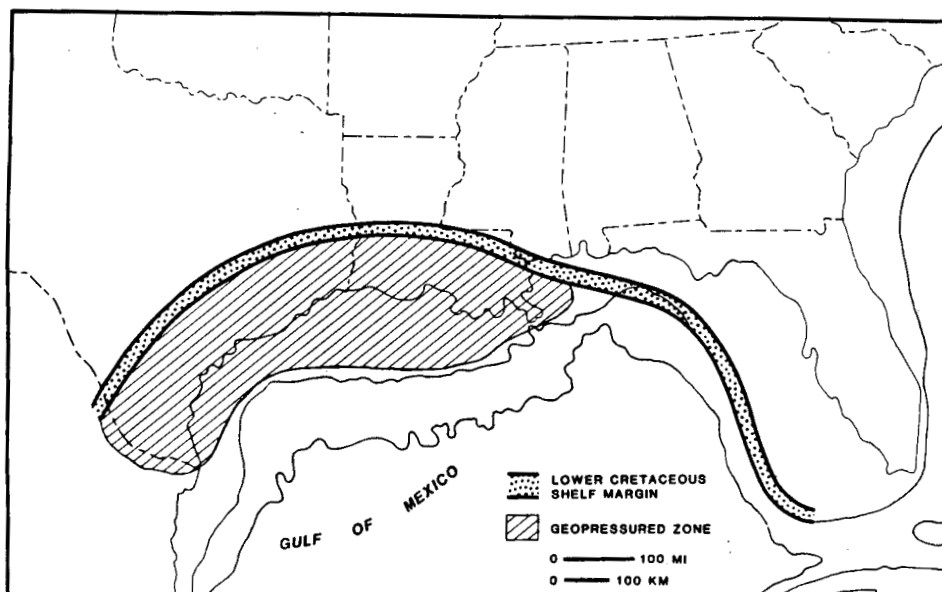 volume.

Figure 1. Subsurface Lower Cretaceous Shelf Margin And Geopressured Zone
In The Northern Gulf Of Mexico Basin (From Bebout et al 1982).

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Gulf Coastal Plain   ⊕   Gulf of Mexico
Continental Shelf

10.5 kPa/m

22.6 kPa/m

(1.0 psi/ft)

(0.465 psi/ft)

MASSIVE
SANDSTONE FACIES
50 percent (or more)
sandstone

ALTERNATING SANDSTONE-SHALE FACIES
15 to 35 percent sandstone

MASSIVE SHALE FACIES
15 percent (or less) sand

Hydrostatic

Representative geopressure gradient

Lithostatic

PORE FLUID PRESSURE

EXPLANATION

⟍ Growth fault
– – – – Depth below which pressure gradient
exceeds 0.5 psi/ft (11.3 kPa/m)
– – – – – – Depth below which pressure gradient
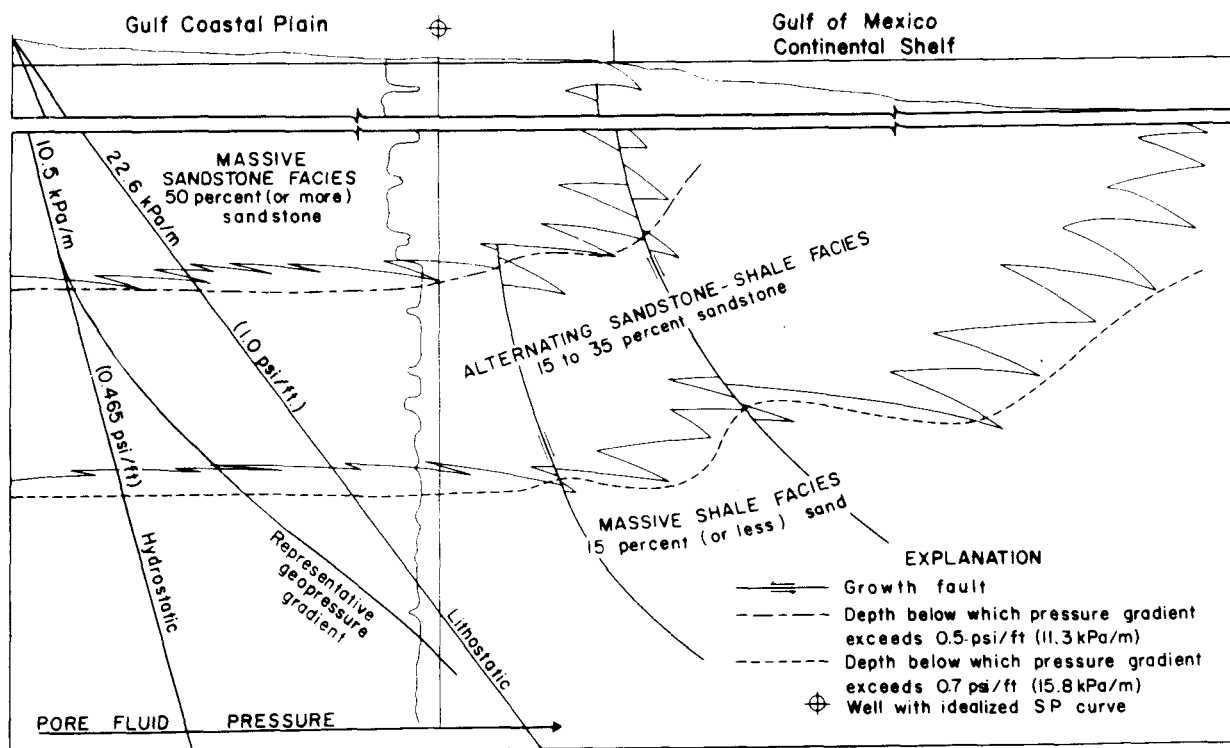exceeds 0.7 psi/ft (15.8 kPa/m)
⊕ Well with idealized SP curve

Figure 2. Generalized Sedimentary Model Of The Northern Gulf Of Mexico Basin, Based On Percentage Sandstone And Showing, Diagrammatically, The Relation Of Gross Lithology To Fluid-Pressure Gradient And Growth Faulting (From Wallace et al 1978).

● a massive shale facies in which sandstone constitutes 15 percent or less of the sedimentary volume.

In general, at any given location the volume of sandstone decreases with increasing depth. The datum of higher-than-normal fluid pressures is associated with the alternating sandstone and shale facies and the massive shale facies. Faulting and salt tectonics have complicated the depositional patterns and influenced the distribution of geopressured reservoirs (Wallace et al 1978).

The sandstones in the alternating sandstone and shale facies have the greatest potential for geopressured-geothermal energy development. Due to the insulating effect of surrounding shales, temperatures of the geopressured-geothermal brines typically range from 250°F to over 350°F, and under prevailing temperature, pressure, and salinity conditions, the brine contains 20 or more cubic feet of methane per barrel. Wallace et al (1978) estimated the geopressured-geothermal energy in Gulf Coast sandstone pore fluids to a depth of 22,500 feet to be 5,700 TCF of methane and 11,000 quads of thermal energy.

GEOPRESSURED-GEOTHERMAL RESEARCH PROGRAM GOAL AND OBJECTIVES:

Since its inception in 1975, the goal of DOE's Geopressured-Geothermal
Research Program has been to provide a technology base sufficient for
industry to make rational investment decisions about the economic use
of the resource. Recently, the goal was amended with a quantitative
objective based on the cost of power: improve the technology for
producing energy from the geopressured-geothermal resource at a cost
equivalent to 6 to 10 cents/kWh by 1995. This compares with a current
cost estimated at about 30 cents/kWh (Negus-deWys et al 1989). The
goal has served as the planning focus throughout the course of the
Program.

At present, program objectives are being pursued under four research
categories: resource analysis, brine production, energy conversion,
and support operations. The objective of resource analysis is to
improve the understanding of how geopressured reservoirs behave over
extended periods by decreasing uncertainty in reservoir performance.
This will enable predictions of reservoir performance with 90%
confidence over a ten-year operating period. Research under this
objective is focusing principally on determining reservoir-drive
mechanisms. The objectives of brine production are to prove the
long-term injectability of large volumes of spent brine at multiple
sites and to minimize fluid production operating expenses. Long-term,
large-volume injection has been shown to be feasible at two well
sites. Under energy conversion, the objective is to improve methods
for extracting commercially-useful energy from geopressured fluid. A
small (1-MWe) power plant will soon be tested at a well site to
evaluate a hybrid power system. Under support operations, the objec-
tives are to determine the environmental acceptability of production
and disposal of geopressured fluids and to develop the technology for
automated operation of geopressured production facilities. All design
well sites are monitored periodically for signs of accelerated
subsidence, abnormal seismicity, and ground-water contamination.

PAST ACTIVITIES AND RESULTS:

The strategy adopted by DOE to achieve the goal and objectives
involves testing geopressured reservoirs via "wells of opportunity"
and "design wells." This field activity is supplemented by a compre-
hensive program of university-based research.

"Wells of opportunity" include commercial oil and gas wells that have
ceased economic production and dry holes that have not yet been
abandoned. In exchange for the right to study the geopressured zones
in these wells, DOE assumes liability for final disposition from the
owners. The wells are recompleted by perforating geopressured zones
of interest and flow testing the zones for 10 to 20 days. Parameters
such as gas/water ratio, salinity, temperature, and pressure are
monitored regularly. Since 1977, nine such wells have been tested
successfully. The results are shown in Table 1. In general,

Table 1. Well Of Opportunity Data* (From Lombard And Wallace 1987).

Well	Dates Tested	Formation	Producing Interval Depth (m)	Sand Thickness (m) Gross	Net	Reservoir Pressure (MPa)	Temperature (°C)	Salinity (mg/L)	Porosity (%)	Permeability (md)	Maximum Flow Rate (m³/d)	Production Gas/Water Ratio (m³/m³)
1. Coastal States, Edna Delcambre No. 1	Jan. 29-July 21, 1977	Planulina Zone (Sand 1)	3801 to 3842	10.7	9.1	74.86	112	134.600	~29	100 to 364	~1900	3.6 to 11.0
		Miocene (Sand 3)	3923 to 3935**	15.2	14.6	75.93	114	114.100	~26	~447	~1390	8.5 to 15.3
2. Neuhoff Oil Co. Fairfax Foster Sutter No. 2	May 19-July 10, 1979	MA-6 Lower Miocene	4810 to 4851	41.2	17.7	84.25	132	190.900	~19	~14	~1220	~4.1
3. Southport Exploration, Beulah Simon No. 2	Nov. 17-Dec. 31, 1979	Camerina Upper Oligocene	4473 to 4502**	63.4	56.7	89.74	130	103.900	~19	~12	~1750	~4.3
4. Wainoco Oil & Gas Co. P.R. Girouard No. 1	July 22-Aug. 7, 1980	Frio-Marginulina texana No 1. Middle Oligocene	4494 to 4517**	32.6	27.7	91.03	134	23.400	~26	200 to 240	~2380	~7.1
5. Lear Petroleum Exploration, Koelemay No. 1†	Sept. 12-25, 1980	Yegua "Leger" Middle Eocene	3548 to 3591	42.4	23.5	65.16	127	15.000	~26	100 to 200	~510	5.3 to 56.6
6. Riddle Oil Co. Saldana No. 2	Nov. 16-25, 1980	Upper Wilcox Upper Eocene	2970 to 2993**	27.4	24.1	45.69	149	12.800	~20	~17	~310	8.4 to 9.6
7. Houston Oil & Minerals, Prairie Canal No. 1	Feb. 21-April 4, 1981	Hackberry Upper Frio	4506 to 4517	7.6	4.3	89.23	146	42.600	~25	~95	~1130	7.7 to 9.8
8. Don Ross, Pauline Kraft No. 1	March 19-20, 1981	Frio "Anderson" sand, Middle Oligocene	3880 to 3920	40.2	26.8	76 (est)	128 (est)	23.000 (est)	23 (est)	39 (est)	21	8.6 (est)
9. Martin Exploration, Crown Zellerbach No. 2	June 5-28, 1981	"Tuscaloosa" Upper Cretaceous	5096 to 5105**	11.0	10.7	69.46	164	32.000	~17	~17	~450	~5.9

*Well locations are shown in Fig 3
**Perforated interval.
***Producing gas and oil at test completion

permeabilities of the geopressured reservoirs were found to be higher than initially expected (Wallace 1989). Also, in five of the nine wells of opportunity, the brine salinity was less than that of sea water. Given inherent limitations, such as wellbore diameter which restricts flow rate, wells of opportunity are mainly useful as indicators of resource potential. In addition to using wells acquired from industry, DOE has drilled wells expressly designed to tap geopressured aquifers. To date, four "design wells" have been employed to investigate long-term, sustained flow of geopressured brines at high production rates. Such wells provide useful data about reservoir-drive mechanisms and ultimate recoveries. Results from the design well tests are given in Table 2. These tests have established the existence of very large geopressured reservoirs.

Table 2. Design Well Data* (From Lombard And Wallace 1987).

Well	Years Tested	Formation	Perforated Interval Depth (m)	Sand Thickness (m) Gross	Net	Reservoir Pressure (MPa)	Temperature (°C)	Salinity (mg/L)	Porosity (%)	Permeability (md)	Maximum Flow Rate (m³/d)	Sustained Flow Rate (m³/d)	Production Gas/Water Ratio (m³/m³)
A. General Crude Oil-DOE, Pleasant Bayou No. 2	1979, 1980	Frio Oligocene	4463.5 to 4481.8	18.3	16.2	77.00	152	~131 320	~18	~192	4600	~3000	~4.1
B. Magma Gulf-Technadril-DOE. Amoco Fee No. 1	1981	Miogypsinoides Sand Upper Oligocene	4646.7 to 4649.7 4651.3 to 4657.4 (Sand Zone 3)	10.4	7.3	81.96	145	~168 650	~20	~42 to 140	~1050		3.6 to 4.3
			4690.8 to 4715.3 (Sand Zone 5)	9.9	8.2	83.30	148	~165 000	~22	~162 for r≤60 m** ~12 for r≥60 m	~5800	~2500	4.1 to 4.8
C. Technadril, Fenix & Scisson-DOE. Gladys McCall No. 1	1982-present	Lower Miocene Sand	4620.8 to 4715.3 (Sand Zone 8)	103.0	101.5	88.25	144	~97.800	~16	~160	5800	~5300	~5.3
			4727.8 to 4763.1 (Sand Zone 9)	39.0	34.7	89.02	148	~96 500	~16	~67	~700		~5.7
D. Dow Chemical Co.-DOE. L.R. Sweezy No. 1	1981-83	Upper Frio Oligocene	4068.8 to 4080.7 4082.8 to 4086.2	22.3	17.5	78.67	114	99.700 ±240	27	126	~1700		~3.6

*Well locations are shown in Fig. 3
**Flow data indicate that permeability may change 60 m from the wellbore. Alternatively, the wellbore may be near the apex of a 26° pie-shaped reservoir
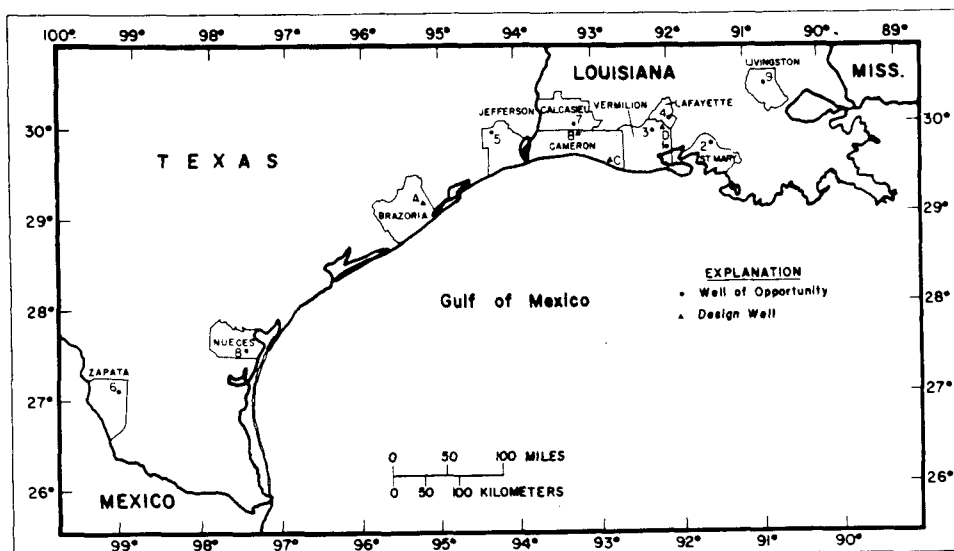
Figure 3. Locations Of Wells Of Opportunity And Design Wells (From Lombard And Wallace 1987; Letters And Numbers Refer To Wells In Tables 1 And 2).

Locations of the wells of opportunity and design wells are shown in Figure 3. Two design wells, the Gladys McCall No. 1 well in Louisiana and the Pleasant Bayou No. 2 well in Texas, are still operational. The Hulin No. 1 well in Louisiana is a well of opportunity currently in the process of recompletion. Testing at all other well sites has been completed.

The wells of opportunity and design wells have tested upper Cretaceous to lower Miocene reservoirs that ranged in depth from 9,745 feet to 16,750 feet at temperatures from 234 to 327°F and salinities from 12,800 to 190,900 mg/L (Wallace 1986). This testing confirmed the size and extent of the resource, demonstrated that the brine is generally saturated with methane, and proved that modified oil and gas technology could be used for brine production, gas separation, and brine disposal. In addition, long-term, high-volume brine production has been accomplished at two wells, and a highly effective scale inhibitor process was developed and successfully tested (Wallace 1986; Lombard and Goldsberry 1988).

Several Gulf Coast universities supported the well testing activities. Geologic studies of the Gulf Coast region identified a number of "fairways" containing prospective geopressured reservoirs where thick sandstone bodies have fluid temperatures higher than 300°F (Bebout et al 1978). Analyses of geopressured brines discerned the presence of aromatic compounds of geologic origin; the concentration of the aromatics was found to vary with cumulative brine production (Keeley and Meriwether 1988). The aromatics appear to be important for understanding hydrocarbon origin and migration in the geopressured zone. Researchers also determined, experimentally, the solubility of methane in brine over a wide range of pressures, temperatures, and salinities (Price et al 1981). Salinities derived from the self-potential log

were shown to be influenced by changes in make-up water resistivity and mud additives used during drilling (Dunlap et al 1985); accurate salinities from logs are necessary for determining the amount of methane that could be dissolved in the brine.

CURRENT RESEARCH - WELL TESTING:

The Program has three active well sites: the Pleasant Bayou site, about 40 miles south of Houston, Texas; the Gladys McCall site, about 6 miles east of Grand Chenier, Louisiana; and the Willis Hulin site in Vermilion Parish, Louisiana, about 23 miles south of Lafayette.

The Pleasant Bayou No. 2 well is completed with 5½-inch production tubing and is perforated from 14,644 to 14,704 feet in the Oligocene Frio Formation. The brine contains about 130,000 mg/L total dissolved solids and has a flowing wellhead temperature of 290°F. At the surface, the solution gas is separated from the brine by two parallel gravity separators at a pressure of about 700 psia. At this pressure, about 19 cubic feet of gas per barrel is removed from the brine, which contains 23 cubic feet of gas per barrel. By mole percent, the separator gas contains 85% methane, 10% carbon dioxide, 3% ethane, 1% propane, 0.5% nitrogen, and smaller quantities of heavier hydrocarbons (C_4), helium, and hydrogen. The gas has a gross dry heating value of 955 BTU/SCF (60°F, 14.73 psia) (Randolph et al 1988). Except for a slightly high carbon dioxide content, the gas is of acceptable pipe-line quality. After separation, the brine flows into a disposal well perforated from 6,226 to 6,538 feet. The journey of the brine from the production well, through the surface facilities, and into the disposal well is driven by the inherent hydraulic pressure of the geopressured brine, obviating the need for brine pumps.

The Pleasant Bayou No. 2 well has been producing geopressured brine since May 1988 at a rate of roughly 20,000 barrels per day. This well produced about 4-million barrels of brine, intermittently, from 1979 through 1983, but testing was plagued by scaling of the production tubing. The current phase of testing has been aided by application of a downhole treatment, whereby scale inhibitor is pumped into the reservoir and adsorbed onto the reservoir-rock grains. During brine production, the inhibitor is released gradually and flows to the surface in sufficient quantities to prevent scaling. Similar inhibitor treatments in the Gladys McCall No. 1 well have been effective for periods up to 21 months, at flow rates up to 30,000 barrels per day.

The Gladys McCall No. 1 well is undergoing long-term, pressure-buildup that began October 29, 1987, after production of more than 27 million barrels of brine and 676 million standard cubic feet of gas. Downhole temperature and pressure measurements are taken periodically to provide data for reservoir analysis.

The Willis Hulin No. 1 well, a well of opportunity, was recently recompleted by DOE for geopressured-geothermal testing. The first phase of recompletion concluded in February 1989. The reservoir of

interest is a lower Miocene sandstone that lies at depths between 20,135 and 20,690 feet, the deepest zone to be studied by the Program. The bottomhole pressure and temperature are about 17,850 psia and 350°F, respectively. A 3½-inch production-tubing string is currently installed in the well, down to a packer at 15,950 feet. In order to clean-out mud used in workover operations, the well was perforated from 20,670 to 20,690 feet and allowed to flow briefly. Preliminary analysis showed that the brine contains about 194,000 mg/L total dissolved solids, 18,400 mg/L calcium, 48,800 mg/L sodium, and 115,000 mg/L chloride. Analysis of the dissolved gas indicates methane to be the most abundant component; a high carbon dioxide content is indicated; very small amounts of other hydrocarbons are present. (Randolph 1989).

CURRENT RESEARCH - SUPPORT STUDIES:

In support of geopressured-geothermal well activities, university-based research is being conducted in rock mechanics, well logging, geology, reservoir engineering, geochemistry, and environmental monitoring.

Compaction testing on cores from the Gladys McCall and Pleasant Bayou wells is providing data to study the effect of pore-pressure reduction on well performance. Data soon to be generated by tensile-failure testing of the cores will be used to study the extent to which rock strength, depth, fluid-flow rate, temperature, and formation stresses are involved in wellbore stability during fluid production. Recent creep testing produced inconclusive results due to a large amount of noise in the data; improved test equipment is needed before more creep testing is attempted. No further work on creep is planned, pending completion of the compaction testing (Gray and Fahrenthold 1988).

Well-logging research is concentrated in two areas: 1) the effect of rock stress, wettability, and shale content on the resistivity log, and 2) the effect on the neutron log of trace elements having very-high thermal neutron cross-sections. The resistivity research is supported in part by industry and the Gas Research Institute. Early experimental work on glass bead packs and Berea sandstone cores showed that the primary variable affecting rock resistivity is wettability; stress has a much smaller effect (Lewis, Sharma, and Dunlap 1988). Theoretical work to study the effect of wettability and shale content on rock resistivity supports the experimental finding that oil-wet rocks typically show substantially higher resistivity than water-wet rocks, for a given level of saturation (Wang and Sharma 1988). Researchers recently have developed a computer program to measure the resistance. Boron, a trace element with a very-high neutron cross-section, has been shown to occur in quantities large enough to affect the logs of several formations in Texas Gulf Coast wells. Boron concentrations of more than 10 parts per million in the reservoir rock will have a significant effect on neutron-log porosity effect of clay lining in a brine-filled capillary tube on its measurements and gas-detection capabilities. Researchers have found a

clear trend toward higher boron content in Frio shales and shaley sands than in relatively clean sand. Boron also occurs in significant amounts in drilling mud constituents, such as bentonite, barite, and lignosulfonate (Dunlap and Coates 1988). The resistivity and neutron-log research enhances the interpretation of these logs for evaluation of conventional oil and gas reservoirs, as well as geopressured reservoirs.

Geologic analysis of the Pleasant Bayou reservoir was completed recently; included were sandstone and mudstone geometries and continuities, structural configuration and fault barriers, effective pore volume, and gas production and pressure trends from nearby wells. This analysis, coupled with pressure and temperature data from the Pleasant Bayou well, is being used to refine the reservoir model. The current model geometry, shown in Figure 4, has a main, high-porosity layer, sandwiched between two low-porosity layers that represent thinner, more isolated sandstones considered to comprise the remote volume of the reservoir. The low-porosity layers are connected to the main, high-porosity layer by cross-flow along circuitous flow paths around shale interbeds and internal faults (Riney 1989).

Figure 5 compares downhole pressure measurements with the pressure buildup response predicted by the computer simulation of the Gladys McCall reservoir with cross-flow as the assumed reservoir-drive mechanism. The cross-flow model requires that other sands be connected to the main Gladys McCall reservoir at some distance from the wellbore. Agreement of predicted and measured values is good, except for the two most recent downhole pressure measurements which are above the predicted downhole pressures.
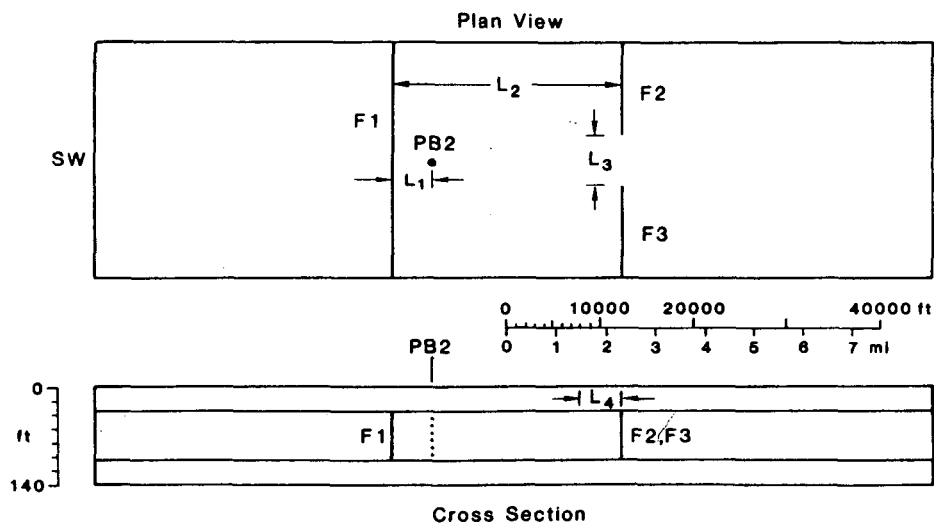

Figure 4. Reservoir Simulation Model Geometry For Pleasant Bayou No. 2 Well. F1, F2, And F3 Are Faults. L1 Equals 990 Meters, L2 Equals 4887 Meters, L3 Equals 1420 Meters, And L4, The Distance Of Vertical Communication Between The Main Reservoir And The Overlying/Underlying Low-Porosity Layers, Equals 1667 Meters (From Riney 1989).
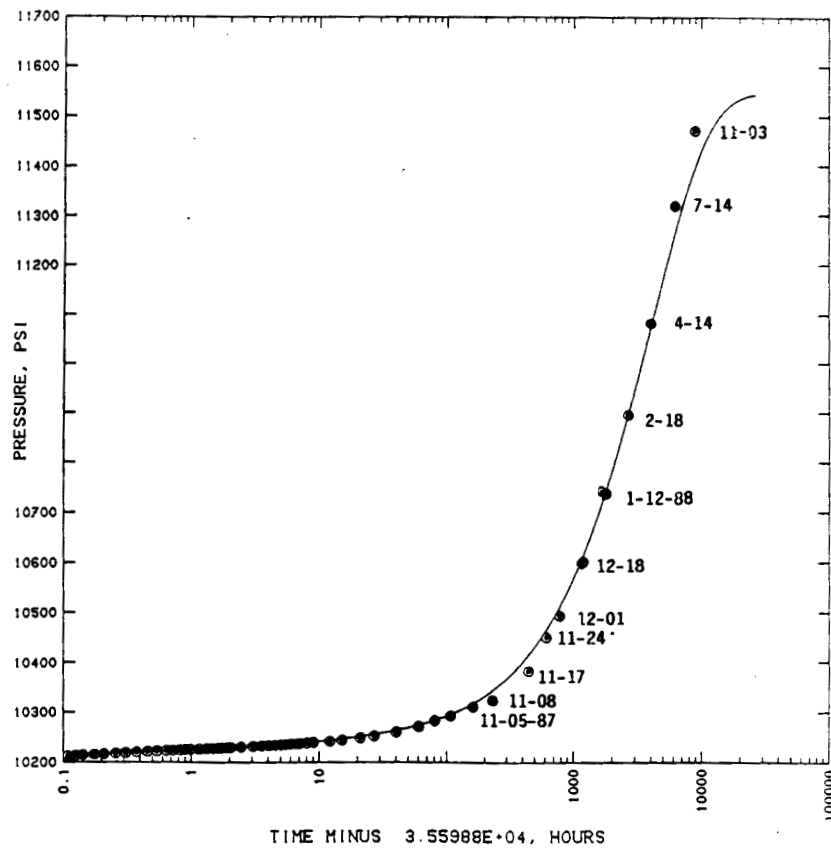
Figure 5. Gladys McCall Well History-Match Simulation Using Cross-
Flow Model Compared With Downhole Pressure Data (From Riney 1988).

Models that match observed reservoir behavior at Gladys McCall can be
devised based on other reservoir-drive mechanisms. Besides
cross-flow, other possible drive mechanisms include stress-dependent
rock-formation compressibility, long-term formation creep, recharge
from shales, leakage along or across faults, and free-gas evolution.

Parametric reservoir simulations, using rock mechanics data for Gladys
McCall reservoir rocks, found that the effects of stress-dependent
rock-formation compressibility were insignificant. Parametric
reservoir simulations of free-gas evolution found that any free gas
evolved during production would be confined to the immediate neighbor-
hood of the well. The ongoing test program for the design wells will
help to distinguish between reservoir-drive mechanisms (Riney January
1988). Downhole-pressure measurements at Gladys McCall are continuing
and are scheduled to be completed by October 1989.

All geopressured brines sampled by the Program contain small amounts
(less than $50\mu L/L$) of C_{6+} hydrocarbons that are primarily aromatic in
nature and range from benzene to substituted anthracenes. The brines
also contain a variety of ions and light C_1 to C_6 aliphatic

hydrocarbons (Keeley and Meriwether 1988). On a monthly basis, the aromatic hydrocarbons in the gas at Pleasant Bayou are sampled, using a dry-ice/acetone bath. The aromatic hydrocarbons in the brine also are sampled using an ice/water bath. These cryocondensate samples, as determined by gas chromatographic analysis, contain over 95 different compounds (Keeley and Meriwether 1985). At the Gladys McCall well, the concentration of cryocondensate in the brine was observed to increase, followed by the onset of oil production. Keeley and Meriwether (1988) postulated that the change in cryocondensate concentration, as a function of cumulative brine volume, results from extration of additional aromatic components from oil migrating into the production zone from adjacent shale.

Environmental monitoring at the geopressured-geothermal well sites assesses whether brine production and disposal have had adverse effects, such as land-surface subsidence, growth-fault activation, or surface and/or ground water contamination. Subsidence monitoring, by means of leveling surveys, has not detected significant correlation between subsidence and withdrawal and disposal of geopressured brine. Also, no significant correlation exists between well testing and microseismicity, as detected by microseismic monitoring networks at the well sites. Quarterly sampling of surface and ground water around the well sites has not detected significant contamination (Van Sickle et al 1988).

DOE and the Electric Power Research Institute (EPRI) are cosponsoring a hybrid-power system test at the Pleasant Bayou site. The hybrid-power system (Figure 6) will use both natural gas and hot geothermal brine for power generation. The system is designed for 10,000 barrels per day of geopressured brine, containing 22 standard cubic feet of gas per barrel of brine. The working fluid in the binary cycle is isobutane. The design output is approximately 650 kWe from the gas engine/generator and 540 kWe from the binary turbine/generator, with parasitic loads of 210 kWe. The power produced will feed into the local power grid. The hybrid-power system will be operated in conjunction with the reservoir testing program of the Pleasant Bayou No. 2 well. Construction of the hybrid-power system will be completed in May 1989; a nominal 12-month testing period is planned. As designed, the system can produce at least 15 percent more electricity than the same amount of fuel and geothermal fluid used in separate power plants. The hybrid concept provides greater flexibility to developers in deciding how to market the energy produced from geopressured-geothermal resources.

The purposes of the DOE/EPRI geopressured hybrid-power experiment are: (1) to evaluate the potential of combustion/geothermal hybrid-power cycles for use in the development of geopressured and low-temperature hydrothermal resources, and (2) to evaluate the role of thermal energy in geopressured development economics.
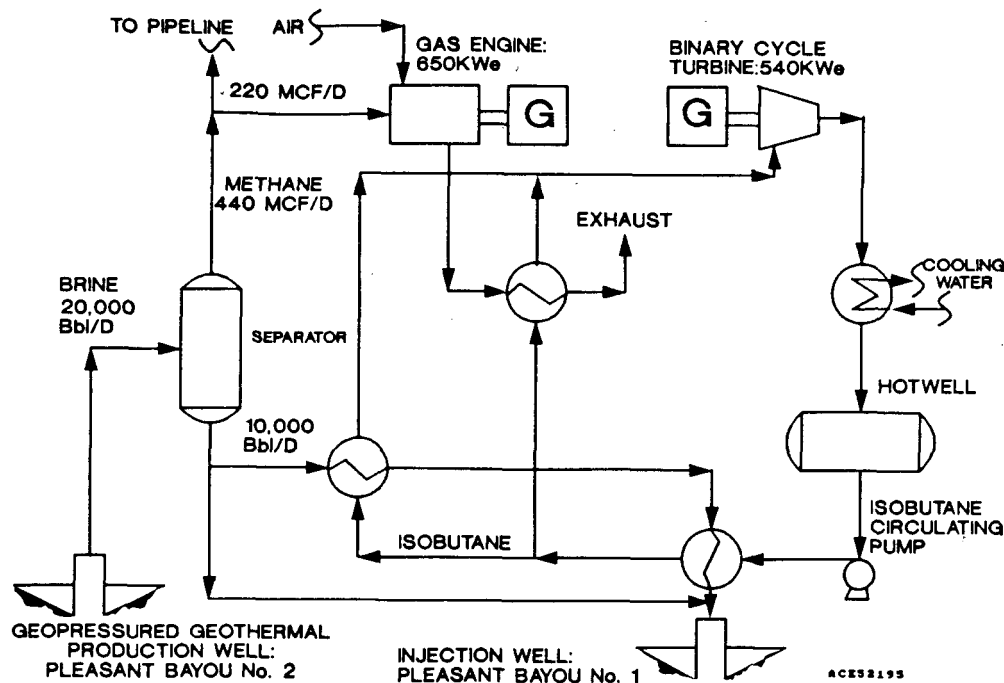
Figure 6. Hybrid Power System Schematic.

POTENTIAL FUTURE ACTIVITIES:

After the pressure buildup test at the Gladys McCall well is completed in October 1989, a final scientific testing program at the well may be implemented. Two questions that need to be answered are: (1) what has been the effect of high-volume production on the sandstone reservoir and surrounding shale units, and (2) what are the drive mechanisms responsible for pressure maintenance in the reservoir? The first question could be answered by coring the reservoir sandstone and the overlying and underlying shales and comparing the cores with pre-production cores; logging the well for comparison with pre-production logs should also be helpful. The second question could be answered by isolating and pressure-testing adjacent sandstone zones to determine if cross-flow from adjacent sandstone zones into the main reservoir has occurred.

The Pleasant Bayou well is currently being tested to acquire pressure drawdown data and to provide geopressured brine and gas for operation of the hybrid-power system, beginning in the summer of 1989. Long-term flow testing will continue at least until the summer of 1990. A long-term pressure buildup test is tentative, pending the outcomes of the drawdown test at Pleasant Bayou and the buildup test at Gladys McCall.

Finally, the Hulin well, which penetrates the deepest, hottest reservoir in the geopressured program, will be flow tested in 1989 for a short period; if the reservoir is capable of long-term production, permanent production facilities may be installed, and a long-term testing program initiated.

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