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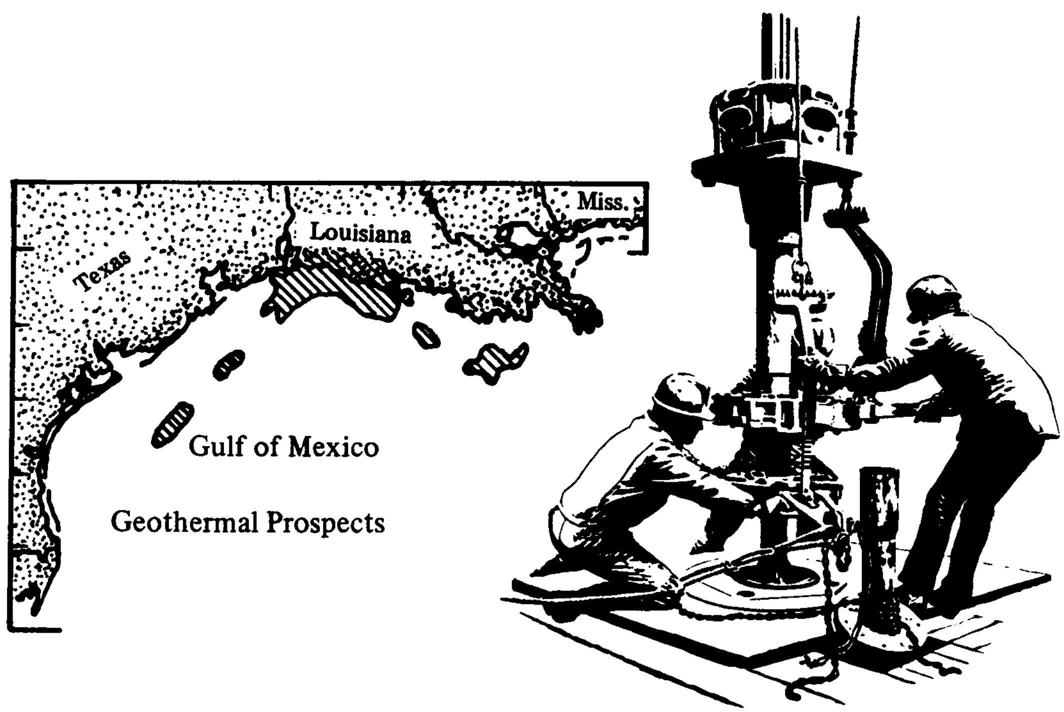
Geopressured-Geothermal Energy Resource Evaluation for the Northern Gulf of Mexico Basin - An Overview



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U.S. DEPARTMENT OF THE INTERIOR / BUREAU OF LAND MANAGEMENT

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GEOPRESSURED-GEOTHERMAL ENERGY RESOURCE EVALUATION FOR THE NORTHERN GULF OF MEXICO BASIN - AN OVERVIEW

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ABBREVIATIONS

atm	atmospheres (pressure)
atm/m	atmospheres per meter (pressure gradient)
bbl	barrels
Btu	British thermal units
Btu/mi^2	British thermal units per square mile
°C	degrees Centigrade
Ca	Calcium
cf	cubic feet
cf/bbl	cubic feet per barrel
Cl	chlorine
DOE	Department of Energy
EPA	Environmental Protection Agency
°F	degrees Fahrenheit
ft	feet
HCO_3	Carbonic acid ion
H_2S	hydrogen sulfide
J	joules
K	potassium
kg	kilograms
kg/cm^2	kilograms per square centimeter
kg/sec	kilograms per second
km^2	square kilometers
KPa/m	kilopascals per meter
KW	kilowatts
kWh	kilowatt-hours
M	meters
MBtu	thousand Btu's
Mcf	thousand cubic feet
mg/l	milligrams per liter
mi^2	square mile
Mscf	thousand standard cubic feet
Msl	mean sea level
MPa	thousand pascals
MW(e)	megawatts (electrical power)
MW-yrs	megawatt-years
Na	sodium
OCS	Outer Continental Shelf
psi	pounds per square inch (pressure)
psi/ft	pounds per square inch per foot (pressure gradient)
scf	standard cubic feet
scf/km^2	standard cubic feet per square kilometer
SiO_2	silica
SO_4	sulfate ion
SWF	secondary working fluid
USGS	U.S. Geological Survey
yrs	years

ACKNOWLEDGEMENTS

This report is based on a report originally prepared by Mr. Jack Rebman. Gratitude is expressed to Mr. Ray Wallace of U.S. Geological Survey for his critical review of the manuscript.

OFFSHORE RESOURCES

An executive reference map, entitled "Geopressured Geothermal Energy in Reservoir Fluids of the Northern Gulf of Mexico Basin," was published in February 1979 as Map-3 of USGS Circular 790. The map showed that formations containing fluids with pressure gradients greater than 0.5 psi/ft (11.3 kPa/m) could be encountered at depths less than 3,000 ft (914 m) to more than 18,000 ft (5486 m) in the basin. The map also showed the distribution of the 11,000 x 10^{18} joules (~ 11,000 quads) of thermal energy and the 6,000 x 10^{18} joules (~ 6,000 quads) of thermal equivalent dissolved methane energy estimated by Wallace, Kraemer, Taylor, and Wesselman (1979) to be contained in the waters of sandstones below the top of the geopressured zone to a depth of 22,500 ft (6.86 km) below msl in the 120,000 mi^2 (310,000 km^2) area. Almost 50% of this energy occurs beneath the federal OCS area, 24% or less beneath Louisiana and the remainder beneath Texas.

The locations of areas of high energy content determined by the regional computer summation techniques described are in good agreement with the locations of fairways or prospects previously identified by others using different methods.

A number of new areas have been delineated where the thermal energy content of sandstones is estimated to exceed 150 trillion Btu/mi^2, and the dissolved methane content is estimated to exceed 30 billion scf/km^2. These high concentration areas are located predominantly in about six trends, five offshore and one onshore. Preliminary investigation of the five offshore trends led to the delineation of five new prospects with potential for geopressured-geothermal resource development. These prospects are: the South Timbalier, the Eugene Island, and the Cameron prospects offshore Louisiana (Figures 1, 2, 3, and 4); and the Brazos and Brazos South-Mustang Island East prospects offshore Texas (Figures 5, 6, and 7). Excellent thicknesses of geopressured sandstones occur in all five prospects. Pressures and temperatures are also favorable, but water salinities appear to be high. More detailed evaluation will be required in the future to determine the physical and chemical characteristics of the water and reservoir extents and properties.

The potential for economically extracting solution methane from water is one of the most attractive aspects of the offshore geopressured-geothermal prospects. Investigation of the technical and economic viability of producing water for methane extraction upon depletion of conventional oil and gas reservoirs is thus suggested as an alternative to plugging of wells and removal of production platforms.

The petroleum crisis of 1973 caused an awakening of many countries to the need to evaluate and develop alternative energy sources. Consequently, during the past six years, geothermal exploration, utilization, and research have taken a dramatic upswing, both in the United States and throughout the world. This upswing in the United States has resulted in new information, improved exploration, extraction and utilization technologies, and a greater understanding of resource characteristics. But has this expanded activity of the past few years resulted in a significantly different assessment of the geothermal resource? To answer this question, the U.S. Geological Survey, with the support of the Department of Energy, has evaluated the geothermal resources of the United States in the light of nonproprietary data available in June 1978. This new geothermal resource assessment is reported in USGS Circular 790, "Assessment of Geothermal Resources of the United States - 1978," to which the reader is referred for background information.

A careful distinction is made between the geothermal energy in the ground to a specified depth (the resource base) and the thermal energy that could be extracted and used at some reasonable future time (the resource). It is the resource, not the accessible resource base, that is of real significance to man and that can be compared with other energy resources.

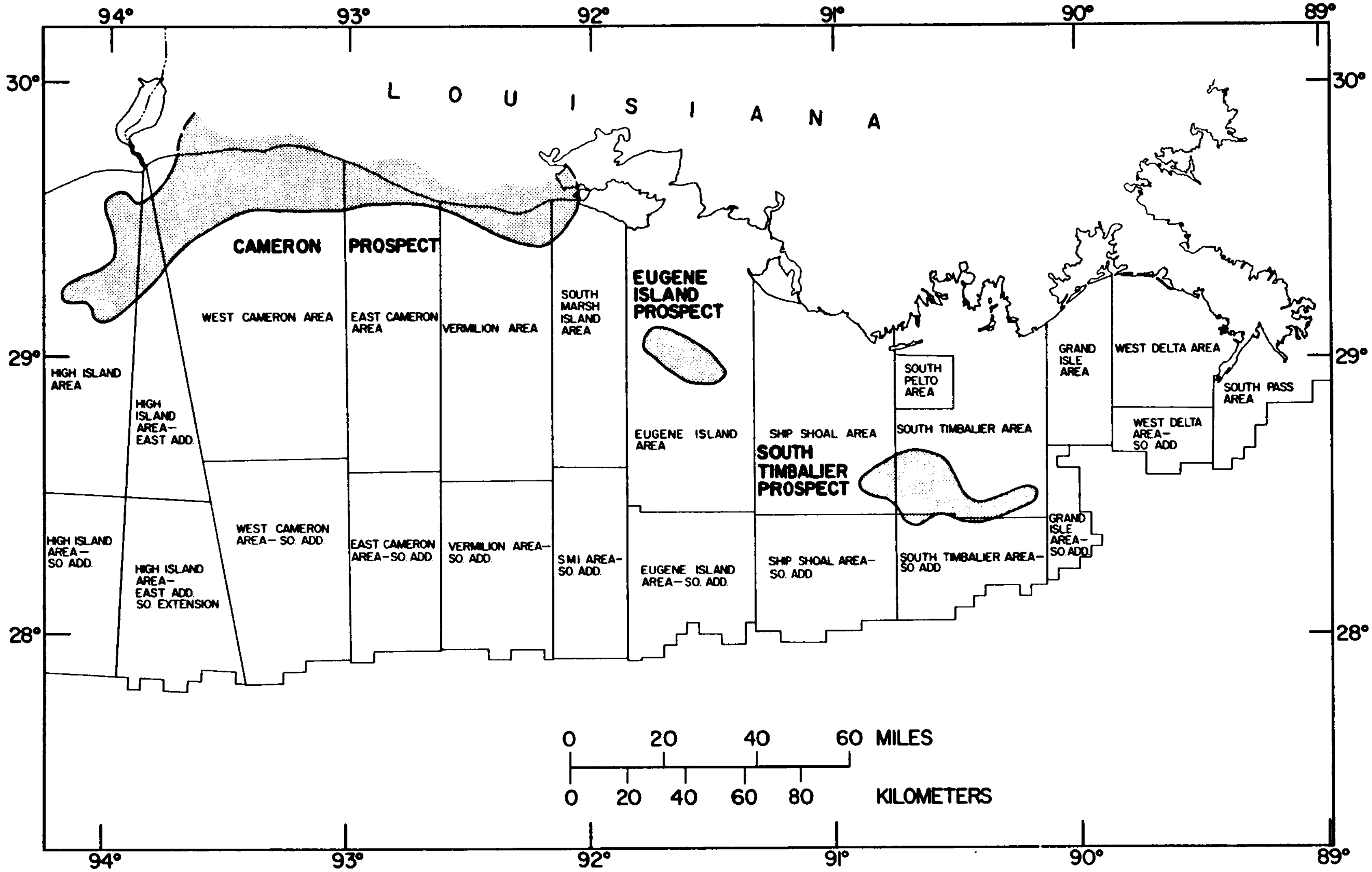


Figure 1. Location of geopressured-geothermal prospect areas occurring offshore Louisiana.

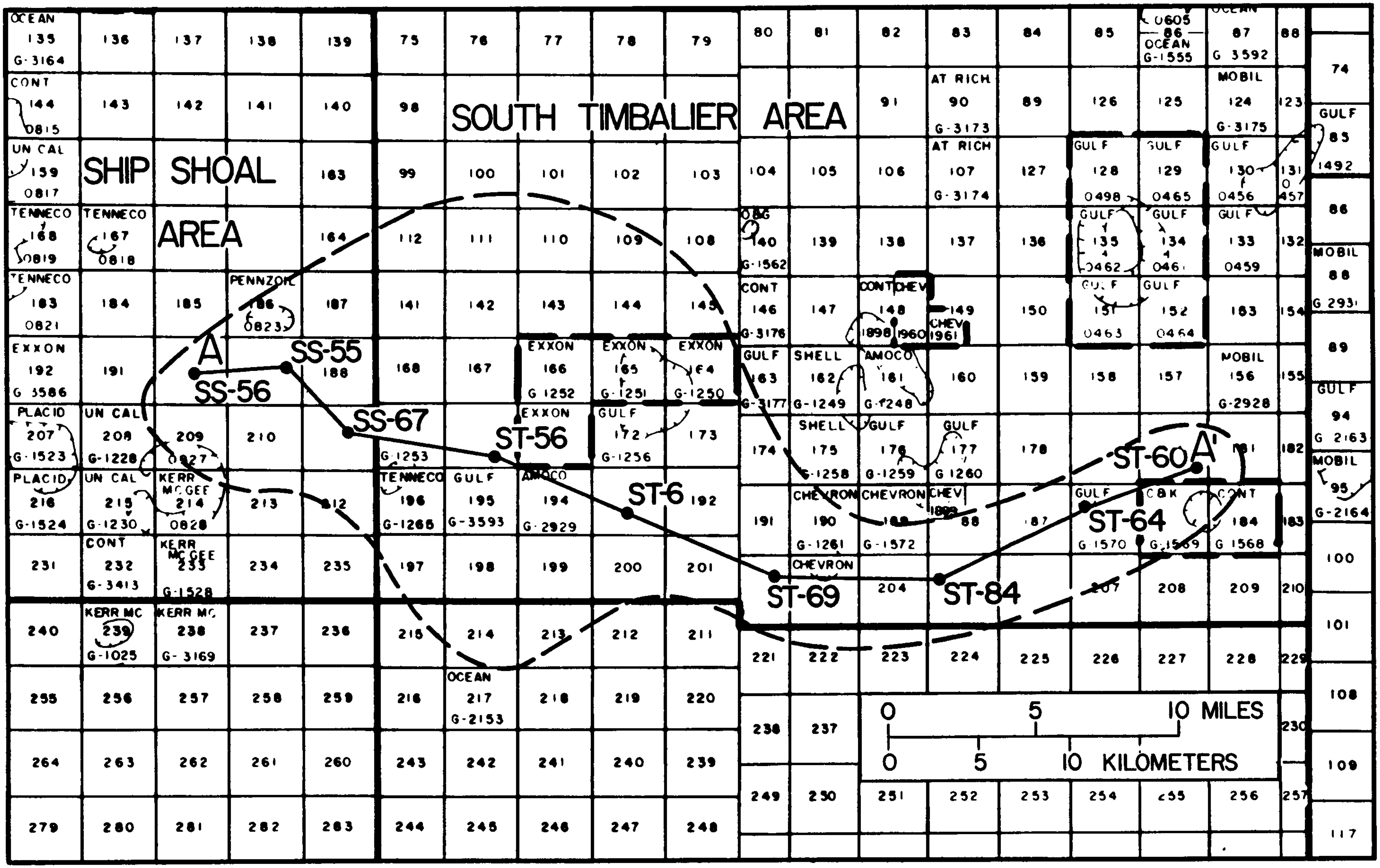


Figure 2. Preliminary boundary of the South Timbalier prospect, offshore Louisiana.

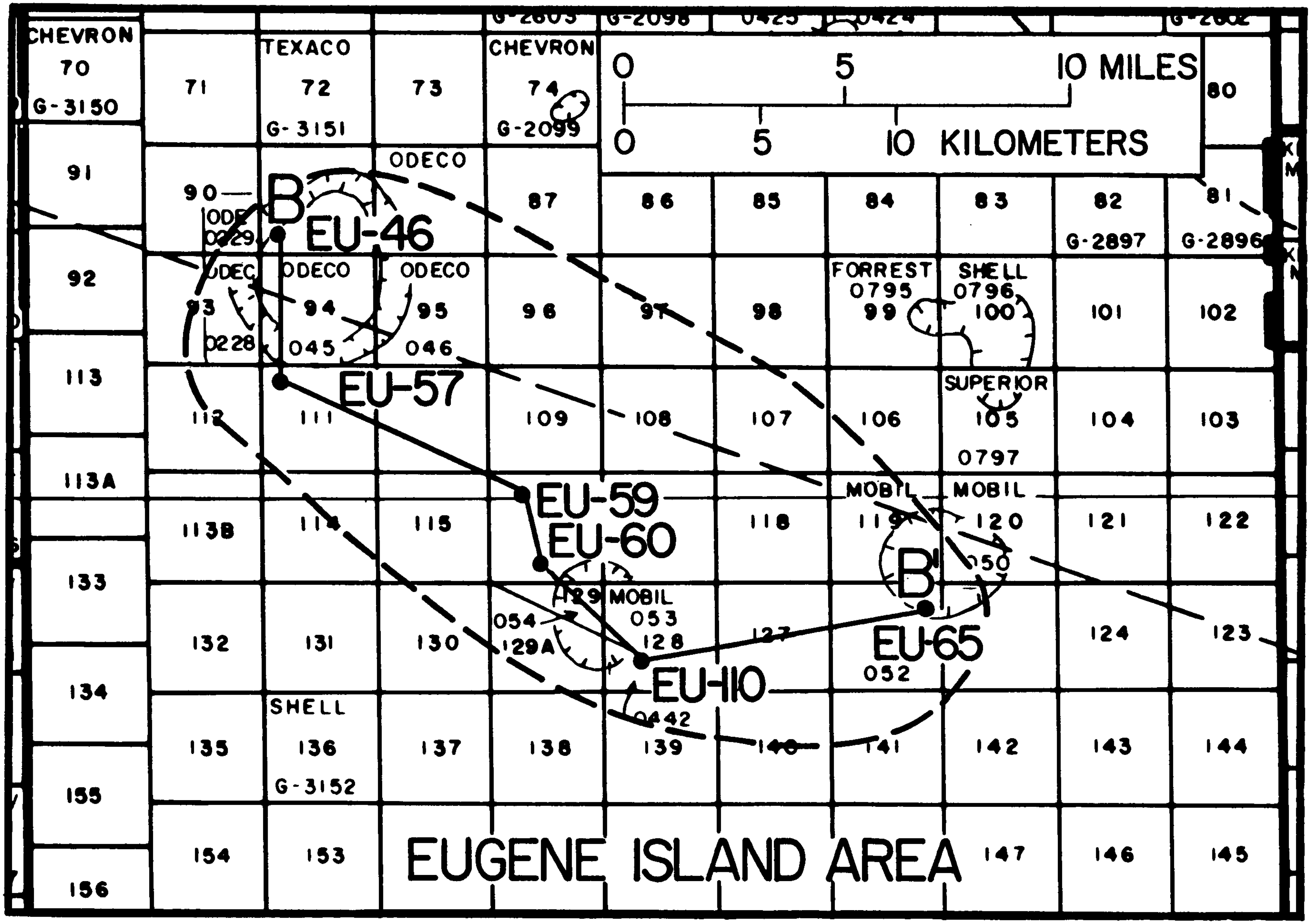


Figure 3. Preliminary boundary of the Eugene Island prospect, offshore Louisiana.

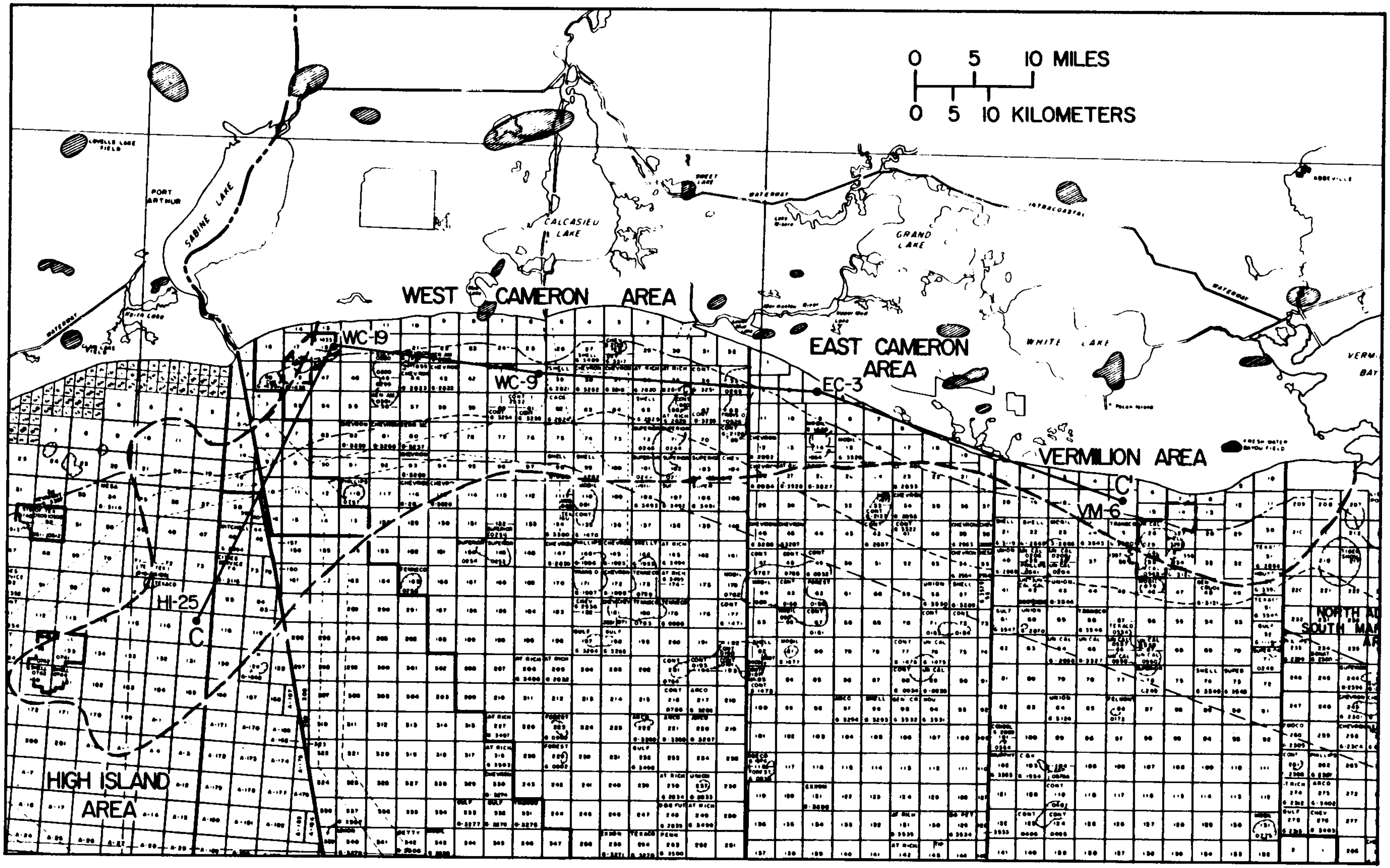


Figure 4. Preliminary boundary of the Cameron prospect, offshore Texas and Louisiana.

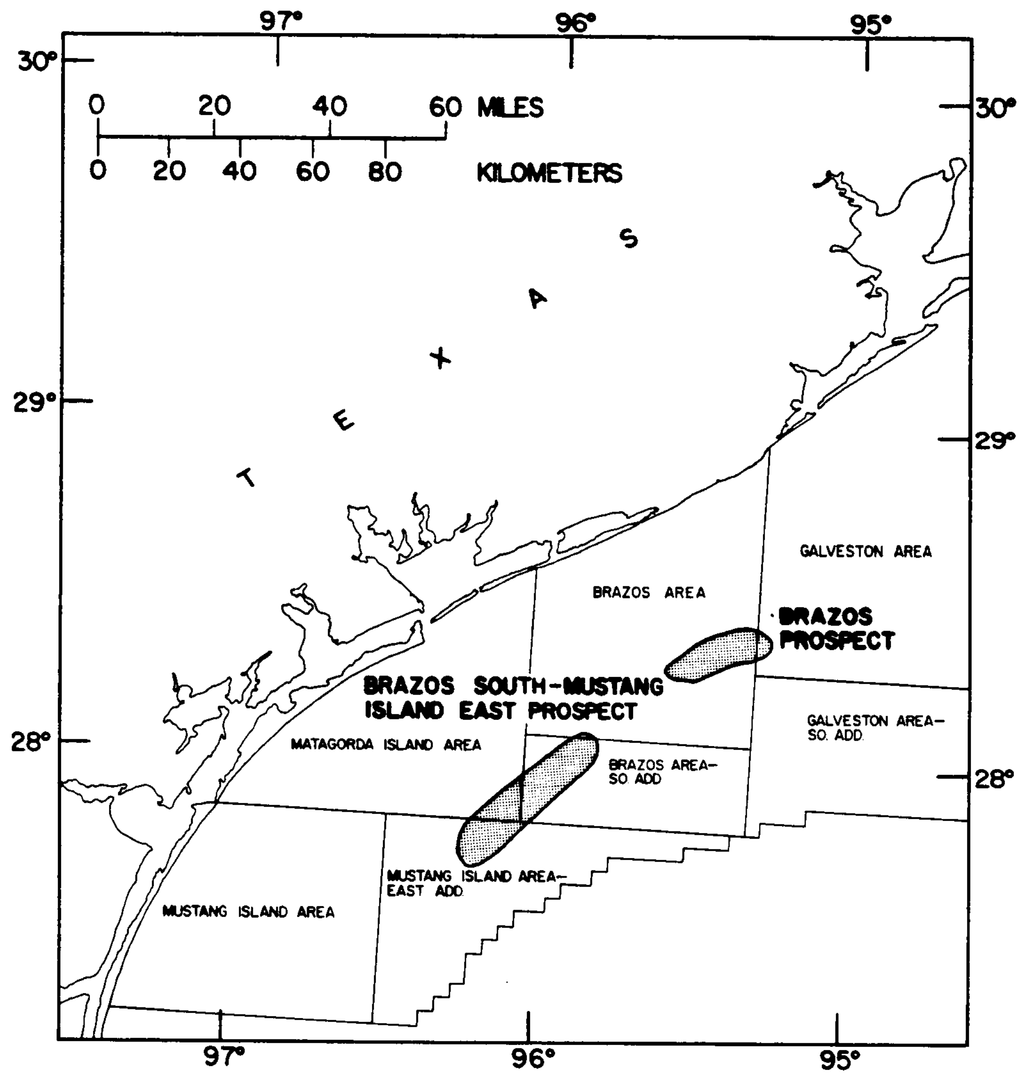


Figure 5. Location of geopressured-geothermal prospect areas occurring offshore Texas.

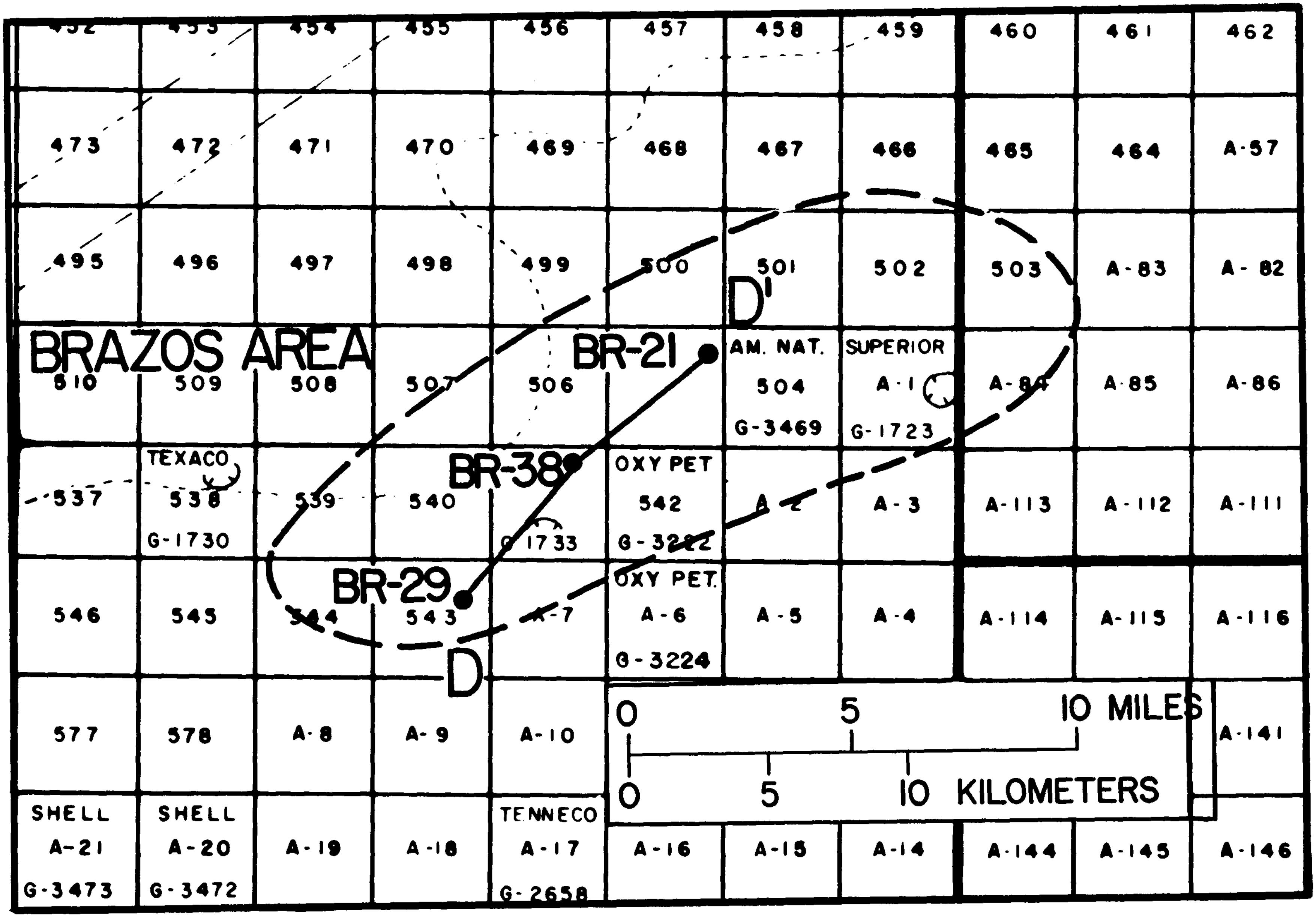


Figure 6. Preliminary boundary of the Brazos prospect, offshore Texas.

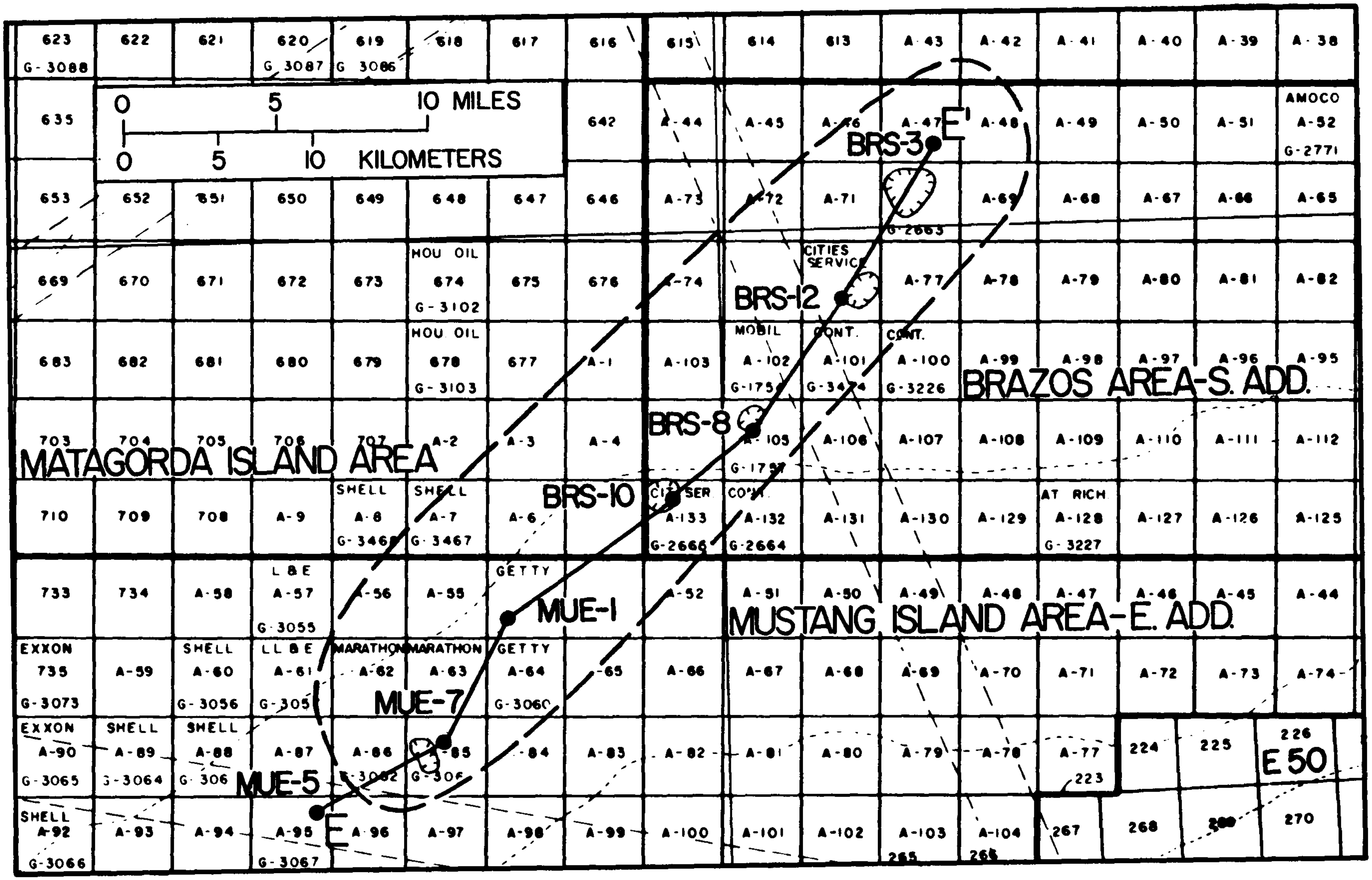


Figure 7. Preliminary boundary of the Brazos South-Mustang Island East prospect, offshore Texas.

The following sections were taken from EPA's Interagency Energy-Environment Research & Development Program report, "Environmental Assessment of Geopressured Waters and Their Projected Uses," by J. S. Wilson, et al., April 1977.

1. Resource Description
2. Origin of Geopressure
3. Origin of High Temperature
4. Nature of Geopressured Geothermal Fluids
5. Geopressured Reservoirs
6. Resource Utilization

RESOURCE DESCRIPTION

Four broad categories of geothermal systems have been recognized:

- Magmatic
- Hot, dry rocks
- Convective
- Geopressured

Technology has not yet been developed to exploit the first two types; therefore, they will not be discussed.

The third type, convective geothermal, is the only type now being commercially exploited. In convective systems, circulating fluids within a bounded reservoir transfer heat from a deep source to near the surface. Isotope ratios and trace element studies indicate the source of the convective water to be principally meteoric. Rainwater percolates downward, probably along fault planes, becomes heated, and where impermeable rock overlies the permeable reservoir, escape of the water is prevented and a convective system is created.

The ultimate source of heat to drive the convective engine is from magmas within the earth's crust. These may be basaltic, such as in Iceland; acidic intrusions, such as the Circumpacific geothermal areas frequently associated with andesitic volcanics; or merely a thin crust composed of highly conductive rock, such as in the Hungarian basin or the Battle Mountain, Nevada area.

Two major subtypes of the convective system exist: vapor-dominated and liquid-dominated systems. Vapor-dominated systems are relatively rare but account for most of the commercial geothermal energy being produced today, notably at Geysers, California, and Larderello, Italy. The fluid produced is dry, superheated steam characterized by an absence of volatile constituents. Liquid-dominated systems, such as Wairaki, New Zealand, produce a mixture of wet steam and hot water. These fluids frequently possess high saturations of soluble, nonvolatile substances, such as SiO_2, and the ions Na, K, Ca, Cl, SO_4, HCO_3, etc. The characteristics of liquid-dominated systems vary widely, and numerous subtypes exist.

Geopressured zones occur throughout the world in basins where rapid sedimentation and contemporaneous faulting are taking place and are characterized by abnormally high pressures and temperatures. The most studied and best understood geopressured region in the world is the Gulf coast of the United States.

ORIGIN OF GEOPRESSURE

Numerous authors have attributed the origin of geopressure to undercompaction of the sediments. Much confusion arises from the use of the word "undercompaction" as a genetic rather than as a descriptive term. In theory, sediments, predominantly clays, accumulate in a rapidly subsiding basin. It has been demonstrated off the Mississippi delta that pore water in the upper layer of this sediment can constitute 70% or more by volume. As the process of burial occurs, the stress of an accumulating overburden causes energy potentials to be created in the system according to the formula:

$S = P + O$
S = Vertical component of geostatic stress
P = Interstitial fluid pressure
O = Normal component of grain-to-grain pressure

Burst (1969), in a definitive paper, discusses the diagenesis of Gulf coast clayey sediments. He describes fluid expulsion in three separate stages; however, for purposes of explanation, the first stage has been subdivided into two parts.

Approximately 80% of the clay deposited in the Gulf is composed of montmorillonite, or swelling clay. The clay lattice contains two interlayers of tightly bound water and may contain many interlayers of loosely bound water.

Stage 1 in the burial process is the expulsion of excess pore water, which represents about 60% of the original volume. This occurs at very shallow depths and is essentially complete at depths of a few hundred feet. The clay platelets are not in contact, but are greatly swollen with loosely bound interlayer water.

The second part of Stage 1 involves the loss of this excess interlayer water, which can occur at depths of 600 m or less, still well within the hydropressure zone, and is a purely mechanical process. The clay lattice is now in stable form, containing two interlayers of water. The sediment is "compacted," with grain-to-grain contacts supporting the lithostatic component of the overburden load and the capillary pore pressure supporting the hydrostatic component.

Burial continues until the sediments have reached a depth corresponding to the critical temperature necessary for the second stage of clay dehydration to occur. Burst demonstrates that this is a temperature-dependent phase change occurring between 95°C and 100°C, which releases the next-to-last water interlayer. The pressures and temperatures of the geopressured zone are insufficient to liberate the last water interlayer.

When fluid escape is possible within the system, water will move from the higher energy potential to the lower in accordance with Darcy's Law. If the rate of accumulation of geostatic stress is very great and exceeds the ability of the sediment to dewater under Darcy's Law, then the interstitial fluids must assume an increasing proportion of the total overburden load and geopressure will occur. Fluid pressures in the geopressure zone commonly represent 0.5 - 0.95 of the total overburden. This process is generally implied by the statement that geopressure is caused by the undercompaction of sediments.

If the escape of fluids is restricted vertically by the sedimentary column and laterally by contemporaneous faulting, facies changes, or permeability pinch-out, then the change of relative volumes of the solid and liquid phases forces the liquid to support a proportionally greater part of the overburden load; i.e., the formation becomes geopressured. Pressure gradients in the geopressure zone may approach lithostatic, or approximately 0.2 atm/m (1 psi/ft of depth). Mechanical energy available at the well head is approximated by the bottom hole pressure minus the hydrostatic head and frictional losses in the bore hole.

If the aforementioned theory is entirely correct, one would expect to see uniformly increasing geopressure with depth; such, however, is not the case. Sediments in the Gulf coast geosyncline are found in two distinct, bounded pressure regimes: the upper hydropressured regime, extending to an approximate depth of less than 1,000 m to more than 5,000 m, and the lower geopressured regime which is at variable depths. The boundary between the hydropressured and geopressured zones may be distinct and is characterized by increased pressures, thermal gradients, flowline temperatures, penetration rates, decreased seismic velocity, shale density, and shale resistivity.

ORIGIN OF HIGH TEMPERATURE

In a thermal system in equilibrium, heat can be neither created nor destroyed, and the heat flow from the deep crust and mantle of the earth must equal the heat flow at the surface. If this were not so, the crust of the earth would soon heat up to temperatures sufficient to vaporize all rock.

The relationship of heat flow, thermal gradient, and thermal conductivity is governed by Fourrier's Law, expressed as:

$Q = rK$;
Where Q = heat flow;
r = thermal gradient;
K = thermal conductivity

The "subcompacted" geopressured sediments and the isolated fluids possess a much lower thermal conductivity than the overlying "compacted" hydropressured sediments. Because heat flow remains constant, any decrease in conductivity must be counterbalanced by a proportionally increased thermal gradient. This blanket effect traps the upward flowing heat causing the anomalously high temperatures encountered in the geopressured zone. Temperatures may range from 110°C at depths shallower than 3,000 m to more than 260°C at 6,000 m and deeper.

Some expert opinions have been expressed at various geopressure symposia that salt diapirs, found in many of the geopressured areas, are the true source of the heat. These long columns of salt could act as heating rods to convey high deep heat to upper areas; mass transfer of heat could also occur up fault planes (forced convection). In any case, it must be concluded that the explanation of the origin of the heat leaves much room for further research.

NATURE OF GEOPRESSURED-GEOTHERMAL FLUIDS

Geothermal fluids possess several other characteristics in addition to high temperatures and pressures. Water salinities are usually lower than those found in the hydropressured zone. This statement is based upon salinity estimates which can be obtained from spontaneous potential measurements on electric logs. These potentials are analyzed in terms of the dissolved solids in formation water, expressed as mg/l of sodium chloride. This is a generally accepted procedure in the petroleum industry, and thousands of geopressured well logs have been examined in this way.

A plot of salinity versus depth from such a well shows very high salinity as the well enters the geopressured zone, followed by a sharp decline. Such a curve taken from Schmidt is shown in Figure 8. Samples of these waters have confirmed these low salinities. Most samples obtained from the top of the zone show misleading high salinity while deeper water is of relatively low salinity. Typically, geopressured waters have salinities in the range of $<10,000$ to 270,000 mg/l, as compared with 160,000 mg/l or greater in the overlying sediments. The cause of this is two-fold. First, the water expelled from the clay lattice during the second stage of dehydration is essentially fresh. It dilutes the residual saline pore water, thus reducing overall salinities. Second, the shale itself may act as a semipermeable membrane, concentrating brines at certain interfaces and thus freshening adjacent waters. This phenomenon is imperfectly understood at present. The abrupt change in salinity and reverse of the salinity gradient is very apparent on electric logs and has long been considered diagnostic of the geopressured zone.

Buckley et al (1958), Burst (1969), Phillippi (1965) and others have demonstrated that hydrocarbon maturation begins at a temperature of about 65°C. The methane formed and dissolved could be the largest component of geopressured-geothermal energy in both financial terms and in terms of extractable energy. Some H_2S (hydrogen sulfide) may be associated with the methane in the lower Tuscaloosa and other Mesozoic formations.

Silica (SiO_2) results from dissolution of quartz and is also a by-product of diagenesis of montmorillonite. Geothermal fluids are expected to be near the saturation level for SiO_2. This could present scaling problems in the borehole and wellhead equipment, and may lead to a permeability barrier developing around the wellbore, if pressure drawdown is allowed to occur too rapidly. This would plug the well. Therefore, careful pressure maintenance programs must be followed. The silica problem common in other geothermal fluids is also present in the geopressured waters.

GEOPRESSURED RESERVOIRS

The geopressured zone of the upper Gulf coast occurs in a broad band 300-500 km wide that stretches from below the Rio Grande along the coast to the mouth of the Pearl River, a distance of more than 2,000 km. The geopressured zone extends offshore at least to the shelf edge and contains an accumulation of clastic sediments that exceeds 15,000 m in thickness in some areas.

The sediments range in age from the Upper Cretaceous, approximately 70 million years old, to Pleistocene, only about 1 million years old. Three major sedimentary facies predominate: a massive sandstone facies and an alternating sandstone; shale facies of the great deltas which shaped the coast in the geologic past; and a massive shale facies, formed offshore and now generally occupying the deeper portion of the Gulf coast geosyncline. The sands may be of the transgressive type, where wave action of an encroaching sea has produced a blanket of clean, well-sorted sandstone overlain by a marine shale; or they may be regressive, or progradational, sand bodies composed of lenticular units that represent ancient barrier bars and the other discontinuous types of sand units that are formed as a delta progrades into the sea. The transgressive sands are by far the most favorable for fluid production, possessing greater porosity, permeability, continuity, and areal extent.

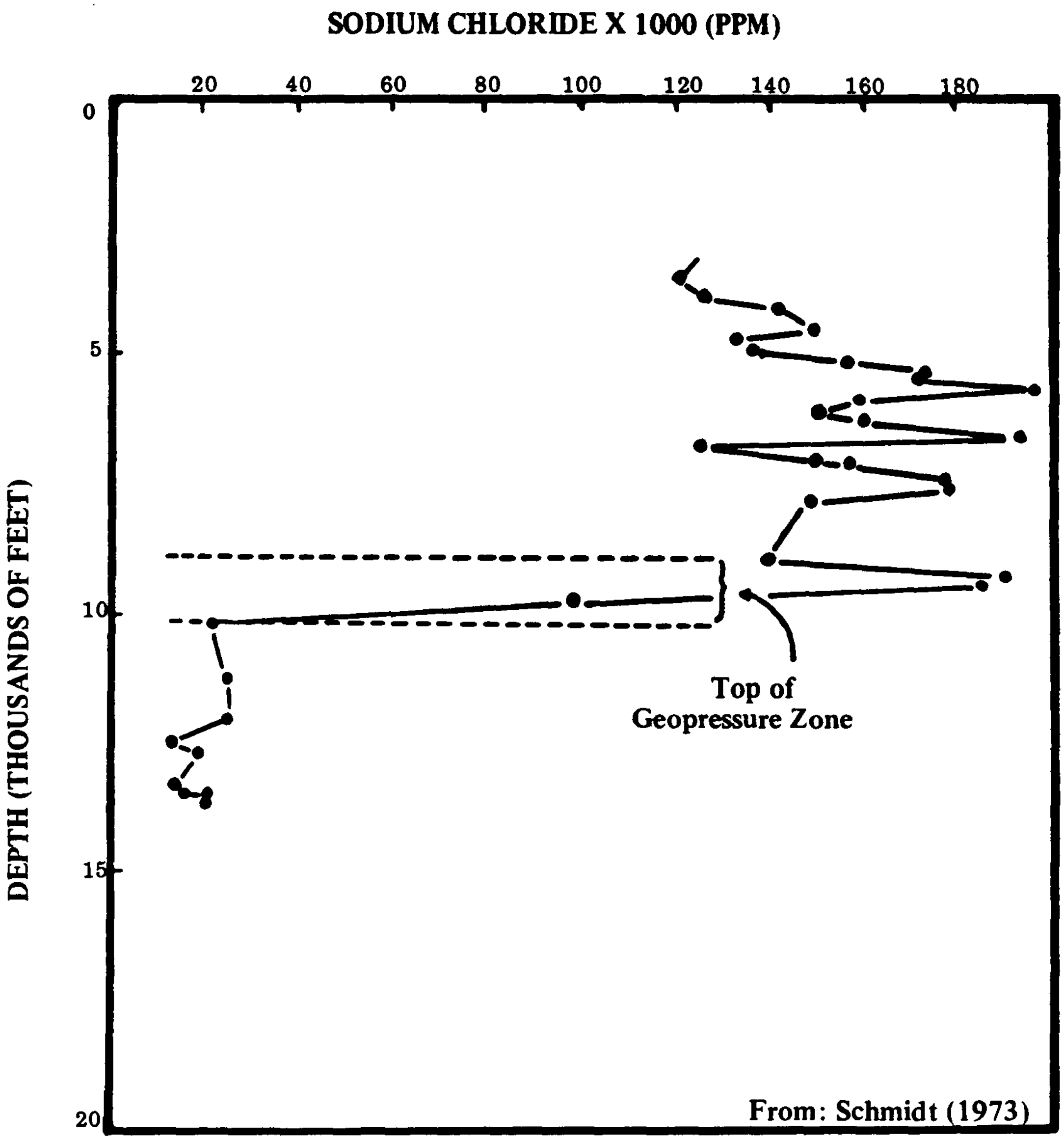


Figure 8. Change in formation water salinity with depth, in relation to the occurrence of the geopressure zone, Manchester Field, Calcasieu Parish, Louisiana.

Unfortunately, regressive type sand bodies predominate on the Gulf coast. When a sand body is contained in an interval of geopressured shale, it becomes charged with the geothermal fluids and thus becomes a potential reservoir.

The pattern and distribution of the sand bodies is determined largely by the numerous contemporaneous, or growth, faults that lace the coast in a subparallel trend to the present shoreline. These faults may have throws of 1,000 m or more and act as effective barriers to retard the escape of geopressured waters (i.e., they may form reservoir boundaries). Sand distribution is further affected by complex diapirism and flowage of shale and salt underlying tertiary sediments.

The general distribution of sediments is in the form of a series of over- and off-lapping clastic wedges or pads, each representing a cycle of deltaic deposition, the oldest far inland and the youngest still being formed offshore in the Gulf of Mexico.

GEOLOGY AND HYDROLOGY OF THE TIGRE LAGOON GAS FIELD, EASTERN VERMILION PARISH, LOUISIANA

The degree of methane saturation of geopressured-geothermal water is of prime importance to recoverable resource estimates. In an attempt to determine methane saturation levels in geopressured reservoirs, Coastal States Gas Producing Company's Edna Delcambre No. 1, Vermilion Parish, Louisiana, was recompleted in 1977 under a DOE contract with McNeese State University, Lake Charles, Louisiana, and OHRW Engineering, Bryan, Texas. A summary of the results of this well, as prepared for DOE by Hankins and Karkalits (1978), follows.

The Tigre Lagoon Gas Field in east-central Vermilion Parish, Louisiana, occupies a complexly faulted northwest-southeast trending structure. As mapped on the top of the Planulina zone, it is about four miles long and two miles wide, and is located about four miles due west of the Avery Island salt dome. Nonassociated gas is produced from several high-pressure conventional reservoirs formed by extensive sand bed systems in the geopressured zone. In the field area, geopressure occurs below a depth of about 12,000 ft; the geopressure "seal" is a shale bed only 300-500 ft thick. The depth pressure gradient in the Coastal States Gas Producing Company's Edna Delcambre Well No. 1 was 0.52 psi/ft at 12,070 ft and 0.86 psi/ft at 12,410 ft; a pressure differential of 4,300 psi occurs in a depth interval of 340 ft. The Coastal States Edna Delcambre Well No. 4, less than 1,000 ft north of Well No. 1, blew out and cratered in 1969 from a depth of about 14,000 ft.

The gas reservoirs of the Tigre Lagoon Field, formed by a narrow rollover fold, are located immediately southwest of a major growth fault that is the landward boundary of a lower Miocene depositional basin. Subsidence occurred as the basin was rapidly filled by deltaic, coastal, and nearshore marine sediments. These deposits were capped by a transgressive marine shale that can be identified in drill cuttings by a Planulina marker fossil. The Tigre Lagoon rollover anticline is cut diagonally by arcuate branch faults which fill out westward at distances of 2-3 miles. At least five widespread sand bed aquifers, probably formed by the winnowing action of waves in ancient coastal lakes, occur between depths of 12,500 and 14,000 ft. These sand beds range in thickness up to about 250 ft in the eastern part of the Planulina basin, but generally are no more than 100 ft thick; their areal extent is commonly greater than 50 mi^2. The hydraulic continuity of these aquifers regionally is interrupted by fault displacements and, except to the westward, fluid movement is much influenced by geologic structure.

Natural gas in the producing reservoirs at Tigre Lagoon is not associated with oil. The solubility of natural gas (methane) in water of moderate to low salinity is very great at the elevated pressures and temperatures of the geopressured zone; each barrel of water rising from depths of 15,000-20,000 ft in the Planulina basin may, at low salinity, contain up to 100 cubic feet of methane. As the pressure and temperature of the rising water are reduced along the path of flow and the salinity is increased by hyperfiltration, as water escapes through the shale-bed "seal," methane comes out of solution and released vapor-phase gas accumulates in structural traps and forms commercial reservoirs. A pressure drop from 16,000-6,000 psi, at 400°F, for example, reduces methane solubility in fresh water by 52 cf/bbl; a temperature drop from 400°F to 200°F, at 10,000 psi, reduces it by 49 cf/bbl.

The Tigre Lagoon structure has been a focus of water flow from deep in the Planulina basin for millions of years with continuing leakage into the overlying hydropressure zone–mainly by movement up fault planes when fluid pressure exceeds rock pressure. The clay bed is thin and the pressure differential across it is large. Even today the fluid pressure is very close to the fracture pressure required for leakage up growth faults and branch faults. Hyperfiltration of saline formation waters that seeps through the clay bed "seal" as a consequence of the great pressure differential has concentrated the dissolved solids in the uppermost aquifers of the geopressured zone, where water salinities locally exceed 100,000 mg/l. As water salinity is increased, methane solubility is substantially reduced–as much as 30% if salinity is raised from 10,000-100,000 mg/l. The combined effects of pressure, temperature, and water salinity changes have resulted in methane exsolution and accumulation in the Tigre Lagoon structure, and commercial gas reservoirs are found in six of the uppermost eight sand bed aquifers in the geopressured zones.

Coastal States Gas Producing Company's Edna Delcambre Well No. 1 was recompleted in 1977 to produce waters from the first and third aquifers below the top of the geopressured zone and to measure their methane content. Neither of these sand bed aquifers is known to form commercial natural gas reservoirs. Recompletion and production tests were designed to enable collection of formation water within the well at depths near aquifer depth, to enable continuous sampling of produced fluids at the well head under controlled rates of flow at measured pressures, and to monitor the rate of sand influx through perforations at selected flow rates.

Hydrologic data obtained from the tests lead to the following interpretations and conclusions:

1. All formation waters in tested aquifers are at saturation *in situ*; vapor phase gas is also present as dispersed bubbles that become entrained in the flow to the well during flow tests.

2. The gas/water ratio of produced water is highly sensitive to flow rate; for aquifer no. 1, it increased from 16.8 cf/bbl at a flow rate of 1,165 bbl/day to 64.2 cf/bbl at 7,599 bbl/day. Data for aquifer no. 3 are not usable because there is a zone of free gas a few feet thick at the top.

3. Formation water salinity maps reflect long-term leakage through the Tigre Lagoon pressure "seal" from a rather broad area as a marked increase in salinity is evident near its crest–a consequence of hyperfiltration of water leaking through the clay bed "seal."

4. Upwarps of isothermal surfaces reflect the upward movement of hot water, indicating that the southern part of the Tigre Lagoon structure has long been a zone of fluid leakage from the geopressured zone.

5. Aquifer maps, structural maps, and geologic sections show that the combination of subsurface conditions that result in the natural exsolution of dissolved methane, and the trapping of vapor phase gas to form commercial reservoirs, *do not favor the large-scale production of water necessary for commercial geopressured-geothermal resources development.*

6. Both of the aquifers tested could be developed, using water-well technology and equipment, to produce at least 50,000 bbl/day of geothermal brine with free gas. At these flow rates, the gas/water ratio should exceed 50 cf/bbl initially, gradually falling to about 18 cf/bbl in 5-10 years. This ratio should hold for the remainder of the well life.

Geologic and hydrologic studies made in the Tigre Lagoon Field area, together with interpretation of data obtained from the flow tests in the recompleted Coastal States Edna Delcambre No. 1 Well, provide the basis for identification and assessment of aquifer systems and the mapping of conditions in those systems most favorable for resource development. Criteria to be used in site selection will differ depending upon the product to be developed: for geothermal resources, wells should produce from thick, highly permeable aquifers of broad (regional) extent in which little or no structural deformation has occurred; for natural gas, wells should tap moderately thick, regionally extensive aquifers and be drilled on structural highs, preferably a few thousand feet from hydraulic barriers (faults or pinchouts) which restrict flow and amplify head declines caused by fluid withdrawals from producing wells.

TEXAS GEOPRESSURED-GEOTHERMAL EVALUATION

The geological parameters used in geopressured-geothermal fairway evaluation and test-well site location, Frio Formation, Texas Gulf coast, was presented at the Third Geopressured-Geothermal Energy Conference by Dr. D. G. Bebout (1977). A summary of that presentation follows.

Within the drainage area of a single geothermal well in the Austin Bayou Prospect, Brazoria County, Texas, it can be inferred that more than 10 billion barrels of water with temperature higher than 300°F occur in place in the prospective sandstone reservoir. This water volume represents 1,733 MW-yrs of potential electrical energy and 200-250 billion cubic feet of methane in solution. The estimate of geothermal potential of the Austin Bayou Prospect is being tested by a deep well--the General Crude and DOE No. 2 Pleasant Bayou. The long-term flow test is now in progress with the well producing some 30,000 bbl/day water and 30 Cf/bbl gas.

The Austin Bayou Prospect in the Brazoria Fairway is composed of a sandstone and shale section with seven progradational depositional events, several of which are characterized by low-porosity prodelta and distal delta-front shale and sandstone at the base and porous distributary-mouth bar and delta-plain sandstone and shale at the top. Three hundred (300) feet of sandstone was present between the depths of 14,600 and 15,700 ft. About 100 ft has porosity of 15%. Permeability as high as one darcy was measured. Temperature at the top of the sandstone section will be 300°F. Water produced at a rate of 20,000-40,000 barrels per day will be disposed by injection into shallower sandstone reservoirs.

Factors controlling geopressured-geothermal reservoir quality for the Frio sandstone facies along the Texas Gulf coast was presented by Loucks and Moseley, Bureau of Economic Geology, University of Texas at Austin at the Third Geopressured-Geothermal Conference (1977). A summary of the presentation follows.

Geopressured-geothermal reservoir quality along the Texas Gulf coast is controlled by sandstone depositional environment, mineralogical composition, and consolidation history (compaction, cementation, and leaching).

The best Frio reservoirs occur at the top of deltaic progradational sequences in distributary-mouth bar and distributary-channel sandstone facies. Poor reservoir quality characterizes proximal delta front and distal delta-front sandstones. Along the upper Texas Gulf coast, sandstone mineralogical composition varies from quartzose, feldspathic, volcanic litharenite and quartzose, lithic arkose to a feldspathic, volcanic litharenite rich in carbonate rock fragments along the lower Texas Gulf coast.

Frio sandstones exhibit the following four major stages of consolidation:

1. Near-surface to shallow subsurface compaction and cementation stage (0-4,000 ft ±). Porosity is reduced from 40% to approximately 25%.

2. Intermediate subsurface cementation stage (4,000-8,000 ft ±). Porosity is commonly reduced to 10%.

3. Intermediate subsurface leaching stage (8,000-11,000 ft ±). Leaching of grains and cements may resurrect porosities to as high as 30%. This is the zone of geothermal reservoir development.

4. Deep subsurface cementation stage (11,000 ft ±). High reservoir quality necessary for geothermal prospects depends on the absence of this late cement.

Geothermal reservoirs are not composed of simple primary porosity between grains, but consist of secondary leached porosity. The Austin Bayou Prospect in Brazoria County, Texas, is a prospective geothermal reservoir that is the product of secondary leached porosity. However, it must be noted that it is difficult to differentiate between primary and secondary porosity.

The General Crude Oil Co. Pleasant Bayou No. 1 was the first well in the United States designed specifically to test the geopressured-geothermal resource. The planned total depth was 16,500 ft. Sand beds were planned to be tested sequentially in decreasing depth to 15,645 ft. The well was lost, however, and plugging operations were completed January 13, 1979, with a cement plug of 200 ft set from 8,381-8,581 ft inside the 13 3/8" casing. The hole was then temporarily abandoned with a cement plug at the surface. It is in prime condition for use as a saltwater disposal well at a future date. During the interim the rig has been moved some 500 ft southwest; the No. 2 Pleasant Bayou was drilled to a depth of 16,500 ft.

ASSESSMENT OF RECOVERABLE ENERGY - THE RESOURCE

A preliminary estimate of the geopressured-geothermal energy of the northern Gulf of Mexico basin was presented by Papadopulos, Wallace, Wesselman, and Taylor (1975) in Circular 726. Using data from 250 wells, they estimated that 46,000 x 10^{18} J of thermal energy was contained in geopressured waters of the onshore tertiary sedimentary rocks of the Gulf coast to depths of 6 km in Texas and 7 km in Louisiana. They also estimated that an additional 25,000 x 10^{18} J of energy was represented by methane dissolved in these geopressured waters. Undiscovered and unevaluated geopressured geothermal energy in offshore, deeper Tertiary, and onshore Cretaceous sedimentary rocks of the Gulf coast was estimated to be 1½ - 2½ times the identified energy. The total identified and undiscovered thermal and methane energy in geopressured fluids of the northern Gulf of Mexico basin was thus estimated to be approximately 106,000-178,000 x 10^{18} J.

Wallace, et al. (Circular 790, 1978), presents an estimate of the thermal and dissolved methane energy contained in the entire northern Gulf of Mexico basin, both onshore and offshore, to depths of 22,500 ft (6.86 km). Their estimate, based on data from over 3,500 wells, in general substantiates the preliminary estimate of Papadopulos, Wallace, Wesselman, and Taylor (1975). The total identified thermal energy in fluids of both sandstone and shale is estimated to be 170,000 x 10^{18} J.

The major uncertainty in geopressured-geothermal resource assessments lies in determining the *amount of fluid that can be recovered at the surface*. The few production tests carried out to date have not significantly modified the recoverability analysis presented by Papadopulos, Wallace, Wesselman, and Taylor (1975). Application of this analysis to data of Wallace, et al. (Circular 790), suggests that the recoverable thermal energy from geopressured waters of the northern Gulf of Mexico basin ranges from 270 x 10^{18} J under plan 3 (controlled development with limited pressure reduction and subsidence) to 2,800 x 10^{18} J under plan 2 (depletion of reservoir pressure). Recoverable methane energy ranges from 158 x 10^{18} J under plan 3 to 1,640 x 10^{18} J under plan 2. If 8% of the recoverable thermal energy could be converted to electricity (as assumed by Papadopulos, Wallace, Wesselman, and Taylor, 1975), the electricity produced would range from 23,000 MW(e) for 30 years under plan 3 to 240,000 MW(e) for 30 years under plan 2.

Garland Samuels, in his May 1979 "Geopressure Energy Resource Evaluation," has given an opinion on the geopressured-geothermal energy potential for DOE's Oak Ridge National Laboratory. The abstract from that evaluation follows.

The geopressured aquifers that extend along the northern Gulf of Mexico are a large, perhaps the largest, potential source of geothermal energy and natural gas in the United States. Because of the high cost of completing wells into these formations and their relatively low temperatures (200°-400°F), the utilization of the geothermal energy will be highly dependent on, and of secondary importance to, the value of the methane.

The economics of extracting either the geothermal energy or natural gas from these aquifers does not look promising. The combined requirements of high well flow rates (40,000 bbl/day), long life (20 years), and the necessity for close well spacing to minimize the cost of the collection system may be incompatible with the actual characteristics of the reservoirs. These factors place such stringent requirements on the reservoir size, permeability, and compressibility, or specific storage coefficient, that the number of promising production areas may be severely limited.

It must be noted that the high production rates noted above may not be necessary if natural gas were the only resource one might be attempting to recover. Research is in progress to study annular flow in dry and abandoned wells to determine if wells drilled for hydrocarbons could feasibly produce geopressured-geothermal energy.

The recoverability of energy from geopressured reservoirs depends on the amount of water that can be produced by wells tapping these reservoirs. In turn, this production depends on the hydrogeologic properties of the sandstone and shale that comprise the reservoirs. The most important hydrogeologic factor is transmissivity.

In order to provide an "order-of-magnitude" assessment of recoverability, Papadopulos, Wallace, Wesselman, and Taylor (1975) selected three development plans on the basis of hydrogeologic, economic, and environmental factors and then applied these plans to generalized "conceptual" reservoirs. Each plan specified the transmissivity, production period, well diameter, flow rate, and allowable drawdown (or wellhead pressure). In plan 1, wellhead pressure was restricted to a minimum of 14 MPa (2,000 psi). In plan 2 wellhead pressure was unrestricted, and in plan 3, wellhead pressure was kept sufficiently high to limit ground subsidence to 1 m. Recoverable energy as a percentage of accessible fluid resource base was 2.1% for plan 1, 3.3% for plan 2, and 0.5% for plan 3. Mechanical energy was calculated for plans 1 and 3 only, and constituted only 2.6% and 3.8%, respectively, of the total energy produced.

In the most recent assessment by Wallace, et al. (1979), the ratio of sandstone volume to the total volume of sedimentary rock has been determined to be 36% less. Furthermore, it is estimated that only one-half of the sandstone volume will be developed. The net result of these adjustments is that the transmissivities for this assessment are reduced by 66% from those assumed in the previous assessment.

Following the methodology of Papadopulos, Wallace, Wesselman, and Taylor (1975, p. 140), a two-thirds reduction in transmissivity gives corresponding reductions in recoverable energy of about 20% in the case of plan 3. This adjustment results in a range of recoverable energy of 0.25%-2.6% of the accessible fluid resource base. See Table 1 for estimates of recoverable energy by area and development plan.

Using these percentages, the total recoverable thermal energy and energy equivalent of methane is estimated to be between 430 x 10^{18} and 4,400 x 10^{18} J. This range encompasses the range of most of the recoverability estimates of others discussed previously in this report.

TABLE 1

Energies given in units of 10^{18} joules
Methane = 3.73 x 10^7 J/m^3
10^{18} joules = 10^{15} BTU; 1 bbl oil = 5.6 x 10^6 BTU

		Plan 2	Plan 3
Texas	Thermal	1220	117
	Methane	790	76
	Total	2010	193
Louisiana	Thermal	490	47
	Methane	270	26
	Total	760	73
Federal Outer Continental Shelf Area	Thermal	1080	104
	Methane	580	56
	Total	1660	160
TOTAL NORTHERN GULF OF MEXICO BASIN	Thermal	2800	270
	Methane	1640	158
	Total	4440	430

These estimates assume that the geopressured-geothermal water is saturated with methane. If significant quantites of free gas are trapped in the pore space of the reservoir, recoverable energy in excess of 2.6% may be possible; however, if the water is undersaturated in methane, the recoverable energy will be proportionally less.

Garg, Pritchett, Rice, and Riney (1977) concluded that energy recoverable from a geopressured-geothermal reservoir would be increased 5-10 times with reinjection into the producing reservoir. If the reservoir volume is one-half of the sandstone volume and if sandstone constitutes 10% of the total sedimentary volume, the upper estimate of recoverable energy would increase to approximately 5% of the total accessible fluid resource base.

Credible estimates of the amount of recoverable geopressured-geothermal energy, based upon reasonable production scenarios, must await the results of ongoing and future tests of aquifers designed to accurately determine their hydraulic properties. Short-term test data currently available, although encouraging, are inconclusive. Reservoir parameters, especially transmissivity and individual reservoir extent, which are the most critical factors determining ultimate resource recoverability, are no better defined now than they were in 1975.

RESOURCE UTILIZATION

POSSIBLE USES OF GEOPRESSURED-GEOTHERMAL WATERS

Geopressured-geothermal water along the Texas and Louisiana Gulf coast contains three forms of energy capable of utilization through technology:

- Thermal
- Kinetic
- Dissolved methane

This energy may be harnessed to produce heat or electric power, as well as feedstock for the chemical industry; however, as in the conversion of most types of potential energy to readily usable forms, special problems exist requiring some development work and unique solutions. Geopressured-geothermal water is not without these problem areas. These, plus the unproven nature of the resource, cast doubts upon the near-term (5-10 yr) usage of this potential energy source. Should the resource prove out and development take place, practical application will likely take form as follows:

PRODUCTION OF ELECTRIC POWER FROM GEOTHERMAL ENERGY

Geothermal water, as with all hot waters, can be used directly as a heat source in the warming of buildings and for some other direct heating uses; however, the distance to which such heat can be transmitted economically is limited to an estimated 50 km. The generation of electric power produces a form of energy capable of widespread, economical distribution and utilization for many purposes. Because of its many favorable characteristics, geothermal energy will be used for the generation of electric power. This can presently be done by two methods.

- Flashing steam from the geothermal water by reducing the pressure to a predetermined point and passing the steam through a low-pressure expansion turbine connected to an electric generator.

- Transferring heat from the geothermal water to a suitable secondary fluid which is, as a result, vaporized and passed through an expansion turbine connected to an electric generator.

Electric power may also be generated from the kinetic energy of the geopressured waters. It is believed that well head pressures as high as 140 kg/cm^2 (2,000 psi) will be realized. This pressure may be converted to electric power by a hydraulic turbine in much the same manner as hydroelectric power is produced. This pressure, however, would decline with time.

If all the potential geopressured-geothermal resources of the Texas and Louisiana Gulf coast–offshore as well as onshore–could be economically exploited without adverse ecological impact in the form of small 10-100 MW(e) power plants, the highest estimates are 10,000-40,000 MW(e) centuries of available electrical power.

OTHER POTENTIAL USES

A number of possible uses of geopressured-geothermal energy other than electrical power generation have been suggested, dependent on the heat and kinetic energy content of this resource. It is doubtful that many of these alternatives are economically viable without base load use of the geopressured-geothermal brine for power generation and without methane extraction for additional saleable energy value. Ecological considerations, such as possible subsidence and brine disposal, indicate that location of early sites will be remote from highly urbanized or industrialized areas, further limiting a number of these nonelectrical power generation uses.

It should be noted, however, that the efficiency of use of geothermal resources for nonelectrical purposes is greater than for electrical power generation. The conversion efficiency for electrical power production approximates 8%-15%, while conversions of up to 85% energy efficiency may be reached in some nonelectrical applications such as direct contact heating.

Highly corrosive or scaling brine may require the use of a secondary fluid and heat exchange system for circulation in heating systems and equipment. Fossil fuel-fired peaking units may also be required with many of these applications. Nonelectrical applications of geothermal resources are already of primary importance in some parts of the world for space heating and industrial power and to a lesser extent for greenhouses and miscellaneous uses. Among these locations are Iceland, New Zealand, Hungary, France, Rumania, Italy, U.S.S.R., Japan, and several cities in the U.S.A.; however, none of the geothermal sources for these applications are of the geopressured-geothermal type covered by this report.

Industrial Uses

- Heat source for sugar cane and pulp and paper operations.
- Sulfur frasching if fluids can be obtained in reasonable proximity to salt domes containing sulfur resources.
- Steam turbine-driven natural gas and petroleum pipeline pumping and compressing.
- Low level process and space heat for chemical, petroleum, petrochemical, and other industries.
- Lumber, brick, and concrete block curing kilns.
- Water desalination by either flash steam condensation or by process heat supply to distillation-type desalting units to provide industrial boiler and pure process water.
- Injection of brine effluent for secondary recovery of petroleum.
- Drying and evaporation operations (cement, clays, fish, or other marine products).
- Mineral recovery from hydrothermal fluids (salt concentration, chemical extraction, etc.).
- Absorption refrigeration and freeze-drying of foodstuffs.
- Gasohol plant energy source.

Agricultural Uses

- Greenhouse heating for limited specialty crops and ornamental plants.
- Rice and grain drying.
- Hydroponics temperature and humidity control.
- Refrigeration and frozen food preparation.
- Aquatic farming.
- Processing of agricultural products (waste disposal or conversion, drying, fermentation, canning, etc.).
- Animal husbandry including space and water heating, cleaning, sanitizing, and drying of animal shelters. Creating optimal thermal-environmental conditions for maximum growth and production may become increasingly important.

Municipal and Residential Uses

- Homes, multi-unit dwellings, and buildings: closed hot water or steam space heating systems or district heating by thermal distribution systems.
- Water (potable, hot/cold utility, etc.) heating.
- Deicing bridges, overpasses, and driveways.
- Heating of swimming pools, fish hatcheries, etc.
- Waste treatment (disposal, bioconversion, etc.).
- Absorption refrigeration and space cooling.

ENGINEERING ASPECTS OF ELECTRICAL POWER PRODUCTION FROM GEOTHERMAL BRINES

The two primary methods of electrical power generation, the flash steam process (one- or two-stage) and the secondary working fluid cycle, including sample economics for the coastal area, have been presented by Wilson, et al. (1976), and updated and expanded by Dorfman, et al. (1976).

The details of two proposed electric power production systems can be found in the "Proceedings–Second Geopressured-Geothermal Energy Conference." These are the flash and the secondary working fluid cycles.

Advanced power production methods are under study. Lawrence Livermore Laboratory is developing a "Total Flow" expander using the nozzle principle and Jet Propulsion Laboratory is investigating a helical rotary screw expander approach. These efforts are in the research stage and likely some years away from commercial application. Should they prove practical, geopressured-geothermal fluids would be well suited for the feed. These conversion methods would utilize both the hydraulic pressure and the heat energy in one step. The environmental aspects of such conversion, however, would not differ greatly from those of the flash or secondary fluid systems.

A combined flash-secondary fluid system is presently being tested by San Diego Gas and Electric Company. This facility uses very high salinity geothermal fluids, and the flash system was installed to avoid the excessive scaling of a normal heat exchange step. Much development work is underway to cope with this type of scaling, and it is anticipated that geopressured development will not necessitate the use of the combined cycle system.

ECONOMICS OF GEOPRESSURED-GEOTHERMAL POWER PRODUCTION

Studies on the economics of power production from geopressured-geothermal fluids are subject to many uncertainties due to the lack of firm data on the resource. One of the most exhaustive reports to date has been that of Underhill, et al. (1976). The results of that study will be used in this report.

Two commercial-size, 25-megawatt flash plants were considered. These were a single-flash plant and a double-flash plant, both recovering natural gas and both converting the overpressure to electrical energy. These plants required 12 and 10 production wells, respectively.

The single-flash plant requires $53,067,000 for the fuel plant and $14,487,000 for the power section for a total of $67,554,000. This is the less economical plant.

The double-flash plant required only $43,551,000 for the fuel plant and $15,845,000 for the power portion for a total of $59,396,000. The cost per kilowatt-hour for the power plant only was $678 per kWh. This compares favorably with present-day fossil fuel plants. Comparative costs of the fuel and power plant for single- and double-stage flash are shown in Table 2.

The fuel section for this plant will produce in addition to the hot water, 4,467,600 Mscf of natural gas per year. The value of this gas at a cost of $2.00 per Mscf is $8,935,200 per year. Taking credit for this gas results in a cost per usable Btu of water heat energy to the power plant of $.63 per M Btu; however, the conversion efficiency of the plant is only 10.3%, including the hydraulic source. Unit cost of the electrical power produced was calculated on this basis to be 46 miles per kWh, which is very high. The unregulated cost of geopressured-geothermal-produced natural gas is now $5.00-$7.00 along with a $.50 per Mcf incentive to produce. The unit cost of electrical power produced would be more favorable when taking the credit for produced gas into account.

The conclusion reached is that either the water must be hotter or a more efficient means of conversion must be used if economical power is to be produced from the geopressured zone.

The Center for Energy Studies (Underhill, et al., 1976), University of Texas at Austin, combined the Dow study (Wilson et al., 1976) with some minor changes in economic assumptions, and arrived at a capital cost of \$738/kW(e) for a 25 MW(e) power plant only as shown in Table 3 for a two-stage steam plant and \$786-\$821/kWh for a secondary working fluid plant with an estimated 1980 bus bar price of 47.5 mills/kWh apportioned as shown in Table 4.

INCENTIVES FOR GEOPRESSURED-GEOTHERMAL POWER PRODUCTION

The 1980 census of the 36 counties of Texas which might reasonably have access to the geopressured-geothermal fairways of the Gulf coast shows a population of 3,518,859, ranging in population density from 1-390 persons per square kilometer.

TABLE 2

Unit Cost Summary - 25 Megawatt - Flash Plants

Fuel Plant	Single-Stage Flash	Double-Stage Flash
Capital, M \$	53,067	43,551
Capital, \$/kWh	2,122	1,742
Unit fuel cost, \$/$\overline{M}$ Btu	2.44	2.00
Unit fuel cost, \$/$\overline{M}$ Btu	——	0.63
Power Plant		
Capital, M \$	14,487	16,945
Capital, \$/kWh	580	678
Conversion efficiency*	——	10.3%
New power cost, mills/kWh	——	46

*Includes hydraulic power.

TABLE 3

Important Parameters, Alternative Power Plants

Parameter	Plant A: Flash Steam	Plant B: Flash Working Fluid
1. Brine to power plant		
a. Flow rate (kg/sec.)	6.29 x 10	7.82 x 10
b. Temperature (°C)	160	160
c. Pressure (kg/cm^2)	140	140
2. Geohydraulic turbine/generator output (MW(e))	5.61	6.65
3. Steam or SWF turbine/generator output (MW(e))	20.83	27.84
a. Feed pumps	0.00	5.07
b. Circulating water pumps	1.44	3.26
c. Cooling tower fans	0.73	0.98
d. Other services	0.12	0.18
5. Heat rejection (kW)	6.38 x 10	1.01 x 10
6. Net power output (MW(e))	24.15	25.00
7. Capital costs (total $)*	17,800,000	19,652,000+
8. Installed cost ($/kW(e))	738	786(821)#

NOTES:

* Contingency taken as 15% in flash steam plant, in secondary working fluid plant.
\+ Total capital cost of SWF plant at 15% contingency is $20,546,000.
\# First entry 10% contingency, second entry 15% contingency.

(Does not include fuel plant costs.)

TABLE 4

1980 Apportioned Bus Bar Changes (Power Plant)
(100% DEBT Financed)

Factor	Bus Bar Charge (mills)
Operations, maintenance	6.08
Fuel	13.06
Capital	18.48
Taxes (federal, state, local)	9.88
TOTAL	47.50

Assuming the population growth trend, per capita electrical usage and estimated required generating capacity follow the national trends predicted by Hittman Associates, Inc. (1972). Estimates of the increased required power capacity in the coastal area are shown in Table 5.

TABLE 5

Probable Power Capacities, 39 Counties,
Texas Gulf Coast Geopressured-Geothermal Zone
(Does not include Louisiana area)

Year	Population (10^6)	Per Capita Use (kW)	Total Use (10^6 kW)	Plant Load Factor	Estimated Required Capacity (10^3 MW)
1970	3.53	0.9	3.18	0.64	4.96
1980	3.99	1.5	5.98	0.64	9.34
1990	4.56	2.4	10.94	0.65	16.83
2000	5.29	3.2	16.93	0.66	25.65

Required New Capacity = 20.69
(1970 to 2000)

A minimum of 20,690 MW(e) of new generating capacity must be added in this area to meet the anticipated demand by the year 2000. Traditionally, all power generation in the area has been based on natural gas fuel with some conversion to dual gas/oil capability being added over the last few years. As supplies decrease and costs increase for both these fuels (gas and oil), there is increased interest in other power sources. The importance of the use of gas and oil as refinery and chemical feed stocks rather than fuels is widely recognized by industrial users in this region.

Due to the heavy industrialization of this area in chemical, petrochemical, petroleum refining, ferrous and non-ferrous metal production, etc., however, both the population growth and estimated required generating capacity are probably appreciably higher than the figures indicated in Table 5 based on national averages indicate.

Earlier projections of much of the national energy shortage through the year 2050 being made up by new nuclear power plants are not being realized. High plant capital costs, uncertain future fuel prices, complex regulatory approvals required, and adverse public opinion on the safety and ecological aspects of such plants are all factors in the probability that much of the future Gulf coast power needs through the year 2000 will not be met by nuclear power.

Extensive relatively low-grade coal (lignite) deposits are available several hundred miles from the coastal area. These deposits are in an arc sweeping through Texas from the Rio Grande River in the Texas-New Mexico border region through central and east Texas into Louisiana. Some commercial utilization of these deposits has been made in the past, but interest has been spurred by the recent "energy crisis." Man, industries, and public utilities are now engaged in plans for exploitation of these coal resources as the fuel for power generation in the Texas area for the future. The nature of these deposits is such that "strip" mining is the logical recovery method.

Faced with the possible ultimate loss of the conventional fuel source, natural gas, for electric power production and the long-range economically unattractive alternates: (1) use of increasing amounts of imported oil or (2) costly conversion to coal, the *Gulf coast industrial power producer should be more interested in exploiting the geothermal energy potential in this region than ever before.* It is unlikely, however, that such a high risk venture would be undertaken without federal leadership and funding in:

- Drilling test production and reinjection wells.
- Proving the technical and economical feasibility of the concept and equipment through construction and operation of demonstration plants.
- Solving the complex legal, jurisdictional, institutional, and possible environmental problems associated with exploitation of this energy resource.

NONELECTRICAL POWER GENERATION USES OF GEOPRESSURED BRINES

Worldwide, the greatest nonelectrical use of geothermal energy is in the area of residential and commercial space and water heating, representing over 400 MW(e) average energy consumption. This usage is heaviest in colder climates with relatively high population densities that can support district heating systems. The cost of insulated supply and return brine lines is relatively high; however, well over one-third of the U.S. fossil fuel consumption is used for residential purposes, part of which could be supplied from geopressured-geothermal brines as could absorption refrigeration and air conditioning.

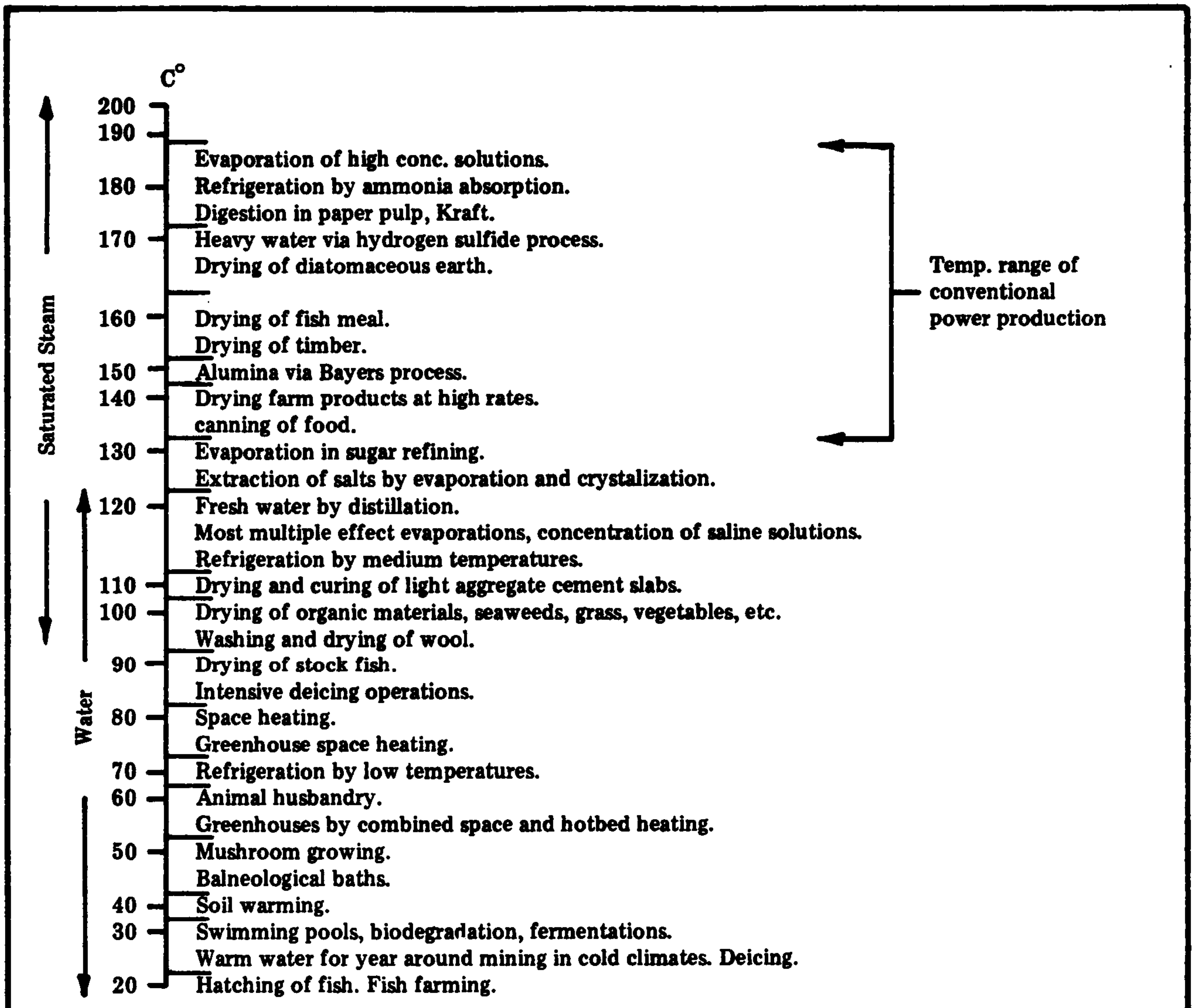
There are many possible examples for future industrial geothermal utilization. Some of the temperature ranges for various processes are shown in Figure 9. By using fluid in the higher temperature range as feed for a slightly lower temperature for a number of processes down to ambient temperature, maximum thermal energy can be extracted in a "cascading" effect.

The concept of integrated agricultural applications to use geothermal energy to improve the world's food supply has been suggested by a number of authors.

More recently, Swink and Schultz (1976) have presented a conceptual multi-use integrated process plant for using low temperature (150°C) geothermal water for both electric power production and direct heat utilization in industry. This work is directed to the Raft River area of southern Idaho and uses the "cascading" temperature concept where one process takes as feed brine at a lower temperature from a preceding process. This utilization of the maximum quantity of usable heat, if taken as an economic credit, tends to reduce the required selling price of geothermal electricity to competitive levels when integrated into an "energy park" concept.

It should be noted that the heat exchangers for evaporation, drying, etc., in conventional plants are usually based on steam as the heating agent. Plants using liquid-to-liquid exchangers would have to be specifically designed to utilize cascading temperature geothermal brine as a heat source for many unit operations.

As the chemical composition of the residual brines cannot be completely defined, corrosion and/or scaling could limit their usefulness in industrial-agricultural process equipment.



From: Lindal (1973)

Figure 9: Required temperature of geothermal fluids for various nonelectrical applications.

ENVIRONMENTAL CONSIDERATIONS

Gustavson, et al. (1977) has summarized the potential environmental impact which may result from geopressured-geothermal development for the Texas-Louisiana Gulf coast as follows.

Geopressured-geothermal resources of the Texas-Louisiana Gulf coast are being evaluated as thermal-hydraulic energy sources. Gulf coast geothermal fluids are brines (10-270,000 ppm) with temperatures up to 283°C (555°F). As much as 54,000 m^3 (310,000 bbls) of fluids per day at a temperature of 150°C will be required to feed a 25 megawatt power plant.

Generating systems will probably utilize a one- or two-stage flash steam system or a secondary working fluid system. The secondary working fluid system is advantageous in that geothermal fluids are wholly contained and not released to the environment. Disposal of geothermal fluids will be via injection in moderately deep (600-2,100 m) saline aquifers.

Serious environmental intrusions may result from geopressured-geothermal resource development. Impacts resulting from site development will be largely due to excavation for pipelines and construction of the power plant, holding ponds and roads. The severity of these impacts will be greatest if development occurs in wetland areas.

Withdrawal of large amounts of fluids from the subsurface may induce surface subsidence and faulting. Surface subsidence will most seriously impact low lying urban areas, wetlands or coastal areas.

Waste products attributable to geothermal energy development include spent geothermal fluids, cooling tower fluids, waste heat energy, and sewage.

If residual methane, other heavier hydrocarbons, hydrogen sulfide, ammonia, and boric acid occur in geothermal fluids, they may be released to the atmosphere along with water vapor at cooling towers. Waste cooling tower fluids will contain algacides, herbicides, and corrosion preventors; all detrimental to the surface environment. Waste heat energy will be passed to the atmosphere along with water vapor.

Predictable accidents are blowouts of the production wells during drilling or normal maintenance, or rupture of the pipelines that will carry geothermal fluids from production wells to power plants and back to disposal wells.

White (1978) and others have outlined the preliminary environmental analysis of the geopressured-geothermal test well area to be drilled near Chocolate Bayou, Brazoria County, Texas.

Preliminary environmental data, including current land use, surface lithology, soils, natural hazards, water resources, biological assemblages, meteorological conditions, and regulatory considerations, have been collected and analyzed for approximately 150 km^2 of land, near Chocolate Bayou, Brazoria County, Texas, in which a geopressured-geothermal test well is being drilled. The study was designed to establish an environmental data base and to determine, within spatial constraints set by subsurface reservoir conditions, environmentally suitable sites for the prospect well. Preliminary analyses of data revealed the need for focusing on the following areas: potential for subsidence and fault activation, susceptibility of test well and support facilities to fresh and saltwater flooding, possible effects of produced saline waters on biological assemblages and groundwater resources, distribution of expansive soils, and effect of drilling and associated support activities on known archaeological/cultural resources.

Differential subsidence may occur across known growth faults which, when projected to the surface, strike near the proposed well sites. Although current land use maps show an agriculturally dominated region, facilities that could be adversely affected from significant amounts of subsidence and/or fault activation include two petrochemical plants; a small unincorporated community along Chocolate Bayou; several gas, crude, and product pipelines; and paved highways.

Flood distribution maps, which project "100-year" flood levels between 1-3 m above ground surface (approximately 3-5 m or 10-16 ft in elevation) in the main prospect area, indicate the need to institute flood-protection measures at the well site. In addition to the possibility of freshwater flooding, saltwater flooding accompanying passage of a hurricane must be considered, as indicated by flood levels associated with Hurricane Carla.

Probable locations of fluid production and disposal facilities should have little direct impact on important biological assemblages and habitats; however, accidental discharge of geothermal brines that may contain significant amounts of boron could affect small areas of freshwater marshes near the well sites and large areas of fresh to brackish and saltwater marshes with their associated estuary habitats along Chocolate Bayou and Chocolate Bayou gulfward of the well sites. These biologically productive areas provide nurseries for commercial shrimp, blue crabs, and game fish.

Although freshwater aquifers underlie the geothermal prospect area, contamination from properly managed temporary emergency surface storage of saline waters is unlikely because of low permeabilities of clay substrates at or near the surface. High shrink-swell potentials which characterize the clays, however, should be considered in the construction of pipelines, roads, and other facilities.

LEGAL CONSIDERATIONS

GEOPRESSURED-GEOTHERMAL AND ASSOCIATED RESOURCES OCS LEASING AUTHORITY

The Outer Continental Shelf (OCS) Lands Act Amendments of 1978 (PL 95-372) grants to the Secretary of the Interior for the first time the authority to grant leases covering geopressured-geothermal and associated resources on the OCS. The current, and only, OCS oil and gas lease form (September 1978) grants to the lessee the nonexclusive right to drill water wells unless the water is part of geopressured-geothermal and associated resources.

As of this time, the Secretary has not yet issued regulations implementing his authority to grant leases covering said resources. When he does, the Secretary will be required to approve a lease form to cover this situation.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.