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ENVIRONMENTAL ASSESSMENT OF GEOPRESSURED WATERS AND THEIR PROJECTED USES

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report deals with the environmental aspects of the proposed development of the deep geopressured hot fluids of the Gulf Coast sedimentary basin for the production of electric power and as a source of heat. Although this development is currently only in the study phase, it is desirable to estimate the environmental considerations at this time and to propose a study program to run concurrent with the development effort.

Geopressured geothermal is a unique resource with its own problems and promises. It is the intent of this report to provide the environmental research community with a source of understanding of the resource, the nature of its waters, and the special problems associated with its utilization. The hard data base is fragmentary, requiring much of the material presented to be of the "consensus" type of information. Updating will be required as real data become available.

The researcher desiring more information on the subject is referred to the Industrial Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, Ohio, 45268.

David G. Stephan, Director
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ABSTRACT

A possible source of alternate energy for the nation is believed to exist in the deep geopressured reservoirs found in the Texas and Louisiana Gulf Coast sedimentary basins. This unproven resource is believed to offer a large potential supply of both natural gas and heat energy. Development is some 5 to 15 years in the future, depending on priorities assigned to the area by ERDA. Private development, because of the risk involved, must await government proving of the resource.

This report considers the potential uses of the geopressured geothermal resource and the environmental aspects of those uses. Economics of power production are estimated as an aid to assignment of priority research and development in the area. Literature values of near 45 mils per kilowatt-hour are considered higher than other geothermal sources.

Principal environmental impacts of any of the proposed uses will result from the waste fluid streams and from possible subsidence of the wellfield. In some cases, the waste stream may be of low salinity and usable as agricultural water. However, in most instances, disposal of this large volume of saline fluid will require reinjection, canaling to a saline water body, or some more imaginative method. Reinjection into the same strata will be uneconomic and require too much energy, due to the geopressure involved.

The area is one of natural subsidence. This may be accelerated by deep fluid withdrawal. However, many experts feel the great depth will be a mitigating factor on surface subsidence.

Environmental research and information will be necessary if the resource is to be developed. However, in view of the uncertainty of extensive resource development and the relatively long time frame involved, only moderate priority is assigned to environmental research effort at this time. Progress of the Energy Research and Development Administration development effort should be monitored, and environmental baselines should be established for the area chosen for initial development. Particular attention should be given to ground levels and other data necessary to establish subsidence values. Close cooperation and joint effort between the Environmental Protection Agency and the Energy Research and Development Administration is recommended.

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LIST OF ABBREVIATIONS AND SYMBOLS

∿	--	approximate
bbl	--	barrel
BOD	--	biological oxygen demand
Btu	--	British thermal unit
CO_2	--	carbon dioxide
cm	--	centimeter
CU	--	copper
Darcy	--	a unit of permeability
db	--	decibel
^{o}C	--	degree centigrade
^{o}F	--	degree Fahrenheit
ft	--	foot
gm	--	gram
μg	--	microgram
gpm	--	gallon per minute
hr	--	hour
H_2S	--	hydrogen sulfide
J	--	Joule, a unit of energy
kcal	--	kilocalorie
kg	--	kilogram
kkg	--	thousand kilograms, megagram
km	--	kilometer
kWh	--	kilowatt-hour
l	--	liter
m	--	meter
μm	--	micrometer
$\overline{M}$	--	million
md	--	millidarcy
mg	--	milligram
min	--	minute
mo	--	month
Mscf	--	thousand standard cubic feet
MWc	--	megawatt century
MW(e)	--	megawatt (electrical)
N_2	--	nitrogen
NH_3	--	ammonia
Nm^3	--	cubic meters at normal conditions of temperature and pressure
NO_x	--	oxides of nitrogen
O_2	--	oxygen
ppm	--	parts per million
psi	--	pounds per square inch
scfm	--	standard cubic feet per minute
sec	--	second

List of Abbreviations and Symbols (continued)

SO_x -- oxides of sulfur
TDS -- total dissolved solids
yd -- yard

ACKNOWLEDGMENTS

In the course of the accumulation of information and data for the preparation of this report, various representatives of industry and government have been contacted. These individuals have contributed significantly to the preparation of the report. Particular appreciation is extended to Dr. Sidney Kaufman of Cornell University for his critique of the manuscript and his valuable comments and recommendations.

Water analyses, not in the open literature, were supplied by Dr. Paul H. Jones of Louisiana State University, Mr. E. R. Blakeman of Superior Oil Company, and Raymond H. Wallace, Jr., of U. S. Geological Survey. Suggestions on water data sources were also received from Mr. John J. Mitchell of Texaco and Mr. D. E. Powley of Amoco.

Information concerning present reinjection and waterflood operations were obtained from Mr. George Singletary, Texas Railroad Commission, Mr. Robert Kent, Texas Water Quality Board, and Mr. Robert Bates, Louisiana Department of Conservation.

SECTION 1
INTRODUCTION

Declining national supplies of petroleum and natural gas along with increased consumption has resulted in the United States becoming dependent upon foreign sources for much of the hydrocarbons needed to supply the energy demands of our society. This is an uneconomic and potentially dangerous situation in terms of the national security. As a result, the nation has embarked upon a program to develop alternate energy sources.

One of the proposed alternates is geothermal energy or energy in the form of heat from beneath the surface of the earth. This heat is most readily obtainable in the form of underground steam or hot water which can be brought to the surface to perform useful work. Only a few steam fields are believed to exist, but many hot water deposits are known. These later may be divided into connective systems and closed systems. The connective waters are regenerated by ground water percolating downward while the closed systems are distinctive pockets or reservoirs and are depletable. Primary among the closed reservoirs are the geopressured hot waters found generally at depths in excess of 3,000 meters in the sedimentary basin of the Texas and Louisiana Gulf Coasts. These waters are under very high pressure, being the load-bearing portion of the unconsolidated formation in which they occur. The available data on this resource has been a by-product of the extensive oil and gas exploration which has taken place in the area. Thousands of wells have penetrated the formations and the existence of the waters is well documented. The extent and productivity of the depletable reservoirs is only a matter of conjecture. Studies, using oil field data, have indicated the resource may be considerable.

Proposed development under the sponsorship of the Energy Research and Development Administration (ERDA) has reached the stage of preparing to test the reservoirs through wells that have been drilled for petroleum and found to be unproductive. One such well in southwest Louisiana is being tested by McNeese State University, Lake Charles, Louisiana under contract to ERDA. Contracts to test other such wells are anticipated.

Paper studies on the economics of power production have been made with resulting marginal economics. However, the potential of the resource, which includes a possible major source of natural gas dissolved in the fluids, is sufficient to warrant continued efforts.

This report describes the resource, the possible uses, the projected resulting emissions, other impacts upon the land, the present stage of development and projections of future developmental plans. Assessments are made of the potential environmental impact and research needs to evaluate and minimize these impacts are proposed.

SECTION 2
CONCLUSIONS

A viable geothermal resource appears to exist in the geopressured hot water reservoirs in coastal areas of Louisiana, Texas, and possibly Mississippi. This resource is as yet unproven, and estimated economics are not sufficiently attractive to encourage private development. However, because of the possible large size of the resource (estimates vary from virtually zero to 20,000 megawatt centuries) and the favorable location in an industrial area, it will apparently be tested and developed through combined government-industry effort.

For technical and environmental considerations, the reservoirs should presently be classified as medium to low salinity and temperature geothermal resources. The salinity, based on oil and gas well water samples, will range from approximately 1000 TDS to as high as 10% salinity. The waters will most assuredly be saturated with SiO_2 (silica) and the components of the clays with which they have been associated. However, there is evidence to suggest that hydrogen sulfide, heavy metals and other components associated with highly mineralized waters will be absent or at very low levels. Temperatures may range as high as 260°C (500°F) but most reservoirs will be in the 120°C (250°F) to 204°C (400°F) range.

This water is also estimated to be at or near saturation with natural gas (primarily methane). Values up to 8.9 Nm^3/m^3 (50 scf/bbl) have been estimated in the hotter, higher pressure reservoirs. This gas may someday be of sufficient value to justify production of the waters for their gas content alone. In such case the waters would most likely be reinjected into non-geopressured, but still deep, sands. Many of the environmental considerations discussed in this report would be equally applicable to the operation of such a gas field.

The geopressured geothermal resource is currently being considered primarily as a source of electrical power. However, the waters may also be used for process and space heating, air conditioning, and other normal heat uses either in combination with electrical generation or, in the case of the low temperature reservoirs, as a low level heat source only.

The economics of the use of the resource in the production of electric power by conventional means are not competitive with other energy sources such as nuclear, coal, solar, or oil. However, if the water is saturated with natural gas which can be recovered and sold, the total process may be an economic power source within the next decade. This could be particularly true if (1) the natural gas is recovered, (2) the high level heat above 120°C is used for the generation of electricity, and (3) the low level heat below 120°C is used as an industrial or commercial heat source.

Environmental impacts of the development of the resource appear to be small. Geothermal development is reported to be a relatively clean energy source from an environmental standpoint and geopressured geothermal is one of the cleaner forms due to the relatively low salinities and the indicated absence of noxious gases such as hydrogen sulfide.

The environmental aspects are divided into two categories--emissions and geological impacts. These are summarized as follows:

EMISSIONS CONSIDERATIONS

Information from three private sources was used to supplement the number of formation-water analyses obtained from two published papers and two open-file reports of government agencies. The relatively few published analyses of the waters obtained from deep wells are usually not accompanied by sufficient additional information to confidently distinguish between a normal and an overpressured water. Conclusive evidence of geopressured origin is lacking for about 70% of the formation waters whose analyses are listed here. These are the brines from wells for which only the formation depth and completion date are available. In these cases a formation depth greater than 2,743 meters and a well-completion more recent than 1962 were arbitrarily chosen as indication that the source formation was of the overpressured type. There is little doubt that the remaining 30% of the analyses do represent geopressured waters, as additionally evidenced by pressure-to-depth ratios, temperatures, or salinity anomalies.

Many of the higher salinity waters likely were obtained from wells which terminated at the first "pressure kick" or at the very top of the geopressured zone where maximum salinity occurs. The data available makes it impossible to further identify these samples.

The TDS content of the waters listed ranges from ∿200 to 340,000 ppm. However, the higher salinity waters should not be considered as typical of those expected to be found and produced for the sand aquifers in question. The waters in these formations are indicated to be within the salinity range of 1,000 to 30,000 total dissolved solids (TDS). Minor elements, where reported, are present at the following approximate levels, in ppm:

Li - <10
Sr - <10
Br - 15-200
I - 5-50
B - 20-60

The concentrations reported for barium in a considerable number of analyses -- between 200 and 1,000 ppm -- are strongly doubted here. In these cases, as in any situation where barite might be used in well-drilling fluids, the validity of the sample must be suspect.

By far, the potential and actual emissions of greatest environmental concern expected from any application of geopressured fluid are those of the water itself and of the spent brine. The former is a potential emission only, and might contact the surface environment as a result of accident, notably during a possible well blowout, but also from possible structural failure of other equipment. Spent brine, a normal, designed effluent stream or emission, can likely be reinjected into a receptor stratum, but could conceivably become a fugitive emission as a result of possible structural failure of equipment. The latter events have less probability of occurring than ruptures in the main stream header, or steam-drum blowouts in conventional power plants.

A waste brine stream will be generated regardless of use of the geopressured waters unless the waters are of such salinity that they become useful for agricultural purposes. Disposal of this stream may be approached either by reinjection into shallower non-geopressured formations or released into existing water bodies of similar salinity. The latter method should be the most economical for fields near the Gulf, even if some water clean-up or cooling is necessary. Each situation will require evaluation on its own merits. For more inland areas, reinjection will likely be the method of choice. The alternate would be piping or canaling to the nearest saline water body.

It should be noted that reinjection into the source formation will be uneconomical. The high pressure in these sands would require large, high energy-consuming pumps which would have serious effects not only on the cost factor but also in the net energetics of the project. Therefore, reinjection must be into shallower hydropressured strata. These, of course, will already contain their own water so compatibility must be established and the possibility of intrusion of salt water into higher levels containing potable water must be examined and monitored.

Accidental, large-volume discharges of either geopressured brine or spent brine, although not expected to be frequent, are capable of causing considerable damage to the environment and harm to personnel if they do occur. Both the relatively high temperatures--82°C to 188°C--and possible high salinities, up to, say, 10% TDS, could completely destroy the vegetation contacted by the brine. The area and time of greatest hazard to the environment is quite obviously in the brine field during the well-drilling period.

Contamination of fresh water aquifers by salt is a possible result of the reinjection of the spent brine. The occurrence of this, although remote, could result from well leakage by corrosion, or from channeling of the brine along a geologic fault induced by the increased pressure of reinjection.

The overall environmental impact of the cooling tower exhaust will be greatly dependent on the exact location of the geopressured facility. In predominantly agricultural areas, there would probably be some measurable, or at least claimed, impairment in the health of row crops or orchards in the vicinity, resulting from drift deposition. In or near a metropolitan area the major impact might be the occasional periods of lowered visibility, the mild increase in corrosion rates of nearby metal objects -- notably, cars in any adjacent parking lots--and, perhaps, noticeable effects on nearby ornamental plantings. Actually, the exhaust expected from the cooling tower operating under the parameters considered here will be far less harsh on the environment than that from most industrial or public utility towers currently operating.

GEOLOGICAL IMPACTS

The primary geological result of resource development is likely to be surface subsidence. The waters to be produced are, at least partially, the load-bearing portion of the reservoir. As withdrawal occurs, compaction of the sands and clays of the reservoir will take place. Subsidence is the normal result of such compaction. However, these are very deep reservoirs and are very large in areal extent. These factors may prevent noticeable surface effects.

The sedimentary basins in which the reservoirs occur are highly faulted. These faults are subsidence faults rather than tectonic faults and are due to naturally occurring subsidence as the sand and clay sections tend to slip gulfward. Increasing the rate of subsidence by water withdrawal will likely increase the activity of such faults and result in micro-earthquakes. However, no damage from the movement would be anticipated.

SECTION 3
RECOMMENDATIONS

The two events which together would furnish the greatest impetus in advancing the planned use of geopressured brine from its present conceptual stage toward commercialization are the successful completion and operation of a test well and the continuous disposal of the brine into the required number (probably two) of reinjection wells. The concurrent operation of a methane separator and the means of disposal for the methane are necessary appendages whose successful functioning has already been demonstrated. Unfortunately, the size of the necessary investment is relatively large, estimated to be about $3.9 million.

Research work of a certain type is strongly recommended to commence immediately following the choice of the tentative locality for a prospective test well or demonstration plant. This work would be a "pre-plant" environmental survey and would extend through the construction and well-drilling phases. The program should be sustained for perhaps several years past the initial well production or plant start-up. Some of the work should continue throughout and perhaps even after the active life of the geopressure project. The purpose of the first part of the survey would be to establish "base-line" values or to indicate the state of the natural (or artificial) environment before the physical start-up of the geopressure project, and the later phases would measure the environmental effects of the operation relative to the base-line values. The survey should include:

- Land surface evaluations
    - Establishment of a system of local (say, 3-mile radius) benchmarks of accurately determined evaluation relative to Mean Sea Level or other relatively constant datum
    - Monitoring of benchmark evaluations periodically after withdrawal of geopressured water has commenced
- Groundwater information
    - Measure water tables and water composition of reinjection formation and of aquifer chosen as source of water supply
    - Periodic analysis of other fresh water aquifers for TDS; temperature readings
- Local natural surface water
    - Periodic determination of TDS
- Monitoring of surrounding vegetation
    - Color photographs of indigenous vegetation, ornamental plants and economic crops

- Periodic evaluation of vegetation by qualified agriculturalists or botanists

- Atmospheric quality measurements
  - Total particulates
  - Sodium chloride
  - Unburned hydrocarbons
  - Hydrogen sulfide, if present
  - Ammonia

- Seismic measurements
  - Obtain recommendations from geologists or seismologists

- Photographs and other documentation of the condition of the exterior of existing nearby buildings, particularly in the prevailing downwind direction

In addition to the above environmental base-line effort for a given well location, certain items of general concern should be given deeper study than possible in this report. These suggested items are:

- Reinjection and other disposal methods
- Subsidence related to deep fluid withdrawal
- Micro-earthquakes related to reinjection or withdrawal of fluids

It is suggested that competent experts survey current experience in the three above areas and prepare exhaustive reports on the current knowledge, experiences of the past, and risk factors involved in each major area. Geopressured geothermal resource development appears to be one of the favorable alternate energy sources from the environmental viewpoint. However, the above three items could present serious consequences should their impacts prove to be negative to the environment. The risks involved should be clarified to the extent possible before major development of the resource begins.

Large volumes of fluids of somewhat uncertain salinity must be disposed of. Also the possibility of accidental discharge is always present. Release of these fluids into local surface waters will be detrimental to the fish and wildlife of the area. Monitoring of the surrounding water bodies should be carried out for the life of the project.

The need for such research is manifest but the timing is still uncertain. The present state-of-the-art in geopressured geothermal development is in its infancy. The Energy Research and Development Administration is in the process of assigning contracts for the sampling of waters from existing depleted or dry oil wells. Following this phase, test wells may be drilled in fiscal year 1977. A normal time span for preliminary research and testing would indicate at least a 5-year period will pass before the first demonstration plant will be constructed. Negative results on test wells would negate the entire development. In view of this possibility and the long time frame before resource development could begin, it is recommended that a moderate priority rating would be proper for major environmental considerations and research efforts.

Environmental studies aimed primarily or partially at geopressured geothermal energy utilization are underway. The Energy Research and Development Administration has taken the lead in this area. Their program as of September 1976 includes:

- A general environmental assessment underway at Oak Ridge National Laboratory
- A program plan for controlling subsidence to be prepared by Lawrence Berkeley Laboratory
- Guidelines for the preparation of environmental reports by Argonne National Laboratory
- Background studies of Gulf Coast subsidence being carried out by the U. S. Geological Survey

In addition to the above, work is expected to start soon on the establishment of base line data on Gulf Coast elevations for later use in subsidence evaluation.

Work is also underway on removal or control of hydrogen sulfide emissions in geothermal power plant operation. This effort is aimed primarily at connective geothermal systems where the sulfide is much more prevalent than is expected in the geopressured zone.

It would be desirable for the Environmental Protection Agency to work closely with and participate in the ERDA effort. This would serve to avoid duplication and should result in increased information dissemination.

One area which must be explored as soon as possible is the disposal of waste fluids. Very large volumes of wastewater, mostly saline, will be generated. This brine must be reinjected, released into saline Gulf waters, or otherwise disposed of in such manner as will be economically compatible with the environment. Research on the problems of reinjection, the economics of transportation to the Gulf, and any alternate methods needs to get underway.

The second most important item of need is in the subsidence area. Every effort should be made to determine the possibility of subsidence and the early detection of subsidence. Studies of oil field subsidence in geopressured oil and gas reservoirs should be made. Basic research on subsidence and prediction of subsidence would be desirable. The Gulf Coast involved is an area of natural subsidence laced with resulting faults. This increases the potential hazard of extensive water withdrawal.

Another important area of environmental research is the problem of dealing with accidental geothermal fluid releases. This may occur as a result of a well blowout, pipeline rupture, or other accidents. Methods of coping with these possible occurrences should be determined and preventive measures taken prior to drilling of test wells. Such fluid flows may be difficult to control and release large volumes of saline water which could contaminate hundreds of acres of farm land.

SECTION 4
DESCRIPTION OF THE RESOURCE

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 the Geysers, California, and Larderello, Italy. The fluid produced is dry, superheated steam characterized by an absence of nonvolatile 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

Rubey and Hubbert[1], and other numerous authors have attributed the origin of geopressure to be due to undercompaction of the sediments. Much confusion arises from the use of the word "undercompacted" 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[2], 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 occurs above depths of 1,000 m., 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.

Where 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 0.6 to 0.8 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 not restricted vertically by the sedimentary column, and laterally by contemporaneous faulting, 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.). Thus, bottom hole pressures in the range of 680-1,360 atm. (10,000-20,000 psi) would commonly be encountered. 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 1,500-3,000 m., and the lower geopressured regime. The boundary between the hydropressured and geopressured zones is very distinct and is characterized by abruptly increased pressures, thermal gradients, flowline temperatures, and penetration rates, and 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; and
K = thermal conductivity

The "subcompacted" geopressured sediments 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 geopressured 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. However, hot geopressured zones do exist in the absence of salt diapirs. Considering both theories it must be concluded that the explanation of the origin of the heat leaves 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 considerably lower than those found in the hydropressured zone. This statement is made with little supporting analytical data. Jones[3] states that, "Waters of the geopressured zone decrease in salinity with depth, and dissolved solids in the range of 5,000 to 20,000 mg/l. may be common." 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 Jones[3] is shown in Figure 1. Difficulties in obtaining samples of these waters have precluded extensive analytical confirmation of these low salinities. Most samples have been obtained from the top of the zone and thus show misleading high salinity. We believe the water will be of low salinity. However, in the environmental aspects of this report, we have taken somewhat higher salinities to provide for what we feel may be the worst cases. Typically, geopressured waters have salinities in the range of 5,000 to 20,000 ppm, as compared with 100,000 ppm 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 semi-permeable membrane, concentrating brines at certain interfaces and thus freshening adjacent waters. This phenomenon is imperfectly understood at the present time. 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[4], Burst[2], Phillippi[5] and others have demonstrated that hydrocarbon maturation begins at a temperature of about 75°C. Most, if not all, of our hydrocarbon reserves have been generated in the geopressure zone from indigenous carbonaceous matter present in the original sediments. Thus it is no surprise that the geothermal fluid is expected to contain dissolved hydrocarbons, principally methane, in large quantities. Culberson and McKetta[6] have shown that under the temperature, pressure, and salinity environment postulated for the geopressured aquifers, the fluids could contain 1,132 std. liters (40 scf) or more of methane per barrel. This dissolved methane 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. However, the consensus of most researchers seems to be that no H_2S will be present.

Because another by-product of the diagenesis of montmorillonite is silica, the fluids are expected to be near the saturation level for SiO_2. This could

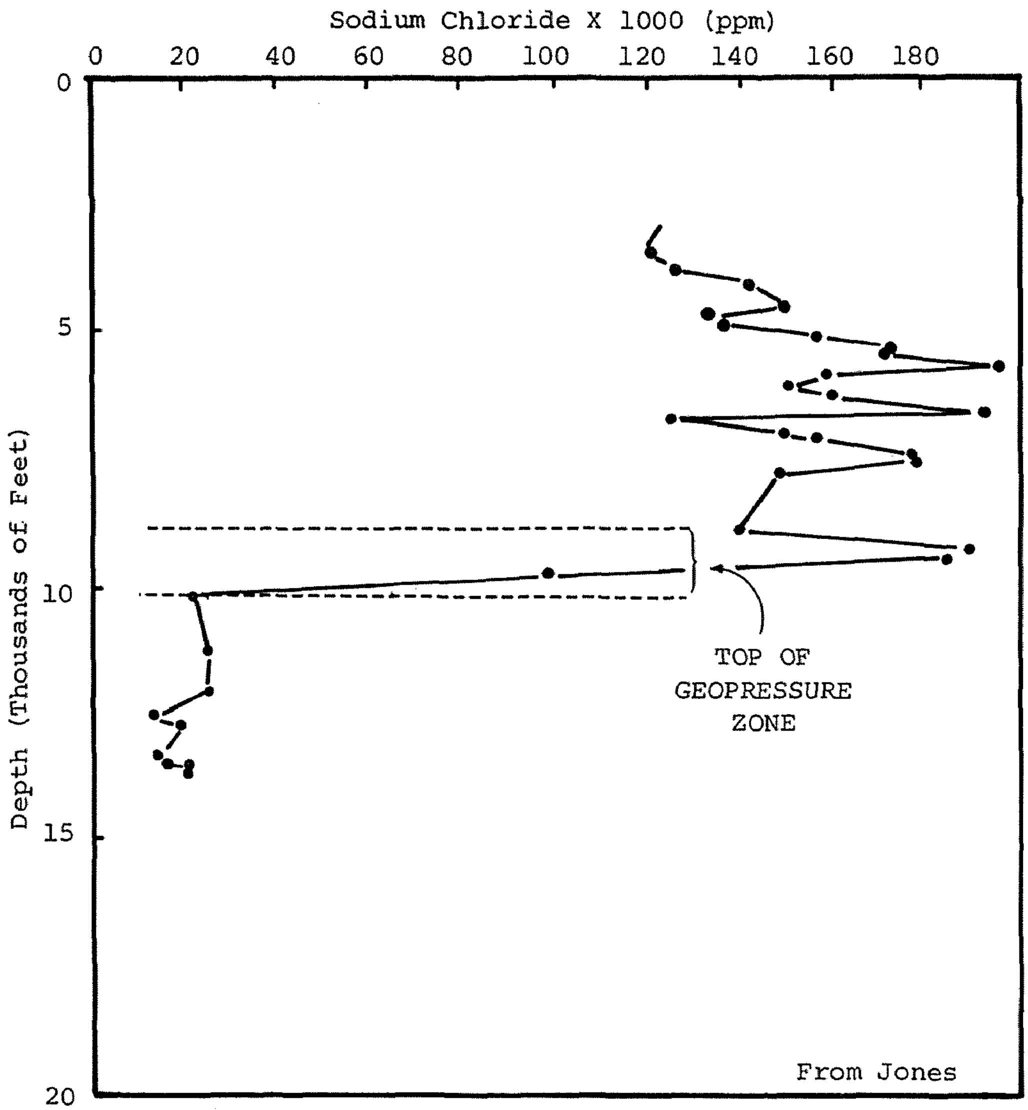


Figure 1. Change in formation water salinity with depth, in relation to the occurrence of the geopressure zone, Manchester Field, Calcasieu Parish, Louisiana.

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 zones of the upper Gulf Coast occur in a broad band 300 to 500 km. wide that stretches from below the Rio Grande, along the coast and into southern Mississippi and Alabama, a distance of more than 2,000 km. The geopressured zones may extend offshore a distance of several hundred km. and contain an accumulation of clastic sediments that exceeds 15,000 m. in thickness in some areas.

The sediments range in age from the Eocene Wilcox formulation, approximately 50 million years old, to Pleistocene, only about 1 million years old. Two types of sediments predominate: sands and lagoonal shales formed in the great deltas which shaped the coast in the geologic past, and marine shales, 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 overlaid 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. 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 300 m. or more and act as effective barriers to the escape of geopressured waters; i.e., they form reservoir boundaries. Sand distribution are further effected 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 offlapping 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. The top of the geopressure zone is deepest in the oldest formations and becomes progressively shallower as growth faults are crossed in a coastward direction, thus indicating that the fault planes have acted as "valves" and eventually have allowed excessive pressure to bleed off.

Papadopulos, et al[7], studied the onshore area of the upper Gulf Coast, approximately 150,000 km^2. They divided the area into 21 subareas, as shown in Figure 2, based on age, lithology, and fault-trends, and calculated an "idealized conceptual reservoir" for each subarea by assuming that all the sand occurs in one thick, continuous bed bounded on both top and bottom by

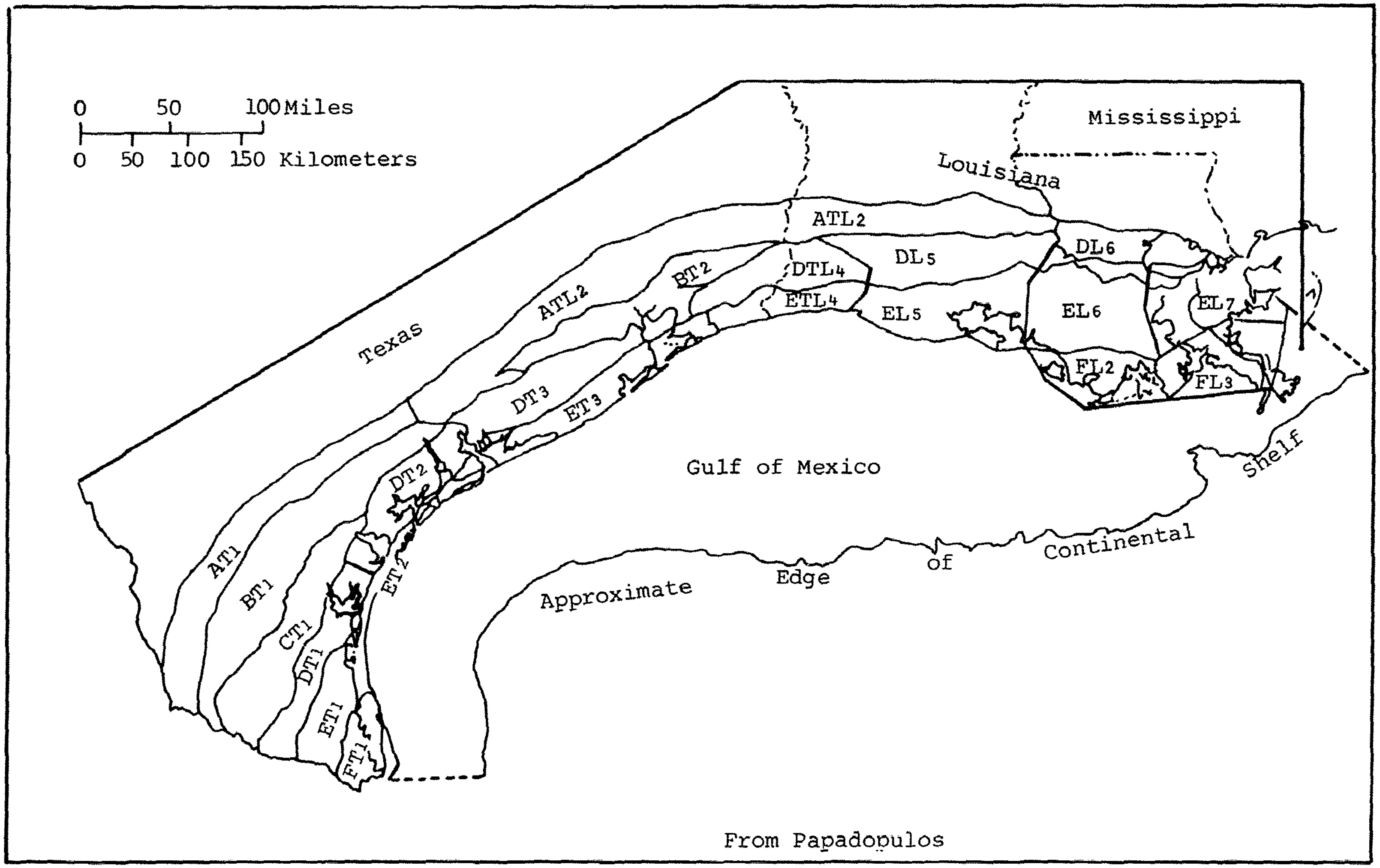


Figure 2. Location map showing the extent of the assessed geopressured zones.

geopressured shale. Using this approach, a total volume of water of 78.39 x 10^{12} m^3 is calculated for the Gulf Coast. Thermal energy contained is 457.5 x 10^{20} J, equivalent to 14.5 x 10^6 megawatt centuries (MWc), and contained methane energy is 252.6 J, or 8 x 10^6 MWc. These numbers represent the total resource base and do not in any way indicate the ultimate recoverable energy. Factors such as recovery technology, reservoir size and location, costs, and potential legal conflicts were not considered.

Dorfman[8], Bebout[9], and others have used the "geothermal fairway" approach. First, maps are prepared showing net sand in a given paleostratigraphic interval. These maps are then correlated with isogeothermal maps and top of geopressure maps. The result defines regions where favorable sand conditions, high temperatures, and shallow geopressure combine to form "geothermal fairways" or areas favorable for exploitation. The results of this approach indicate that approximately 20,000 MWc of thermal energy may be available for power generation. Bebout's fairway selection is shown in Figure 3.

The failure of the "geothermal fairway" approach is that it does not identify or describe individual geothermal reservoirs. Since faults constitute a barrier to water movement, each fault block must be considered individually for geothermal potential. Tremendous quantities of water will have to be produced over long periods of time to sustain a commercial geothermal electric power facility; therefore, any fault block that is physically too small to satisfy these requirements is not potentially productive. This eliminates approximately 50% of the entire Gulf Coast area for the production of electricity but not necessarily for other uses. Other problems such as sand distribution permeability, transmissivity, legal, and environmental restrictions may eliminate 50% of the remaining fault blocks. Conversion efficiencies for thermal energy are also low, on the order of 10%. These factors when applied to Dorfman and Kehle's[8] estimate of available electrical energy of 20,000 MWc implies a practical recoverable energy on the order of 500 to 1,000 MWc, not including dissolved methane.

DIFFICULTIES AND LIMITATIONS

There are two broad categories of problems that may be encountered in the development of the geopressured resource: problems related to producibility, and legal and environmental problems.

It has already been noted that a reservoir must be of a sufficient size to be commercially viable. Moreover, the sand bodies that constitute the reservoirs are more often than not of the regressive, discontinuous type. In order for these discontinuous sand bodies to be productive over long periods of time, it will be necessary for the surrounding shales to dewater into the sands and replenish the withdrawn fluids. Jones[3,10,11] has postulated that this will occur; however, no hard data now exists to either confirm or refute this hypothesis. Knapp and Isokrari[12] have suggested that a test well located close to the sand/shale reservoir boundary could determine the influence of shale dewatering in a short period of time.

Aquifer permeabilities must be adequate to provide the enormous flow rates required by a commercial facility. Papadopulos, et al[7], report average

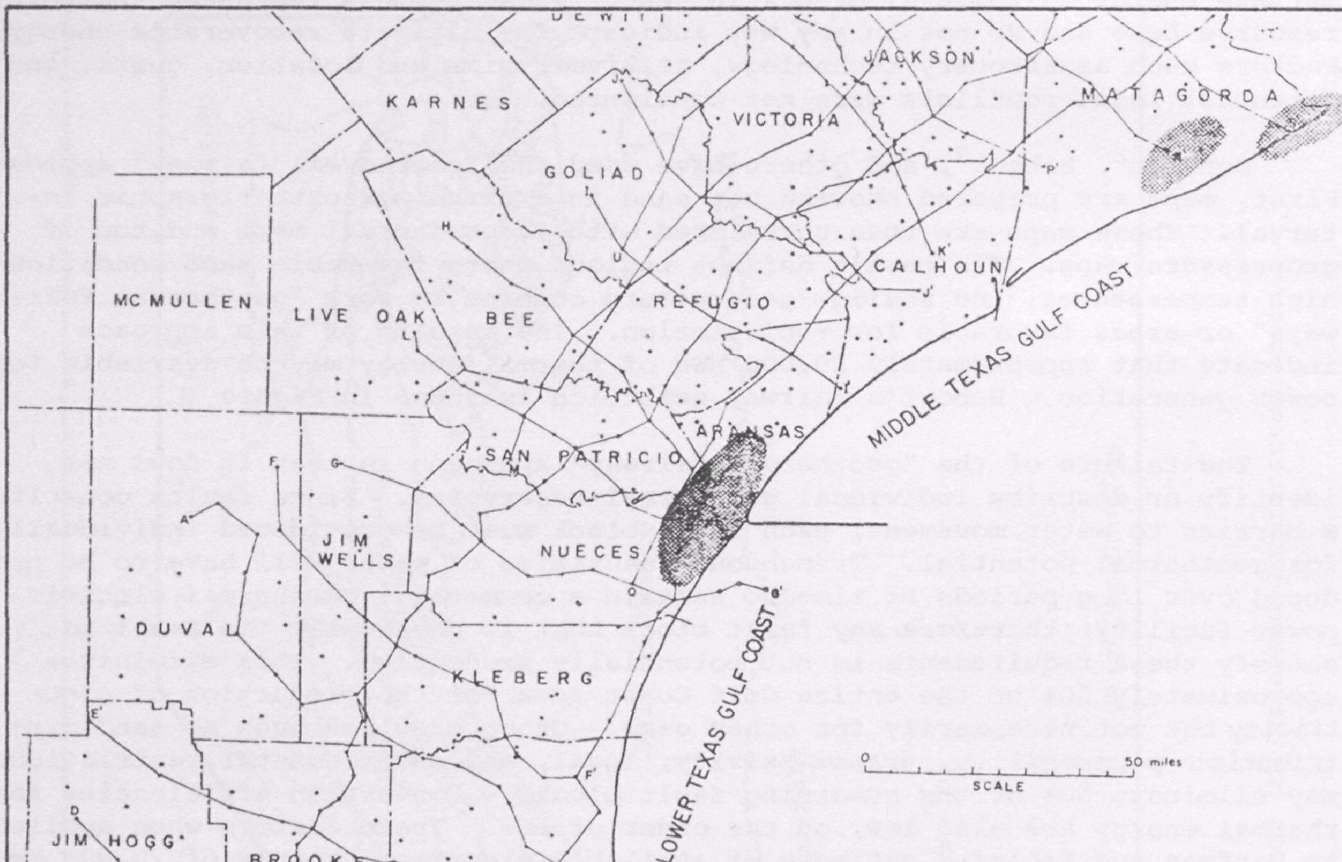
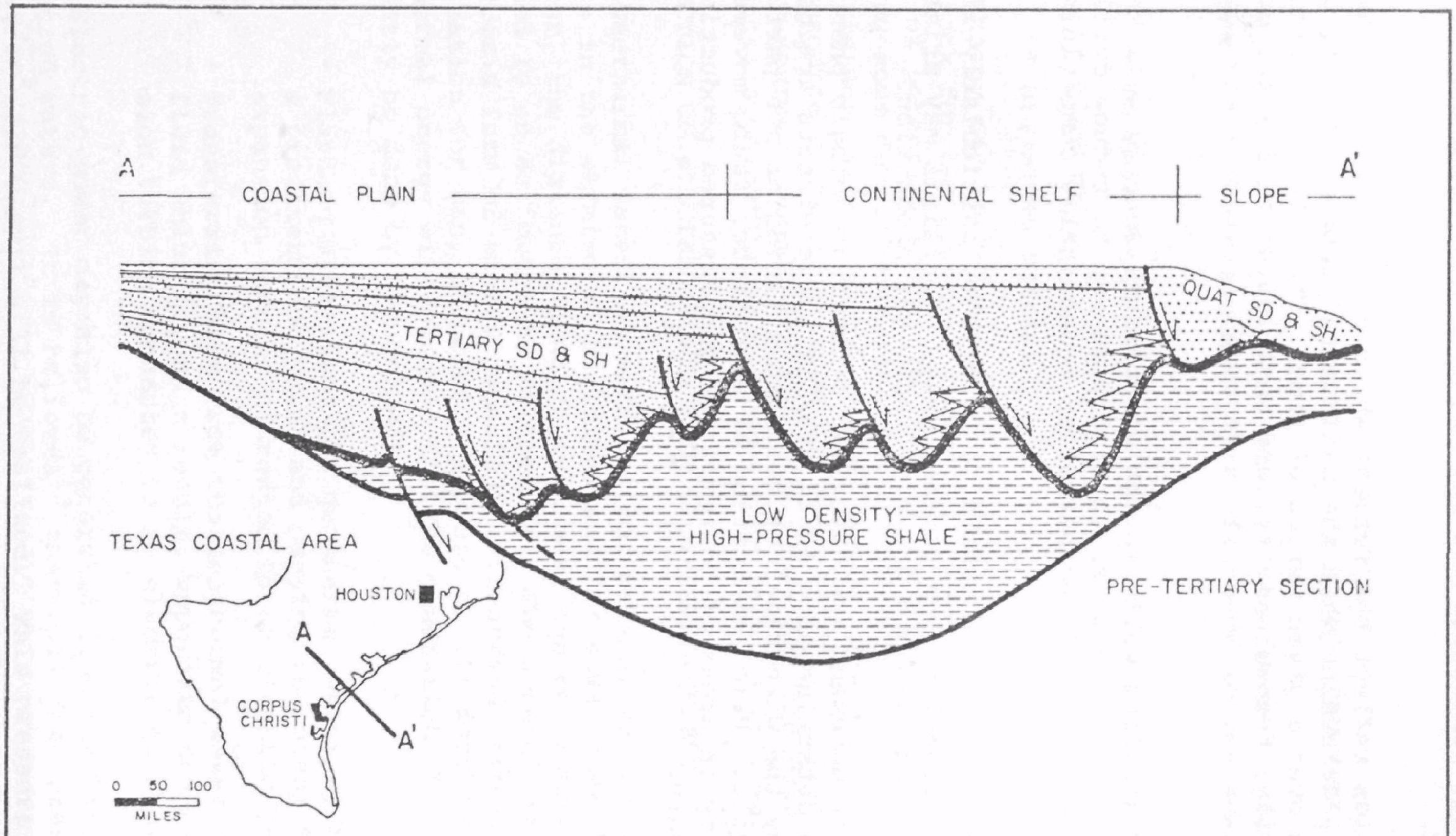


Figure 3. Geothermal fairways of the lower and middle Texas Gulf Coast.



From Bebout

Figure 4. Depositional style of the tertiary along the Texas Gulf Coast.

permeabilities in the range of 15 to 50 md. with porosities of about 20%, which would probably be sufficient. Other data[9], however, indicate that permeabilities of less than 1 md. and porosities of 10% are not uncommon. It is generally accepted that permeabilities are highest in Louisiana and lowest in the south Texas area.

Transmissivity ratios reflect the rate at which an aquifer will draw down during production; i.e., determine what the maximum allowable flow rate would be to ensure production over a given period of time. The actual, in-situ parameters of permeability, transmissivity, and shale water influx are essentially unknown, but can be established with a thorough program of static and dynamic well tests.

The technology for drilling wells in the geopressure zone is well known, but costs are high. It may be necessary to find some way to reduce drilling costs in order to make geopressured geothermal an economically competitive form of energy.

Legal problems may develop with regard to ownership, particularly if a well is produced for the dissolved gas content only. Conflicts may arise if a geothermal well depletes the pressure drive of updip gas production.

Subsidence and fault movement are naturally occurring geologic phenomena. It will be difficult to determine in a local area if these effects are being caused or intensified by the withdrawal of geothermal fluids or are part of the natural geologic cycle. Prior monitoring of subsidence, fault movement, and microseismic activity in areas of contemplated geopressured production will probably be necessary.

SECTION 5
POSSIBLE USES OF GEOPRESSURED GEOTHERMAL WATERS

As pointed out by Wilson, et al[13], geothermal, geopressured water along the Texas 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 casts doubt 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 kilometers. 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[13] that well head pressures as high as 140 kg/cm^2 (2000 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.

If all of the potential geopressured geothermal resources of the Texas Gulf Coast -- offshore as well as on-shore -- 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[8,11,13,14].

OTHER POTENTIAL USES

A number of possible uses of geopressured geothermal energy other than electrical power generation have been suggested[14,15,16] dependent on the heat and kinetic energy content of this resource. It is doubtful that many of these alternates 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 non-electrical power generation uses.

However, it should be noted 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 10-12%, while conversions of up to 85% energy efficiency may be reached in some non-electrical 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, 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.).
- Adsorption refrigeration and freeze-drying of foodstuff.

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.
- De-icing bridges, overpasses, and driveways.
- Heating of swimming pools, fish hatcheries, etc.
- Waste treatment (disposal, bio-conversion, 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[13] and updated and expanded by Dorfman, et al[15].

The details of two proposed electric power production systems can be found in the *Proceedings Second Geopressured Geothermal Energy Conference* referred to in reference no. 17. These are the flash and the secondary working fluid cycles. Outlines of this fuel plant for supplying these systems plus those of the electric power generating plants are described further in Section 6 where the possible emissions and other environmental considerations are treated. These models are used because it is felt that they will be the most likely methods of power production for this resource.

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 very 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 would, however, 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. Geopressured fluids are expected to present only minor scaling problems. 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. The most exhaustive study to date has been that of Gault, et al[17]. 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 $50,496,000. 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 1.

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 cents per $\overline{M}$ Btu. This value compares to the intrastate cost of natural gas on today's market of nearly $2.00 per $\overline{M}$ 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 mills per kWh, which is very high.

TABLE 1. 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%
Net power cost, mills/kWh	--	46

* Includes hydraulic power.

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, University of Texas at Austin combined the Dow 1976 study with a Brown & Root study with some minor changes in economic assumptions[17] and arrived at a capital cost of $738/kW(e) for a 25 MW(e) power plant only as shown in Table 2 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 3.

INCENTIVES FOR GEOPRESSURED GEOTHERMAL POWER PRODUCTION

The 1980 census of the 36 counties of Texas which might reasonably have access to the geopressure geothermal fairways of the Gulf Coast shows a population of 3,518,859, ranging in population density from 1-390 persons per square kilometer[18].

Assuming the population growth trend, per capita electrical usage and estimated required generating capacity follows the national trends predicted by Hittman Associates, Inc.[19] in Table 4.

We would estimate the increased required power capacity in the coastal area at:

Probable Power Capacities, 36 Counties,
Texas Gulf Coast Geopressure Geothermal Zone
(Does not include Louisiana area)

Year	Population (10^6)	Per Capita Use (kW)	Total Use (10^6kW)	Plant Load Factor	Estimated Required Capacity (10^3MW)
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 (1970 to 2000)		= 20.69

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

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-oil), there is increased interest in other power sources. The importance of the use of

TABLE 2. IMPORTANT PARAMETERS, ALTERNATIVE POWER PLANTS

Parameter		Plant A: Flash Steam	Plant B: Secondary 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
4.	Auxiliary power requirements [MW(e)]		
	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 3. 1980 APPORTIONED BUSBAR CHARGES [POWER PLANT] (100% DEBT FINANCED)

Factor	Busbar charge (mills)
Operations, maintenance	6.08
Fuel	13.06
Capital	18.48
Taxes (federal, state, local)	9.88
TOTAL	47.50

TABLE 4. MOST PROBABLE POWER CAPACITIES, U.S.A.

Year	Population (10^6)	Per Capita Use (kW)	Total Use (10^6kW)	Plant Load Factor	Estimated Required Capacity (10^3 MW)
1970	205	0.9	185	0.64	320
1980	232	1.5	348	0.64	544
1990	265	2.4	636	0.65	978
2000	307	3.2	982	0.66	1488

gas and oil as refinery and chemical feed stocks rather than fuels is widely recognized by industrial users in this region.

Earlier projections[19] 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, 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". Many 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.

Future costs for coal, either Texas lignite or conventional coal, are difficult to project should Gulf Coast industry become largely dependent on this fuel as an energy source. Coal mining has traditionally been a labor sensitive industry. This combined with the possible high costs of transport to point of useage, cost of conversion of existing boilers from gas to coal firing, additional increased capital for emission controls, and land restoration costs may not make coal as attractive an alternate as it originally appeared.

Compromise bills now before the Senate (May, 1976) seek to end federal price controls on some natural gas and allow prices to consumers to rise gradually (10-15% per year). The current regulated price of \$0.52/1000 scf would be raised to \$1.60/1000 scf for newly drilled on-shore gas sold in interstate markets. Provision would be made for further increases based on inflation. Gas sold within the same state in which it is produced would continue to be unregulated. Some new current gas prices in unregulated contracts in the Gulf Coast area are running as high as $\$1.95/10^6$ Btu. <u>Using natural gas for "boiler fuel" or other low priority industrial uses would be prohibited after 10 years.</u>

Faced with the possible ultimate loss of this conventional fuel source, <u>natural gas</u>, 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 <u>Gulf Coast industrial power producer should be more interested in exploiting the geothermal energy potential in this region than ever before</u>. However, he is unlikely to undertake such a high risk venture 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.

NON-ELECTRICAL POWER GENERATION USES OF GEOPRESSURED BRINES

Worldwide, the greatest non-electrical 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 geopressure geothermal brines as could absorption refrigeration and air conditioning.

As Lindal[20] has pointed out, there are many possible examples for future industrial geothermal utilization. Some of the temperature ranges for various processes are shown in Figure 5. 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[21] 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.

Selection of specific processes, sizing of possible industrial-agricultural plants, energy balances, and optimization of the use of the residue brine from the power plant in an energy park were beyond the scope of this report.

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.

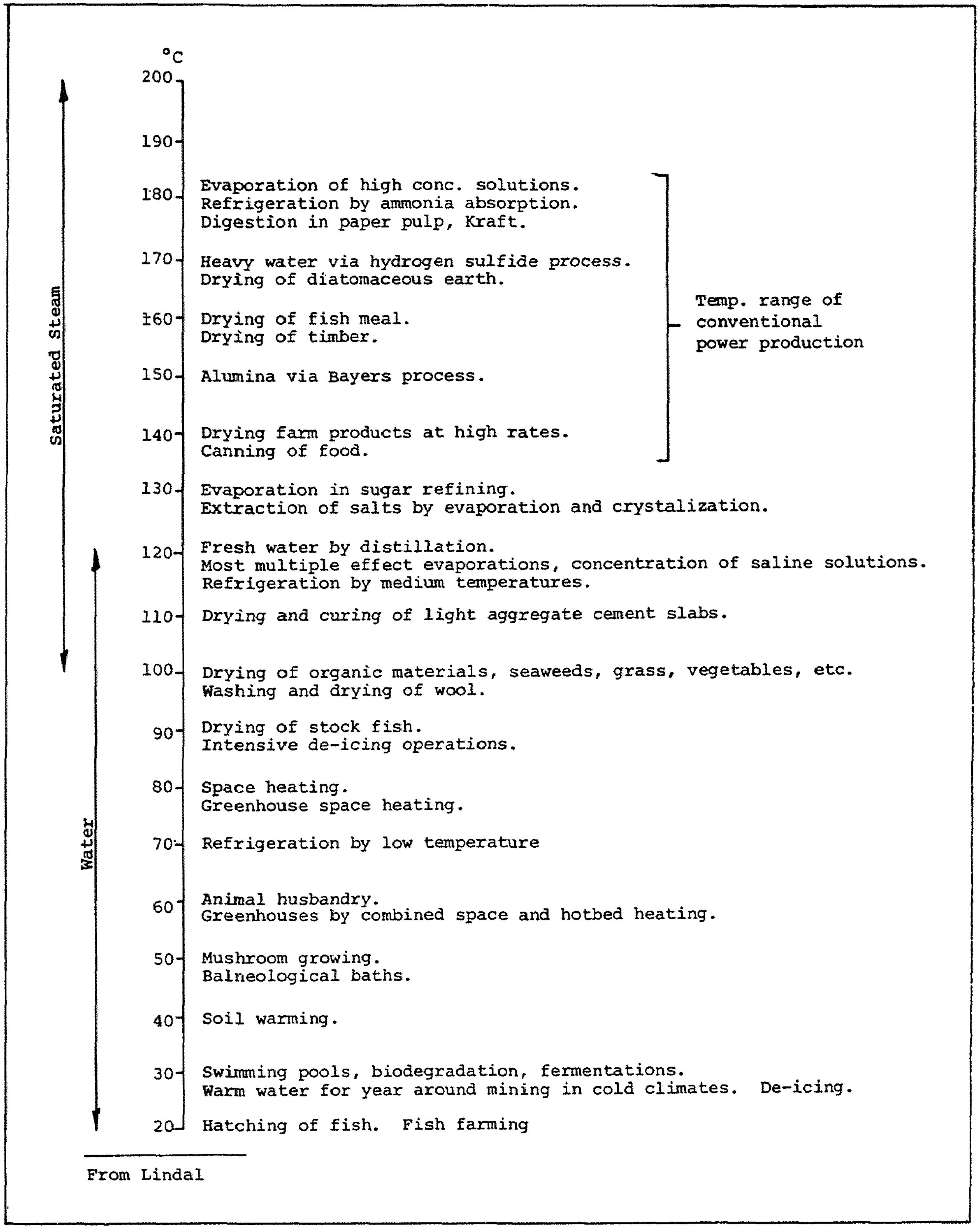


Figure 5. Required temperature of geothermal fluids for various nonelectrical applications.

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.

TIME FRAME FOR DEVELOPMENT

It is difficult to estimate a time frame for development of the geopressured geothermal resources along the Gulf coast despite the many studies which have been made on this potential energy source. The technical and equipment development and problems can be solved within estimable limits, however, less specific barriers are listed by JPL[22,23]:

- Federal and state leasing practices and laws
- Inadequate incentives
- Cost/risk/time relationships
- Complex leasing interactions
- Multiple and complex regulation and approval requirements
- Time-sequential requirements
- Withholding of proprietary information
- Environmental restrictions and complicated procedures by federal, state, and local agencies
- Availability of experienced personnel to carry out assessment and exploration
- Availability of drilling equipment and crews for exploratory geothermal drilling (available rigs and crews can keep quite busy prospecting for oil and gas)
- Availability of deep-hole logging equipment suitable for the higher temperatures of interest for geothermal wells (well-logging equipment companies have not felt it worthwhile to invest in such equipment except to a very limited extent)

These may well determine the time frame for development. Resolution of the non-technological issues impeding geothermal energy development is imperative before real physical progress can be made in utilization of geopressured geothermal energy.

Wilson[24] suggested the time frame to demonstrate the feasibility of the production of electric power, natural gas, and fresh water from the geopressured waters of the Gulf Coast shown in Figure 6 while JPL[23] estimated the time required to complete the development cycle for single geothermal energy plant (California site - Federal land) as shown in Figure 7.

Figure 8 shows the approximate timing and scheduling developed at the University of Texas, Center for Energy Studies by Dorfman, et al[15].

All of the time frames presented are partially directed toward achieving the goals of energy independence by 1985. In view of the actual progress to date they seem extremely optimistic.

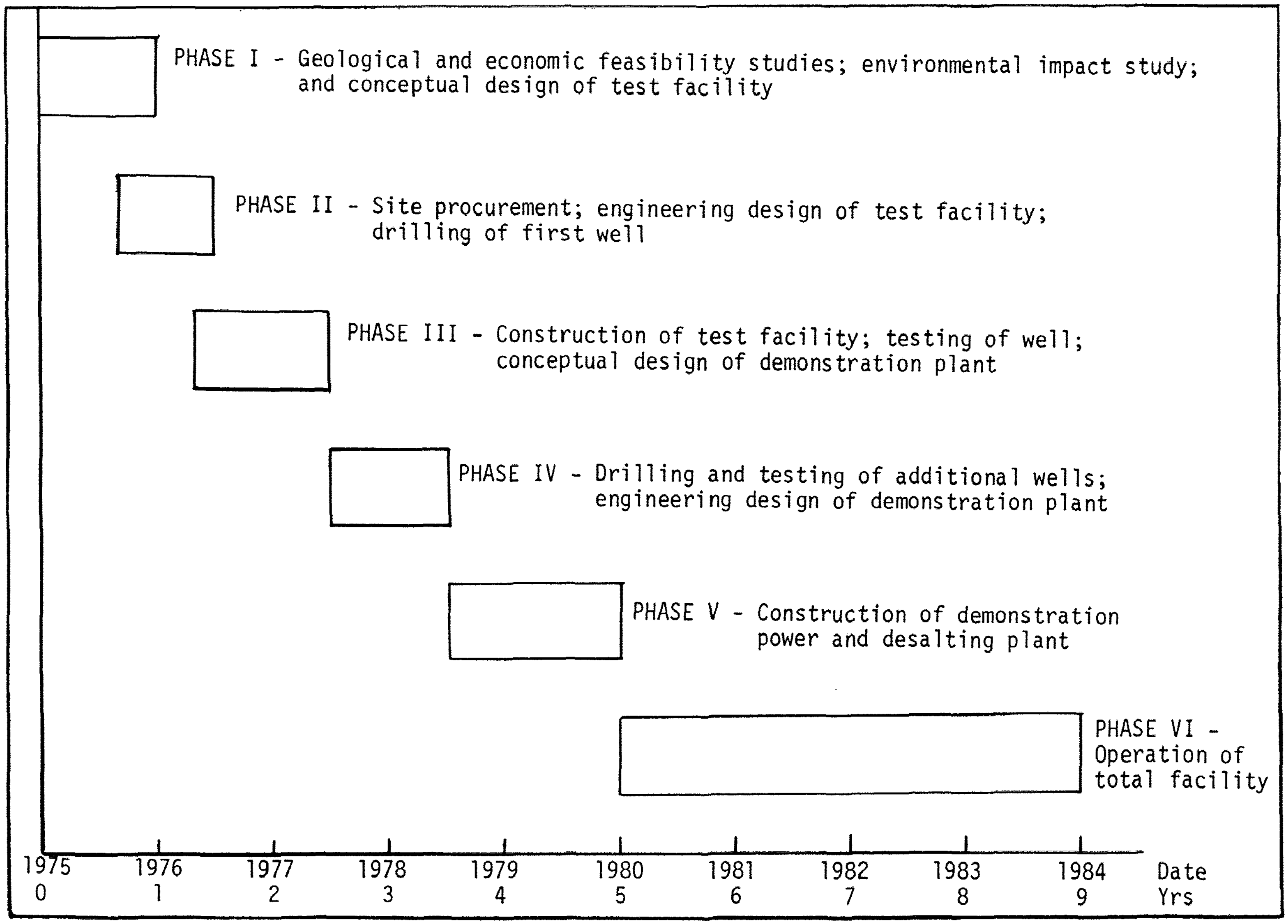


Figure 6. Proposed plan for geothermal energy development on the Gulf Coast.

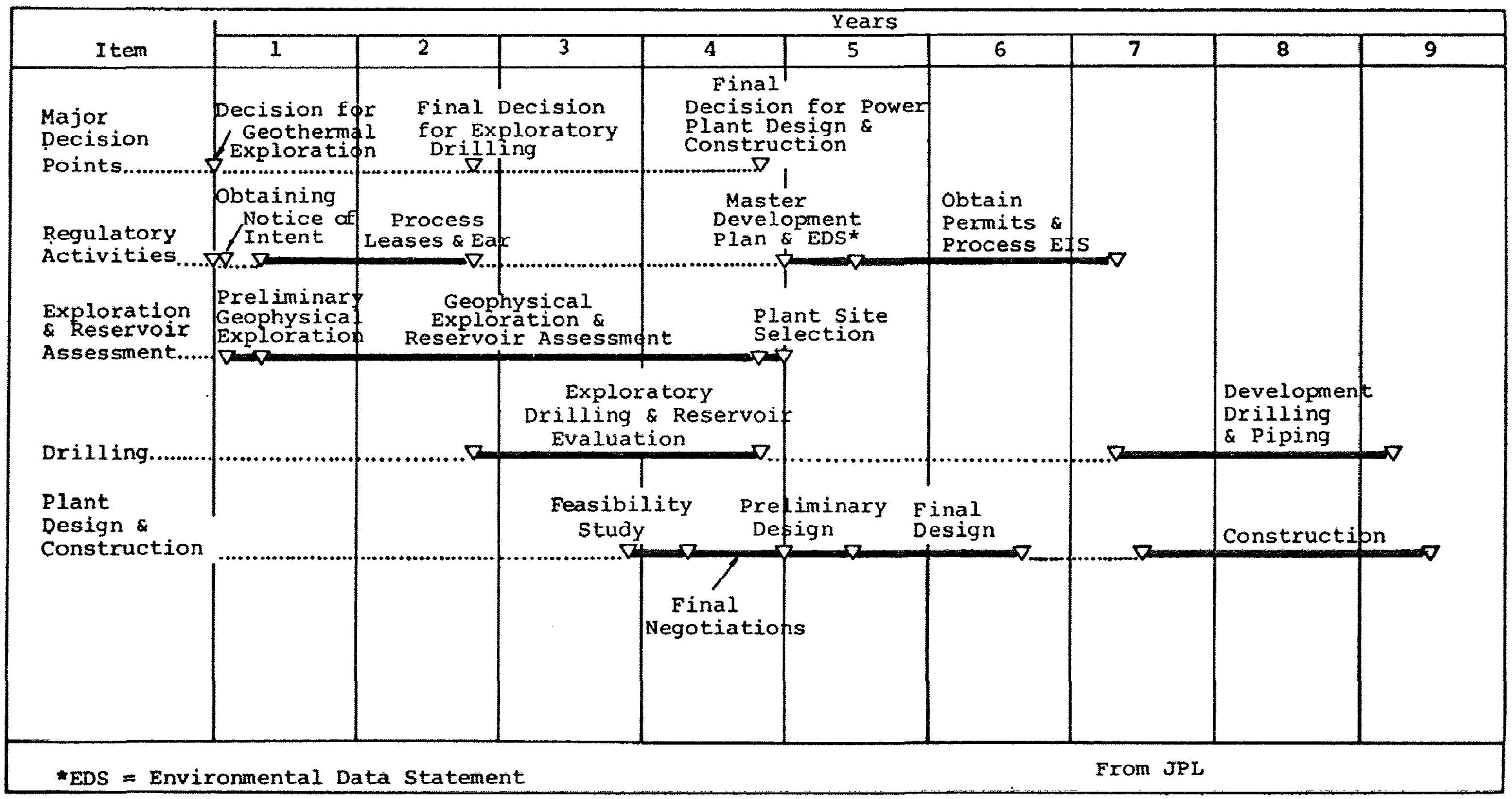


Figure 7. Business-as-usual geothermal plant development timeline (initial development, federal land, noncompetitive bidding).

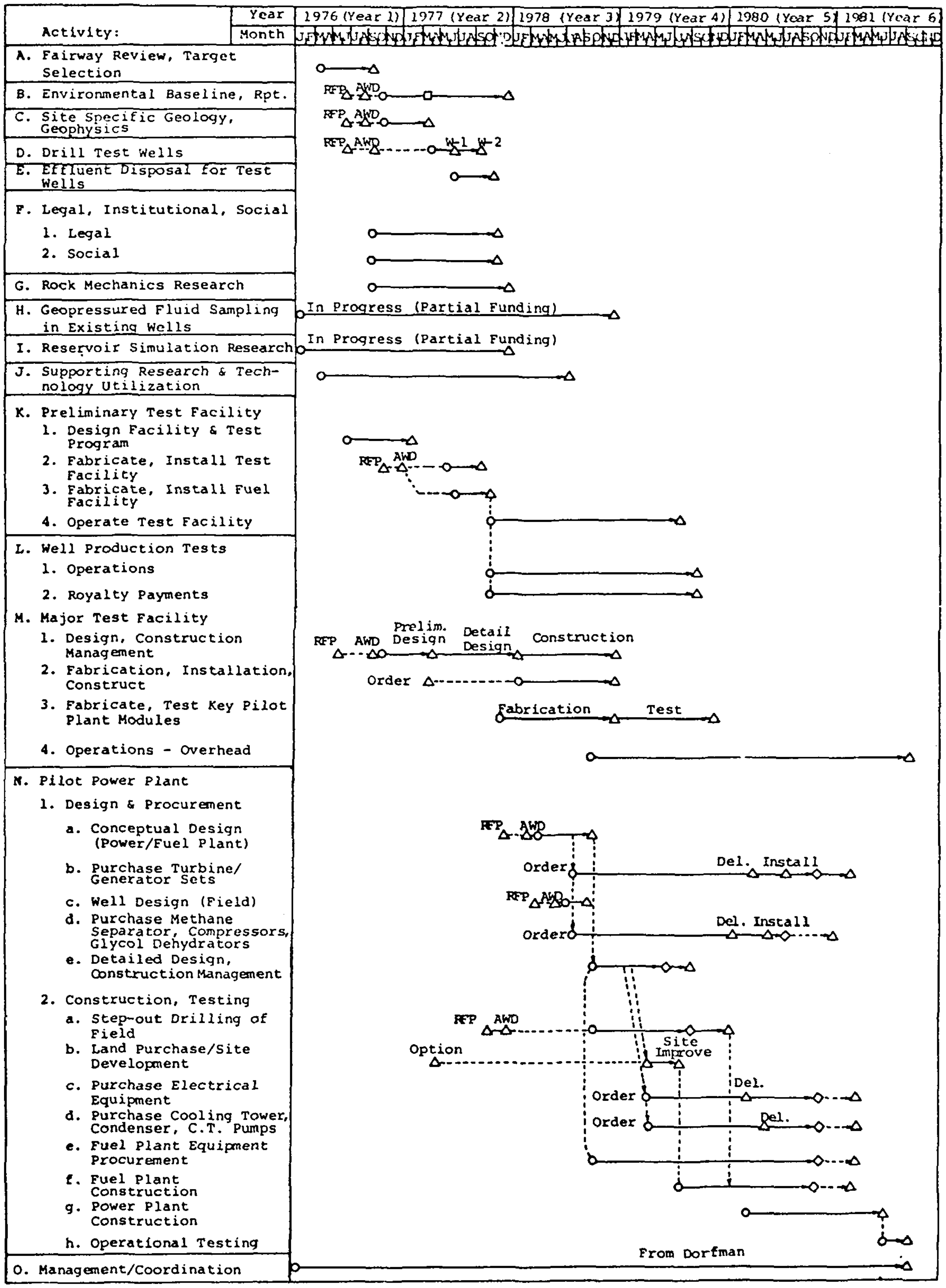


Figure 8. Overall time schedule, major activities

In today's industrial power plant construction, five-year lead time from the decision to proceed to actual plant completion are not unusual. In the case of geothermal plants, much of the critical equipment cannot be considered off-the-shelf items; large hydraulic turbines and low pressure steam turbines must be designed and built to the final plant sizes which are chosen. Many delays ranging from late equipment delivery to unexpected initial drilling and operational problems should be anticipated for relatively new developments on the outer fringes of technology such as the proposed geopressured geothermal plant. If the plant development were to follow sequential steps;

- 1.5 MW(e) test well; prototype equipment test
- 10 MW(e) pilot plant
- 25 MW(e) demonstration plant

appreciably more time may be involved than shown on the time frames given in this section. Factors of 1.5 or 2.0 times number of years shown in Figures 6, 7, and 8 may be more appropriate.

SECTION 6
PROJECTED MULTIMEDIA EMISSIONS AND EFFECTS FROM POTENTIAL USES

ANALYSIS OF THE WATERS

As a preliminary to considering the various environmental aspects of the resource, it is desirable that the composition of the waters be estimated as accurately as possible. Representative analyses of waters from the geopressured strata are limited and, as discussed in Section 4, are subject to considerable question.

All available sources were used to collect a listing of water composition values. However, the reader must recognize that the validity of the water samples themselves is uncertain; few geopressured "sand" water samples are available, with most samples likely being of the "shale" waters and with most samples being from the top of the geopressured zone where salinity is maximum. With these considerations in mind, a listing was prepared.

Water analyses were obtained from the following sources: Dickey Taylor[26], Jones[27], Blakeman[28], Schmidt[29], and the Texas Water Development Board[30]. Each of the approximately one hundred analyses shown on Table 5 represents the water composition of what is believed here to be an overpressured geothermal stratum. The overriding conditions required for including a particular water analysis in the geopressured category were that:

- The source well was completed since 1962, and
- The source formation was encountered at a depth greater than 9,000 feet.

In the absence of further qualifying information, these two conditions were accepted as sufficient evidence that the formation was geopressured. Approximately 60% of the analyses shown in Table 5 were classified as representing geopressured waters on this basis. For the remaining analyses, additional evidence of geopressured origin was available. This was almost always the presence of one or both of the following two characteristics:

- The numerical ratio of formation pressure in psig to depth in feet exceeded approximately 0.45.
- The salinity of the water was distinctly and appreciably less than that of the adjacent overlying stratum, representing a reversal of the trend of the salinity-versus-depth relationship.

Attention is called to the high barium concentration reported in more than a dozen of the water analyses. In one of these cases the recorded value

TABLE 5. BRINE COMPOSITIONS FROM OVERPRESSURED RESERVOIRS

	Formation			Composition in mg/l														
General Location	Depth* Ft.	Press. psi	Temp. °F	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	Li	Sr	Ba	Br	I	B	Ref.
SW	15,300	na	na	54,810	21,445	518	1,074	39	30,866	0	385	10	na	na	35	18	49	25
Louisiana	11,955	na	na	96,508	36,650	247	2,214	369	55,592	407	541	7	na	na	61	22	62	"
"	11,895	na	na	91,361	31,500	200	1,379	213	56,540	234	826	6	na	na	52	21	62	"
"	11,860	na	na	81,993	28,275	204	1,379	194	49,980	38	630	6	na	na	57	21	37	"
"	13,325	na	na	114,539	36,190	267	3,850	583	72,778	tr	448	6	na	na	81	19	43	"
"	10,000	na	na	55,235	19,450	85	1,385	41	33,250	50	503	3	na	na	37	16	32	"
"	10,913	na	na	102,823	41,500	208	2,727	544	51,735	0	180	5	na	na	21	15	18	"
"	10,810	na	na	87,814	31,800	230	2,021	194	58,048	tr	363	4	na	na	91	18	26	"
"	9,995	na	na	97,577	41,732	162	3,048	719	50,858	33	507	6	na	na	70	23	35	"
"	9,683	na	na	52,029	31,100	134	2,310	50	45,310	0	545	4	na	na	35	18	28	"
"	10,060	na	na	82,702	32,500	262	2,951	447	45,596	tr	574	4	na	na	35	22	29	"
"	9,260	na	na	95,051	32,900	181	2,662	389	57,872	tr	586	4	na	na	56	25	26	"
"	10,015	na	na	88,091	32,500	192	1,572	0	52,610	0	579	5	na	na	45	20	34	"
"	10,890	na	na	198,993	57,850	427	21,558	2,178	116,095	0	322	9	na	na	128	26	38	"
"	10,580	na	na	97,812	43,500	315	1,893	408	50,928	67	330	9	na	na	43	18	23	"
"	12,390	na	na	235,634	82,100	813	15,232	1,266	135,385	na	92	9	na	8	154	24	52	"
"	12,018	na	na	131,946	47,840	427	2,951	447	79,250	0	334	10	na	50	169	74	48	"
"	9,608	na	na	81,281	29,400	172	2,662	1,011	46,618	60	741	6	na	5	40	23	46	"
"	9,720	na	na	85,705	33,900	155	2,175	503	47,868	72	788	5	na	5	52	21	48	"
"	9,745	na	na	78,475	31,573	157	na	na	45,758	na	694	4	na	8	na	22	44	"
"	13,250	na	na	218,298	75,590	830	15,655	159	125,470	0	135	15	na	19	64	23	47	"
"	11,580	na	na	146,392	56,750	324	7,387	565	84,530	tr	0	7	na	na	20	22	40	"
"	11,810	na	na	143,635	80,305	376	3,304	na	80,305	0	363	9	na	na	62	20	45	"
"	14,405	na	na	345,470	101,400	782	28,808	2,138	201,325	0	0	17	na	na	213	18	75	"
"	13,962	na	na	327,069	103,000	640	33,160	5,772	183,788	na	0	17	na	na	204	19	67	"
"	11,765	na	na	205,953	78,700	798	14,340	428	111,060	tr	112	12	na	na	94	27	42	"
"	14,080	na	na	208,661	68,330	771	18,446	1,205	119,315	0	76	18	na	na	117	28	52	"
"	12,355	na	na	110,761	44,450	137	3,613	17	61,555	0	550	5	na	na	14	5	67	"
"	12,742	na	na	190,436	69,230	1,154	18,253	1,089	100,069	0	66	17	na	na	201	21	42	"
"	13,860	na	na	180,250	54,500	631	14,436	700	109,300	0	73	13	na	na	71	21	39	"

Table 5 (continued)

General Location	Formation Depth* Ft.	Formation Press. psi	Formation Temp. °F	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	Li	Sr	Ba	Br	I	B	Ref.
				Composition in mg/l														
SW	12,298	na	na	136,694	52,520	392	2,759	35	79,970	77	270	10	na	110	110	34	34	25
Louisiana	11,478	na	na	78,467	31,200	160	1,508	447	44,424	130	244	5	na	na	70	35	36	"
"	10,564	na	na	124,904	47,470	294	3,272	564	72,250	0	234	3	265	41	58	18	33	"
"	12,757	na	na	133,766	na	na	4,555	0	128,720	0	80	na	na	na	174	24	41	"
"	11,815	na	na	201,709	73,760	375	5,614	564	120,545	0	240	5	na	na	134	38	43	"
"	12,255	na	na	104,457	43,300	176	3,208	136	54,495	102	539	5	na	7	40	26	52	"
"	9,249	na	na	127,543	47,800	264	2,951	855	74,420	0	249	2	na	na	79	18	26	"
"	12,287	na	na	83,146	30,250	71	1,784	141	49,714	88	482	2	na	4	60	35	43	"
South	13,675	7,918	248	109,736	39,327	na	2,448	413	66,150	40	614	na	na	630	na	na	na	28
Louisiana	13,747	8,308	249	80,066	1,886	na	3,129	389	73,500	12	593	na	na	550	na	na	na	"
"	13,747	8,308	249	113,312	40,981	na	2,724	73	68,200	10	584	na	na	675	na	na	na	"
"	12,560	8,976	234	na	45	na	10	0	10	10	135	na	na	15	na	na	na	"
"	13,025	8,716	237	110,232	40,041	na	2,259	312	66,488	2	708	na	na	364	na	na	na	"
"	15,930	na	na	29,505	7,728	na	3,180	255	18,254	11	56	na	na	na	na	na	na	"
"	15,007	na	na	175,968	50,729	na	14,400	1,640	108,459	0	91	na	na	647	na	na	na	"
"	16,398	na	na	204,112	12,621	na	28,000	23,781	138,500	45	na	na	na	1,000	na	na	na	"
"	14,700	na	na	128,792	41,729	na	7,080	na	78,860	0	199	na	na	206	na	na	na	"
"	14,945	na	na	189	32	na	30	2	104	11	0	na	na	na	na	na	na	"
"	14,850	na	na	64,441	19,934	na	4,090	493	39,462	0	0	na	na	400	na	na	na	"
"	16,270	na	na	185	10	na	44	9	106	0	13	na	na	na	na	na	na	"
"	19,465	na	na	39,333	11,316	na	3,068	428	23,762	225	394	na	na	60	na	na	na	"
"	15,900	10,740	302	na	138	na	19	0	228	0	37	na	na	na	na	na	na	"
"	14,187	9,276	243	59,376	20,843	†	1,643	219	35,700	45	306	na	na	500	na	na	na	"
"	12,539	6,516	234	103,141	37,071	†	1,642	49	58,950	2	2,501	na	na	375	na	na	na	"
"	13,778	7,586	227	101,383	36,282	†	2,444	243	61,000	45	523	na	na	750	na	na	na	"
"	13,091	5,901	240	102,362	37,586	†	1,442	462	62,000	2	102	na	na	450	na	na	na	"
"	10,542	4,631	202	201	47	†	8	0	33	0	100	na	na	8	na	na	na	"
South	9,043	na	na	38,459	10,129	†	2,788	925	23,369	85	456	na	na	na	na	na	na	26
Texas	13,753	na	na	16,085	5,904	†	266	29	9,457	0	371							"
"	9,315	na	na	185,400	51,966	†	16,200	2,050	11,400	580	634							"
"	9,425	na	na	198,800	55,365	†	17,300	2,540	123,000	360	256							"
"	11,457	na	na	22,641	7,718	†	984	16	13,555	30	270							"

Table 5 (continued)

General Location	Formation Depth* Ft.	Press. psi	Temp. °F	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	Li	Sr	Ba	Br	I	B	Ref.
				Composition in mg/l														
South	10,679	na	na	21,965	7,233	†	1,174	0	13,095	17	277							26
Texas	10,832	na	na	3,380	900	†	350	30	2,100	na	na							"
"	12,180	na	na	4,850	1,370	†	450	30	3,000	na	na							"
"	11,823	na	na	3,165	1,035	†	150	30	1,950	na	na							"
"	11,774	na	na	11,373	3,600	†	760	18	6,890	na	na							"
"	13,430	na	na	14,753	5,347	†	156	22	7,660	88	1,810							"
"	13,200	na	na	19,568	7,030	na	230	57	11,299	17	859							"
E. Texas	9,880	na	na	114,900	41,049	†	2,960	585	70,200	33	56							"
South	10,250	na	na	71,978	20,464	†	6,864	143	44,126	9	182							"
Texas	9,244	na	na	39,947	7,575	†	7,300	122	2,495	na	na							"
"	11,315	na	na	9,805	3,375	†	400	30	6,000	na	na							"
E. Texas	9,863	na	na	134,500	38,951	830	10,500	1,020	82,300	590	312							"
South	11,077	na	na	158,900	na	na	15,050	1,465	98,100	148	243							"
Texas	10,258	na	na	212,400	54,800	2,592	17,510	1,780	135,690	16	27							"
"	11,337	na	na	174,500	40,793	1,300	21,700	1,660	107,000	13	1,990							"
"	12,420	na	na	15,423	5,505	†	394	16	8,883	4	610							"
"	12,495	na	na	40,785	14,641	†	835	143	24,153	0	731							"
"	12,970	na	na	23,204	8,515	†	291	52	12,970	165	1,211							"
"	9,260	na	na	77,285	6,770	†	20,000	1,100	48,850	240	225							"
SW	11,170	na	na	25,800	9,280	65	216	47	14,500	na	1,710	1.9	8.3	2.9	na	na	na	29
Louisiana	12,042	na	na	22,700	8,380	58	109	22	12,400	na	1,810	1.6	5.8	1.3	na	na	na	"
"	12,350	na	na	15,700	5,660	55	57	13	8,200	175	1,520	2.0	3.1	0	26	22	na	"
"	12,400	na	na	49,000	17,300	208	728	112	29,600	183	854	5.8	42	0	43	28	na	"
"	12,753	na	na	16,000	5,640	81	68	15	8,450	232	1,430	2.9	4.4	0	29	22	na	"
"	12,673	na	na	18,900	6,700	84	125	20	9,850	215	1,930	3.5	8.8	1.1	43	24	na	"
"	12,673	na	na	18,300	6,580	86	138	18	9,950	175	1,330	3.1	5.3	0	33	27	na	"
"	12,866	na	na	18,300	6,400	89	158	23	9,700	170	1,710	3.6	11	1.7	27	20	na	"
"	12,866	na	na	17,700	6,330	89	117	21	9,800	128	1,270	3.2	8.1	0	32	25	na	"
E. Texas	15,578	na	280	65,000	na	na	na	230	na	na	na	na	na	na	60	na	na	Dow
"	9,726	na	na	38,542	10,779	na	98	21	15,769	60	1,815	na	na	na	na	na	na	30
"	10,100	na	na	19,213	7,180	na	24	17	9,928	256	1,808	na	na	na	na	na	na	"
"	13,500	na	na	39,500	14,760	na	300	12	22,700	na	1,468	na	na	na	na	na	na	"

Table 5 (continued)

General Location	Formation: Depth* Ft.	Press. psi	Temp. °F	Composition in mg/l: TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	Li	Sr	Ba	Br	I	B	Ref.
South	8,939	na	na	12,539	4,616	na	64	28	6,560	112	1,159	na	na	na	na	na	na	30
Texas	9,402	na	na	17,959	6,424	na	52	51	9,042	66	1,824	na	na	na	na	na	na	"
E. Texas	9,380	na	na	33,675	12,740	na	176	44	19,220	41	1,452	na	na	na	na	na	na	6
"	11,325	na	na	72,266	25,400	na	2,000	329	43,620	0	476	na	na	415	na	na	na	"
"	14,343	na	na	71,540	23,350	na	3,740	366	43,440	4	537	na	na	103	na	na	na	"
"	14,843	na	na	90,378	26,810	†	6,909	592	55,290	0	376	na	na	401	na	na	na	"
"	15,260	na	na	75,008	24,300	na	4,180	317	45,750	5	250	na	na	188	na	na	na	"
South	9,065	na	na	17,160	6,489	57	42	5	8,675	80	1,748	na	6	1	na	na	na	"
Texas	9,183	na	na	9,677	3,289	27	16	15	3,550	130	2,650	na	na	na	na	na	na	"
"	9,524	na	na	13,500	4,673	51	19	7	5,320	170	3,260	na	na	na	na	na	na	"
"	9,792	na	na	13,806	4,795	30	21	10	5,460	120	3,370	na	na	na	na	na	na	"
"	10,026	na	na	9,434	3,128	70	2	2	3,010	100	3,050	na	na	na	na	na	na	"

*Included with Na; not separately determined.
†Average depth of sample interval.

is 1,000 ppm barium for a water whose sulfate concentration is reported to be 45 ppm. These reported high barium concentrations are attributed here to the possible entry into the formation of barium ion from the barite used as weighting material in the drilling mud, and not to the natural barium content of the interstitial fluid. The handbook value for the solubility of barium sulfate in water at 100°C (212°F) is 3.9 ppm[31]. This translates to approximately 1.0 ppm for the barium concentration in a water having a sulfate concentration of 45 ppm. Even allowing for a discrepancy of two orders of magnitude resulting from the effects of increased solubility at higher temperatures and for total ionic strength of the interstitial water, the barium concentration would be limited to only about 10 ppm.

This barium analysis illustrates perhaps the greatest problem affecting the analyses of these waters -- the reliability of the sample. Obtaining a representative water sample, even with the best sampling techniques available today, is precarious at best. No information concerning sampling technique is available for most of these analyses. However, the most probable error source would be partial flashing of the water. This would lead to higher-than-analyzed TDS, or saltier waters. The fact that these waters, as analyzed, contain less-than-expected TDS for their depth is a favorable indication of their nature.

Collectively, the water analyses of Table 5 show that the average salinity of the water contained in apparent geopressured strata encountered in Louisiana is moderately greater than that for the corresponding waters from south Texas. The range of salinity values, 180 to 340,000 ppm TDS, is also greater for the Louisiana waters.

EXPECTED EMISSIONS

The emissions expected from the demonstration plant are classified here into three categories:

- Normal direct emissions - are those unavoidably generated as designed waste streams by the installation during conditions of normal operation-- and can be fairly accurately predicted.

- Indirect emissions - are "induced" by the installation, and include, for example, emissions generated by earth-moving equipment during the construction period, and also the increased amount of household garbage or sanitary waste of the families of new, permanent employees taking residence in the area.

- Accidental emissions - will result infrequently from operational upsets or unforeseen problems. They are expected, in a sense, since no operation is perfect, but their frequency, time of occurrence and magnitude are unpredictable.

Direct Emissions

The potential applications discussed in Section 4 all depend upon the use of the thermal energy of the geopressured fluid. Common to all the applications visualized, regardless of their nature, are the emissions which would result directly from the production of the geopressured brine and associated natural gas, and from the disposal of the spent brine. These are the only emissions expected as a result of the use of geopressured fluid by a particular process or industry in addition to those already inherent in the process. For example, a proposed paper mill designed to use the heat of geopressured fluid to cook its wood chips would still have the disposal of its own process wastes to contend with. It would be spared the responsibility for controlling the SO_X, NO_X and possible ash emissions of its existing conventional counterpart which uses fuel oil or coal to fire its steam boilers.

The number of different types of emissions expected from a geopressured-electric power plant includes all the types visualized from any of the other, non-power, applications. In addition, electrical energy generation will probably be among the first uses for geopressured fluid to be commercialized. The types and quantities of emissions expected from a projected geopressure-electric energy installation would therefore represent at least the maximum number of different kinds of emissions potentially resulting from any of the proposed uses for the geopressured fluids.

One of the two proposed geothermal-electric demonstration plants whose conceptual designs have already been mentioned in Section 5 is taken here as the basis for estimating the types and quantities of emissions to be expected from a typical power application of geopressured fluid. This is the nominal 25 MW(e) plant employing the double-stage flash process. Block flow diagrams for this process and for the associated wellfield and methane recovery are shown in Figures 9 and 10. The character and amount of emissions expected from the alternative secondary-fluid process used in an installation of the same nominal electrical output will be nearly identical to those of the double-stage flash process[17], except for the possible fugitive emissions of isobutane from the former during abnormal operating conditions. Briefly, the fuel plant may be considered as a wellfield and appropriate collection piping, a centrally located methane extraction and purification plant, and a reinjection wellfield, if reinjection is the waste water disposal method selected. Following the block diagram in Figure 9, the collected water and gas mixture from the wells at 140 kg/cm^2 (2,000 psia) is passed through a separator to remove the undissolved gas. The methane gas after passing through a pressure reducer is cooled, dried and sold. The hot water from the methane separator is passed on to the electric power plant shown in Figure 10. Some methane will remain in this water. Most of this gas is separated and returned to the fuel plant where it is cooled, dewatered, compressed, and added to the main stream for final drying as shown in Figure 9.

The power plant receives the hot, high-pressure water stream from the fuel plant. The feed is first passed through a hydraulic turbine, as shown in Figure 10. The pressure drops in this turbine to 21 kg/cm^2 (300 psia) with the production of electric power. This pressure drop releases dissolved methane which is returned to the fuel plant. A further pressure drop to 10.5 kg/cm^2 (9,150 psia) produces more gas which is also returned.

The hot water is then flashed in two stages as shown. The low-pressure steam is used to drive a two-stage turbine to furnish the shaft power for the

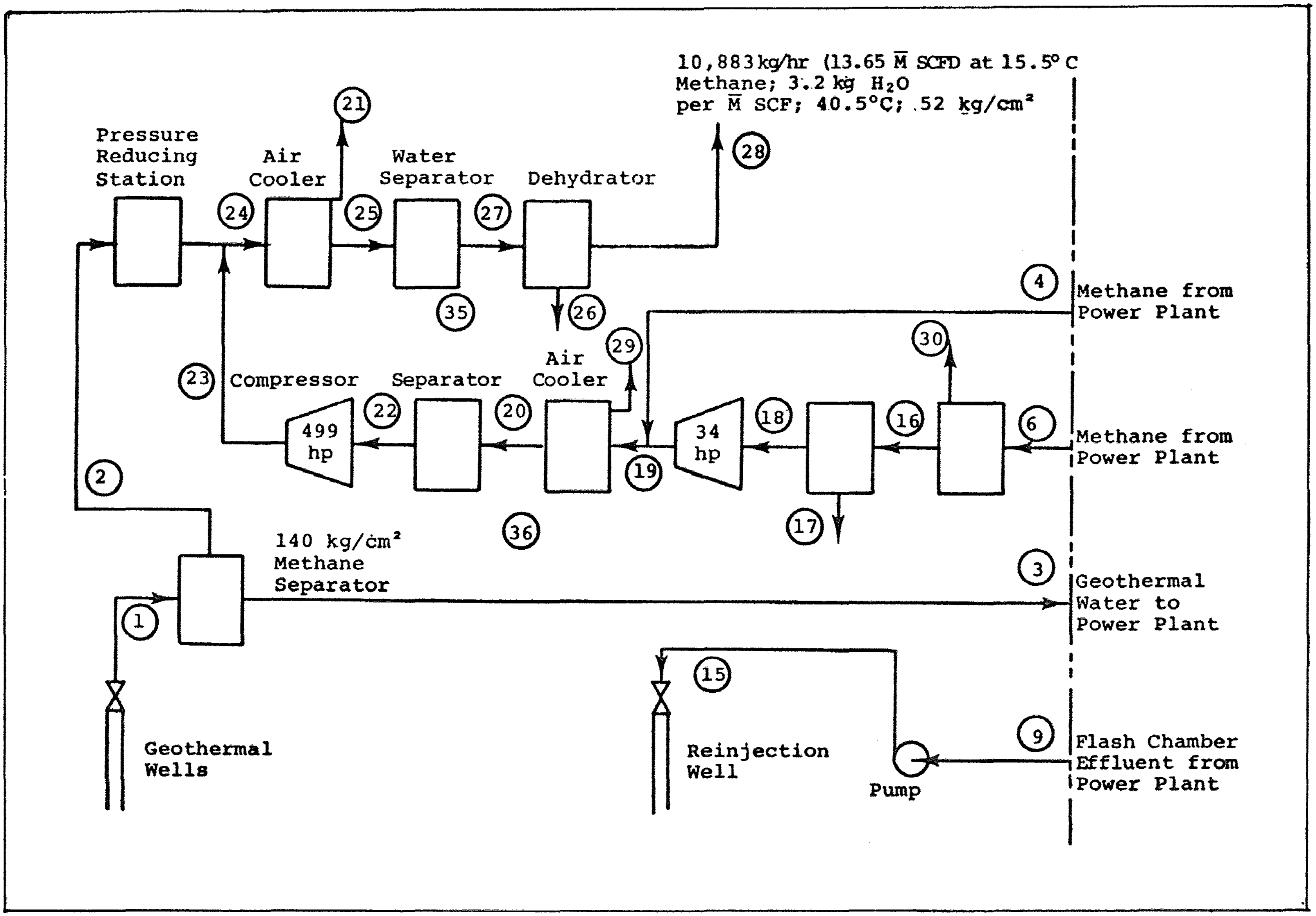


Figure 9. Flow diagram of fuel plant for double-stage power plant - 25 megawatts.

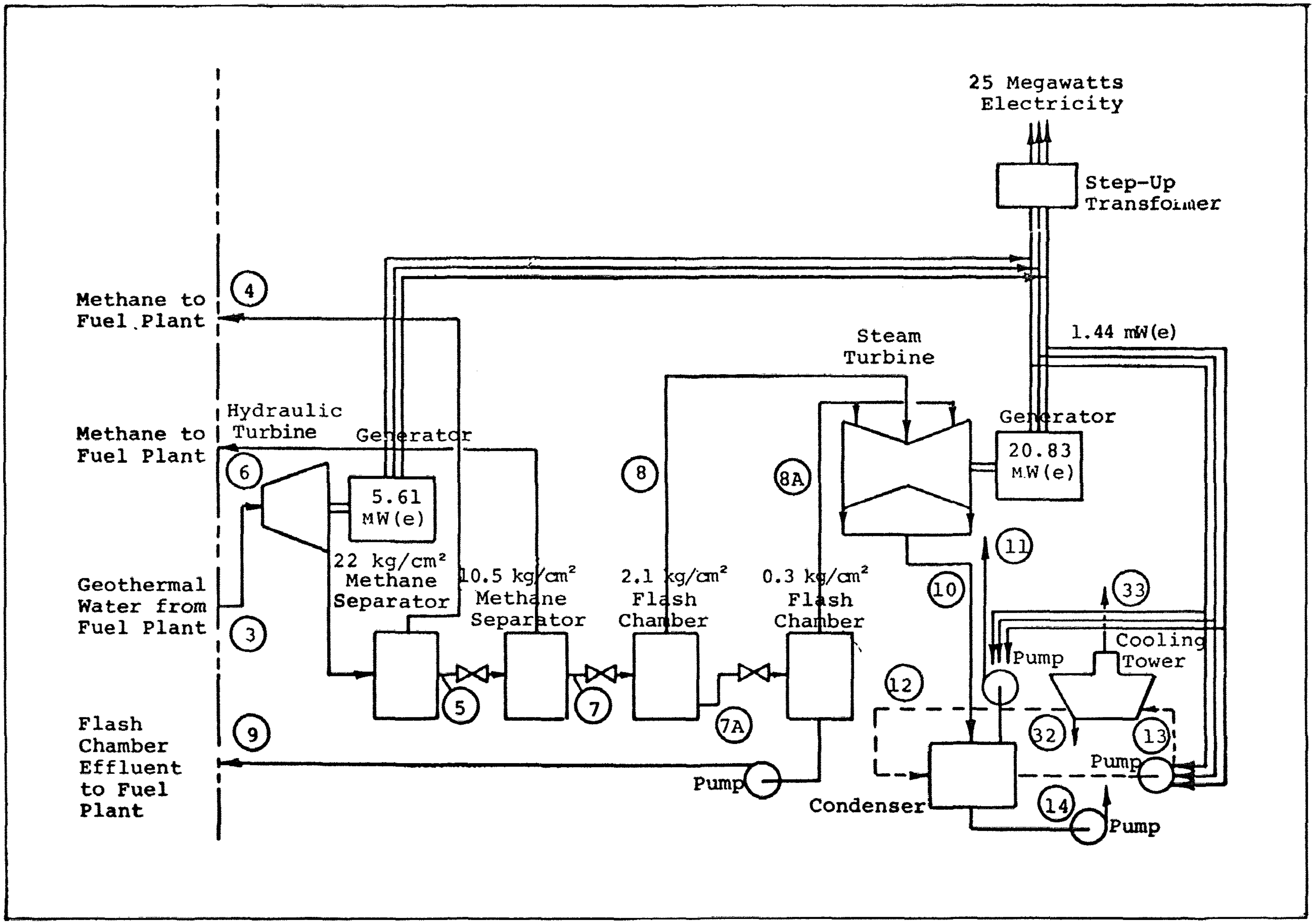


Figure 10. Flow diagram of power plant - 25 megawatts - double stage.

generator. The used steam is condensed in the condenser cooled by water cycled through the cooling tower.

The physical conditions and magnitudes of the various material flows indicated on the block flow diagrams are listed in Tables 6 and 7. From the latter, the character and amount of all the normally resulting emissions have been estimated and are listed in Table 8. These are the projected "normal" direct emissions.

Each of the normal direct emissions listed in Table 8 is further described below.

Spent Geothermal Brine (Stream 15)-- This stream originates at the second of the two flash vessels. If it contains no solids, it is pumped by a centrifugal booster pump via a welded steel pipeline from the power plant to one of several closed, top-vented surge tanks located in the brine field area. From the surge tank it enters the suction line of a multistage centrifugal reinjection pump to be injected into a reinjection well. Barring emergencies (leaks, surge-tank overflows resulting from instrument malfunctions, etc.), this waste stream does not actually contact the environment until it reaches the receptor stratum, at a subsurface depth of 1,850 to 2,000 meters (6,000 to 6,500 ft). The flow is substantially constant except for minor fluctuations and decreases only during turn-downs in power generation. Its temperature of approximately 82°C (180°F) likewise normally undergoes only slight (±1°C;2°F) fluctuations.

If solids form in the spent fluid they must be removed if reinjection is used. Solids would plug the receiving strata. Solid removal by a system of settling ponds would be the most economical. If this should prove unfeasible, alternate disposal methods would be required.

Emissions from the proposed settling ponds would be negligible. Some vapor condensation would occur on cold days with the formation of "fog" clouds over the ponds. Periodically, the ponds would require cleaning to remove the settled matter. This could best be accomplished by the hydraulic dredge method. The resulting sludge, primarily silica, could be disposed of by the landfill method.

The exact composition of the spent fluid will depend on that of the incoming geopressured fluid. Whatever its precise composition, its content of dissolved solids will be approximately 18% greater than that of the incoming geopressured fluids, and the formation of solids will be likely.

If the 25 MW(e) demonstration plant uses isobutane in the secondary fluid process described in Section 4-B, the temperature of the spent brine will be approximately 98°C (208°F), and its flow rate will be 0.79 m^3/sec. (12,500 gpm). All other emissions will be increased by factors of between 1.2 and 1.4.

TABLE 6. PARAMETERS OF STREAMS INVOLVED IN FUEL PLANT FOR 25 MW(e) DOUBLE-STAGE FLASH PLANT

Stream No.*	Temp. °C	Pressure kg/cm²	Mass flow (kkg/hr) CH_4	H_2O	Total	Volume flow m³/min.†	Remarks
1	162.7	140.43	10.84	2248.30	2259.14	41.95	
2	161.7	140.43	6.36	0.36	6.72	1.78	
3	162.7	140.43	4.59	2248.30	2252.89	41.83	
4	161.7	21.06	4.08	1.95	6.03	10.38	
6	160.0	10.53	0.40	0.67	1.07	3.62	
9	82.2	1.76	0.0	1927.79	1927.79	33.22	
15	82.2	21.06	0.0	1927.79	1927.79	33.22	
16	49	10.18	0.40	0.67	1.07	1.12	Excl. 0.01 m^3/min.water
17	49	10.18	0.0	2.97	2.97	0.05	Includes Stream 36
18	49	10.18	0.40	0.67	1.07	1.12	
19	101	21.41	0.40	0.67	1.07	0.63	Excl. Stream 4
20	49	20.71	4.49	1.96	6.45	5.97	Excl. 0.03 m^3/min.water
21	41	1.03	0.0	0.02	0.02	7.1×10^4	
22	49	20.71	4.49	0.03	4.52	5.97	
23	119	53.01	4.49	0.03	4.52	2.82	
24	135	52.66	10.84	0.39	11.23	7.42	Includes Stream 2
25	41	52.31	10.84	0.39	11.23	5.29	Excl. 0.006m^3/min.water
26	93	1.03	0.0	0.02	0.02	2.6×10^{-4}	
27	41	51.96	10.84	0.02	10.86	5.29	
28	41	51.96	10.84	0.0	10.84	5.29	
29	41	1.03	--	--	--	1.7×10^5	
30	41	1.03	--	--	--	7.1×10^4	
35	41	52.31	0.0	0.37	0.37	6×10^{-3}	
36	49	20.71	0.0	2.30	2.30	3.8×10^{-2}	Includes Stream 35

*Refer to Figure 9.

†Actual m^3/min. flowing at stated temperature and pressure.

TABLE 7. PARAMETERS OF STREAMS INVOLVED IN 25 MW(e) DOUBLE-STAGE FLASH PLANT

Stream No.*	Temp. °C	Pressure kg/cm^2	Mass flow - kkg/hr			Volume flow m^3/min.†	Remarks
			CH_4	H_2O	Total		
3	162.7	140.43	4.59	2,248.30	2,252.89	41.83	
4	161.7	21.06	4.08	1.95	6.03	10.38	
5	160.0	21.06	0.57	2,248.90	2,249.50	41.75	
6	160.0	10.53	0.40	0.67	1.07	3.62	
7	160.0	10.53	0.18	2,248.50	2,248.70	41.74	
7a	121.1	2.09	0.08	2,077.90	2,079.00	36.81	
8	121.1	2.09	0.10	170.40	170.50	2,453.80	
8a	82.2	0.53	0.08	147.80	147.90	7,724.30	
9	82.2	1.76	0.00	1,930.30	1,930.30	7.31	
10	43.4	0.09	0.18	318.20	318.40	8.8×10^4	Turbine exhaust
11	65.6	1.05	0.18	0.04	0.20	6.23	Non-condensibles
12	30.6	--	--	--	--	365.11	
13	38.9	--	--	--	--	365.11	
14	43.3	3.52	0.00	318.20	318.20	5.31	Condensate
32	38.9	--	--	--	84.00	0.63	Blowdown
33	37.8	1.03	--	--	--	1.50×10^5	Tower exhaust

*Refer to Figure 10.

†Actual m^3/min. flowing at stated temperature and pressure.

TABLE 8. EMISSIONS FROM 25 MW(e) GEOPRESSURED-ELECTRIC DEMONSTRATION POWER PLANT AND ASSOCIATED BRINEFIELD - DOUBLE-STAGE FLASH PROCESS

Identity of emission	Stream No. (Figs 9 & 10)	Temp. °C	Probable Composition	Discharge Rate kg/hr	Remarks
Direct emissions:					
Spent geothermal fluid (liq.)	15	82	3.5% TDS: 12,479 ppm Na^+ 442 ppm K^+ 438 ppm Ca^{+2} 78 ppm Mg^{+2} 19,415 ppm Cl^- 248 ppm $(SO_4)^{-2}$ 1,465 ppm $(HCO_3)^-$ 175 ppm $(CO_3)^{-2}$ 12 ppm Br^- >1 ppm H_2S 9.2 ∿ pH	1.92×10^6 (0.553 m^3/sec)	0.775 m^3/sec if isobutane used in secondary-fluid process.
Cooling tower blowdown (liq.)	32	39	7,500 ppm TDS No heavy metals	3.8×10^6 (0.01 m /sec)	Assumes 1,500 ppm TDS in makeup water. Volume may be only ∿0.26 m^3/min if condensate is used for makeup.
Cooling tower exhaust (gas)	33	41	Sat'd air containing 0.3 kg/sec drift.	10.2×10^6 dry basis (2.5 x 10^3 m^3/sec)	5 x 10^4 kcal/sec discharged to atmosphere (latent plus sensible)

Table 8 (continued)

Identity of emission	Stream No. (Figs 9 & 10)	Temp. °C	Probable Composition	Discharge Rate kg/hr	Remarks
Septic tank effluent (liq.)	Not shown	Ambient	H_2O cont'g soluble organics	<0.25 l/sec	Discharged to septic field of conventional design.
Indirect & Accidental Emissions:					
Geothermal fluid (liq.; vapor)	1,3,5,7	162	∿3.0% TDS: 10,720 ppm Na^+ 380 ppm K^+ 376 ppm Ca^{+2} 67 ppm Mg^{+2} 16,678 ppm Cl^- 213 ppm $(SO_4)^{-2}$ 1,550 ppm $(HCO_3)^-$ 10 ppm Br^- 10 ppm H_2S 125 ppm CO_2 6.8 ∿ pH	--	Possible emission during mishaps; steam or methane release to atmosphere occurs. Fluid at wellhead contains 7.13 Nm^3 CH_4 per m^3 liquid.
Drilling mud (slurry)	Not shown	Ambient	Contains $BaSO_4$	--	Emissions by possible spills and blowouts during construction per'd
Borehole cuttings (solid)	Not shown	Ambient	Sand and shale particles	∿7,600 m^3 total	Used for earthwork

Table 8 (continued)

Identity of emission	Stream No. (Figs 9 & 10)	Temp. °C	Probable Composition	Discharge Rate kg/hr	Remarks
Dehydrator effluent (liq.)	26	93	Water containing ∿40 ppm glycols	16.3 (0.27 l/sec)	May be combined with cooling tower makeup.
Air-cooler exhaust (gas)	21	8° above ambient	Normal air	3.2×10^5 (80.2 m^3/sec)	175 kcal/sec discharged to atmos.
Air-cooler exhaust (gas)	29	8° above ambient	Normal air	7.7×10^5 (184 m^3/sec)	423 kcal/sec discharged to atmos.
Air-cooler exhaust (gas)	30	8° above ambient	Normal air	1.6×10^5 (40.1 m^3/sec)	87.5 kcal/sec discharged to atmos.
Separator condensate (liq.)	17	∿49	Water; 20 ppm TDS	2.968 (0.82 l/sec)	May be used to augment cooling tower makeup
Purge stream from main condenser (gas)	11	260	25-50 vol% CH_4 10-20 vol% CO_2 5-10 vol% O_2 20-40 vol% N_2 15 vol% H_2O vapor trace H_2S	∿220	Flared to H_2O & CO_2 at flare stack.

Cooling Tower Blowdown (Stream 32)-- The flow of blowdown from the cooling tower shown in Table 8 assumes the following conditions:

- The maximum allowable concentration of dissolved solids in the cooling tower sump is 7,500 ppm.
- A drift loss of 0.005% of recirculation rate.
- Cooling tower make-up is supplied entirely by brackish water containing 1,500 ppm dissolved solids.

The first of these conditions is what might frequently be encountered in industrial towers and should result in drift salinities no greater than those from most industrial cooling towers. The choice of brackish water for make-up requirement assumes that the condensate from the main condenser will be sold for municipal use and will be unavailable for make-up. A dissolved solids content of 1,500 ppm in available shallow well water is a realistic expectation in much of the area of south Texas where a demonstration plant might be located with the minimum risk of unforeseen adverse environmental impact.

An alternative set of realistic conditions assumes that all the exhaust steam is used to supply the major portion of the cooling tower make-up demand, and that the circulation water is carried through 20 evaporation cycles. The requirement of brackish water is then reduced to about 0.44 m^3/min. (117 gpm), and the blowdown rate to 0.27 m^3/min. (71 gpm). Additionally, the concentration of dissolved solids in the drift from the stack is reduced from 7,500 to approximately 2,500 ppm.

Cooling Tower Exhaust (Stream 33) -- This stream issues from the stacks of the cooling tower at an elevation estimated here to be between 15 and 18 meters (50 and 60 feet) above grade. About 4 to 8 tower cells would probably be required. The total flow of exhaust air shown in Table 8 would be equally apportioned among the individual stacks.

The exhaust stream is air, very nearly saturated with water vapor at the temperature shown. It discharges into the atmosphere about 1.8 x 10^8 kcal (7.2 x 10^8 Btu) per hour and carries a fine mist of water droplets despite the use of demisters and foam eliminators of latest design. The expected total quantity of the entrained water will be about 0.005% of the flow of water circulated over the packing (the upper limit of the usual performance guarantee[32,33]) and the value used here in estimating the required flow of blowdown. On this basis, the total amount of liquid in the drift--18 l/min. (∿4.83 gpm)--will contain a maximum of 7,600 ppm TDS when the make-up used is brackish water containing 1,500 ppm TDS. The drift will also contain whatever additives have been used as corrosion inhibitors and fungicides at substantially the same concentration as prevails in the cooling water. Forecasting the identity and concentration level of the additives is limited to conjecture at this time. The use of chromates and phosphates, proven to be the most effective as corrosion inhibitors, and zinc compounds as fungicides, has been prohibited under existing federal regulations[34,35]. However, silicates may be added to the cooling water sumps as corrosion inhibitors.

Dehydrator Effluent (Stream 26) -- This will be a rather small flow of 1.9 l/min. (~0.5 gpm) of liquid water continuously discharged from the methane dehydrator. The stream is discharged directly from the top of the glycol concentrating tower as a vapor. Current practice is to condense the latter in a small air-cooled pipe coil. The stream will contain up to 40 ppm of glycols. The stream will be discharged into the cooling tower sump.

Air-Cooler Exhaust (Stream 21) -- This emission will be a stream of moderately heated air of normal composition discharged vertically upward by the axial-flow fan of the finned-tube air cooler. The latter will be situated between 6 and 9 meters (20 and 30 feet) above grade. The discharge temperature will vary, depending on the ambient. The design parameters assume 32°C (90°F) ambient air temperature and an 8.3°C (15°F) rise across the tube bank. Under these conditions approximately 6×10^5 kcal (2.5×10^6 Btu) per hr. will be dissipated to the atmosphere.

Air Cooler Exhaust (Stream 29) -- Similar to Stream 21, except that the quantity of heat discharged to the atmosphere will be about 1.5×10^6 kcal (5×10^6 Btu) per hour.

Air-Cooler Discharge (Stream 30) -- Similar to Stream 21, except that approximately 3×10^5 kcal (1.3×10^6 Btu) per hour will be discharged to the atmosphere.

Separator Condensate (Stream 17) -- This stream will be discharged from the third of three water separators arranged co-current to the flow of methane. It represents the combined quantities of water separated from the methane in each of the three separating vessels. It is expected to contain a low level of dissolved solids, but may possibly be contaminated with small amounts, say, in the parts-per-million range, of higher-boiling hydrocarbons. This is only a possibility which depends on the composition of the source fluid. The flow will be combined with the cooling tower blowdown.

Main Condenser Condensate (Stream 14) -- If the condensate is sold, surface condensers will be used to condense the exhaust steam from the main turbine. In this event the condensate will be a very pure water containing less than 10 ppm of dissolved solids. However, one contaminant of concern will be copper, acquired by the condensate in passing over the copper-alloy condenser tubes. The copper content of condensate from the main condensers of most utility and industrial steam plants is generally less than 0.05 ppm. This is the value assumed here. The condensate in this case will constitute an indirect emission.

In the alternative case, where the turbine exhaust steam is used for cooling tower make-up, the steam contacts the cooling water in direct-contact, barometric-leg condensers. No discrete condensate stream results. Also, since the direct-contact condensers are of low-alloy steel construction, no copper pick-up by the cooling water is expected.

Main Condenser Purge (Stream 11) -- This stream contains all the noncondensibles from the main condenser plus water vapor. The principle noncondensibles are methane (∿40 volume percent), along with some CO_2. In addition, the presence of minor percentages of H_2S or NH_3 is possible, despite the complete lack of any indication by the available water analyses that they are present in the original geopressured fluid. It should be noted that the absolute amount of H_2S (or NH_3) vented from the main condenser is only a small fraction of the amount of these gases possibly present in the original geopressured fluid, the major part having been removed along with the methane in the three separator vessels located upstream from the flash chambers.

The CO_2 present in the purge stream results from the decomposition of the bicarbonate ion of the fluid as the latter passes through the flash chambers. The concentration of CO_2 shown is an estimate only. With geothermal waters of higher bicarbonate content, the CO_2 concentration of the purge stream may be too great to permit combustion unless additional methane is added.

The presence of O_2 and N_2 results from the inleakage of air at the second flash chamber, at the turbine, and at the main condenser.

After passing through a vacuum pump and chilled-water condenser, the purge stream is routed to the top of a flare stack where it is burned in the atmosphere.

Septic Tank Effluent (not shown on Figure 10) -- This is the clear liquid discharge from a septic system of conventional design.

In addition to the material waste streams, direct emissions from the demonstration plant should include the expected noise generation. All of the rotating equipment and most of the fluid-flow devices are noisy to a certain degree. The items expected here to be the noise sources of greatest intensity are listed in Table 8. The sound levels shown here are estimates only. The actual values may vary considerably depending on the exact type and make of equipment installed from the estimates and on the details of installation. Since the estimates are based on actual measured sound levels of equipment of similar type but of different size, the estimates themselves are subject to wide margin of error. For example, the measured sound level near a 100 MW(e) steam turbine/generator may be as high as 110 decibels. It is difficult to accurately predict from this value the corresponding sound level for a 25 MW(e) turbine/generator rotating at a lower speed.

All the direct emissions considered so far have been those expected during normal operation of the plant. Of equal importance, but perhaps not obviously so, are those which could occur under abnormal, unforeseen conditions. The intent here is not to describe all the possible mishaps and spills connected with a project of this type, but to consider only those accidental emissions which could result in major widespread adverse effects on the environment or on human health. The following types of emission have the greatest potential for causing damage of the proportions just described.

- Leaks of any proportion of either geopressured fluid or spent geopressured fluid from source wells to fresh water aquifers.

- Uncontrolled, large-volume releases at any point in the system of either geopressured fluid, spent fluid, 30-pound steam, or methane.

Indirect Emissions

During the construction phase of the demonstration plant, estimated to require about two years, approximately 300 construction workers will be employed at the site at any one time. Depending upon the locality of the actual site selected, a temporary camp of mobile homes for families of the construction crews may be necessary. This would probably be the case with many sparsely settled areas in south Texas. If the site were within 3 to 6 km (5 or 10 miles) of a city of moderate size, probably no construction camp would evolve, and temporary buildings would be limited to a few field offices plus mobile living quarters for several watchmen.

For development of the wellfield, approximately 5 months is the estimated time required to drill each source well, and about ten weeks for each reinjection well. Three to five years is a reasonable estimate of the time required to complete the wellfield from the start of the initial test well. Most of the time interval would be concurrent with the construction period of the power plant. The estimated time requirements mentioned above are an indication of the duration of the period during which the indirect emissions may be expected.

Listed below are the various indirect emissions to be expected during the construction phase:

Emissions Expected During Development Phase of Wellfield --

- Possible uncontrolled, large-volume releases of geopressured fluid and steam
- Possible spills of salt water
- Possible spills of drilling mud containing $BaSO_4$
- Septic tank effluent
- Domestic wastes from possible trailer camp
- Noise from drilling rigs

Emissions Expected During Plant Construction Phase --

- Scraps from form-lumber, dunnage and crating
- Sand from sand-blasting
- Earth removed from foundation excavations
- Mud discharged to streams during rainy periods
- Atmospheric emissions of unburned hydrocarbons from construction equipment

- Domestic wastes from possible trailer camp
- Septic tank wastes from construction shanties
- Noise from construction tools and equipment

By far the most serious potential emission will be the uncontrolled flow of geopressured brine which could result from a blowout during drilling operations despite precautions employing the latest technology. This will be a hazard to be faced rather than a certain occurrence. Its probability of being realized is conjectured here to be less than 5%.

The quantity of many of the emissions shown in the above list will obviously vary considerably from one location to another. Even for a given location their magnitude would be influenced by such a large number of factors, with the variation so wide, that to express a value here as being "typical" would be meaningless.

ENVIRONMENTAL IMPACT

Air and Water Quality Criteria

Listed in Tables 9 and 10 are proposed and existing standards for air and water quality pertaining to the polluting factors contained in the emissions described in the previous subsection. The conclusion drawn here is that, in general, the available methods for ultimate disposal of the expected emissions will permit operation of the demonstration geothermal plant without violation of proposed or existing air and water quality criteria. Exceptions may arise if the geothermal fluid actually used contains certain pollutants (H_2S, NH_3, Ba or heavy metals) at considerably higher concentrations than those assumed here. For example, if the geothermal fluid should contain more than $\sim$0.8 mg/l of barium, discharge of the spent fluid into tidewater would not be in compliance with Texas Water Quality Standards. The possible impacts of the separate emissions are discussed below.

Impact of Direct Emissions

These are primarily the separate environmental effects of the respective direct emissions, both normal and accidental, but also include local aesthetic values.

Spent Geopressured Fluid (Stream 15) -- The properties of the spent fluid making its disposal an environmental problem are:

- Salinity ($\sim$35,000 ppm TDS)
- Temperature of 82°C (180°F)
- Total quantity of heat to be dissipated
- Essentially zero dissolved oxygen content
- Possible trace amounts of H_2S, NH_3, or toxic metal ions.

TABLE 9. PROPOSED WATER QUALITY AND AMBIENT AIR STANDARDS[36]

Potential Pollutant	Water* mg/l	Waters mg/l	Ambient Air Primary μg/m	Ambient Air Secondary μg/m	Remarks
Ammonia	0.5	0.4	n.s.	n.s.	
Barium	-	0.05	n.s.	n.s.	
Copper	1.0	0.0005	n.s.	n.s.	Value listed for marine water is 1/6 of Cu conc'n in normal sea water.
H_2S	0.002	0.001	0.12 ppm†	n.s.	
Methane	-	-	160§	160§	
Particulates	-	-	75	60	
Temperature	2°C rise#	2°C rise#	n.s.	n.s.	These factors governed by results of environmental impact study in each specific case.
BOD	n.s.	**	n.s.	n.s.	
Total quantity heat	n.s.	n.s.	n.s.	n.s.	
Salinity	n.s.	n.s.	n.s.	n.s.	

NOTE: Except where indicated to the contrary, the values or lack of values shown apply to proposed Federal criteria.

n.s. = no specific standards, existing or proposed.

*Public water supplies
†Texas Water Quality Board Standard, Regulation II, Rule 203.
§Environmental Protection Agency Regulations on National Primary and Secondary Ambient Air Quality Standards. (40 CFR 50; 36 FR 22384, November 25, 1971; as amended by 38 FR 25678, September 14, 1973; 40 FR 7042, February 18, 1975)
#Actually 1°C rise during June thru August and 2°C rise during Sept. thru May. Maximum resulting temperatures limited to 35°C. Water Quality Criteria, FWPCA 168.
**Conc of dissolved O_2 must be >6 ppm.

TABLE 10. METAL QUANTITY LEVELS FOR DISCHARGES TO TEXAS TIDAL WATERS - 1975 STANDARDS OF TEXAS WATER QUALITY BOARD[37]

Metal	Maximum Concentration Allowed, mg/l.		
	Average	Daily Composite	Grab Sample
Arsenic	0.1	0.2	0.3
Barium	1.0	2.0	4.0
Cadmium	0.1	0.2	0.3
Chromium	0.5	1.0	5.0
Copper	0.5	1.0	2.0
Lead	0.5	1.0	1.5
Manganese	1.0	2.0	3.0
Mercury	0.005	0.005	0.01
Nickel	1.0	2.0	3.0
Selenium	0.1	0.2	0.3
Silver	0.05	0.1	0.2
Zinc	1.0	2.0	6.0

It is quite obvious that its discharge to a convenient natural surface feature--say, to a fresh water stream, arroyo, or natural depression--would be catastrophic, resulting in at least the destruction of indigenous wildlife and vegetation, potentially arable land, potable water and aesthetic values. The two most likely methods of disposal of the spent fluid appear to be:

- Reinjection into a subterranean receptor stratum, if such a stratum exists and provided both its geology and permeability are suitable,
- Discharge into naturally saline bodies of surface water.

The choice of which of these two possibilities is actually employed, assuming reinjection is geologically feasible, will be influenced by economics and by the probable environmental consequences of each method. Concentration levels of toxic metals in the spent fluid higher than those shown in Table 10 will definitely rule out discharge into surface waters.

Disposal by reinjection should be feasible throughout much of the extent of the geopressured fairway. In general, there are many highly saline aquifers overlying the overpressured zones, at depths between 1,500 and 2,500 meters (∿4,900-8,100 feet). Many of them are known to communicate at depth with the Gulf, and their permeability and porosity is favorable to receiving the projected volumes of spent fluid. Jones[11] presents data from representative deep wells in south Texas showing a cumulative sand thickness upward of 300 meters (975 ft.) down to a depth of 2460 meters (∿8000 ft). Salinities of the contained waters ranged up to 12% TDS. Neither the temperature nor the salinity of the spent fluid would adversely affect the subterranean environment if injection were into sands such as those just described. A considerable amount of reservoir engineering and testing would be necessary in selection of the most favorable stratum and in the design of the reinjection wellfield.

Reinjection of the spent fluid poses two major environmental hazards:

- Possible seismic effects. These are discussed in a following subsection.
- Possible contamination of fresh water aquifers. This could result from either outright leakage of the injection well, or from possible flow from the receptor stratum along a fault plant into the fresh water aquifer.

Although the likelihood of occurrence of either one of these events is believed to be fairly low, the consequences could be extremely serious if either event does indeed happen.

With surface disposal methods, a consideration of the possible fate of the TDS content of the spent fluid limits the possibilities to discharge into the open Gulf itself, or into certain saline bodies of water having relatively unimpeded communication with the Gulf. Examples of the latter are Sabine Lake and Calcasieu Lake. The ability to accommodate both the salinity and temperature from an environmental standpoint must be determined beforehand, not only for the body of water under consideration, but also for the exact point of discharge. The salinity of the spent fluid, if no higher than assumed in Table 8, will probably not create environmental problems if discharge into the open Gulf is attempted. Discharge into most natural back-bays, having restricted communication and poor tidal interchange with the Gulf, will probably not be environmentally acceptable. Harm to existing ecosystems may result. Favorable results of an estuarine ecological impact study would be one of the requisites for permission to discharge the spent fluid.

The results of such a study would indicate whether the temperature, absence of dissolved oxygen, and the possible trace amounts of H_2S, NH_3, or toxic metal ions (such as Ba^{+2}) in the effluent would be non-injurious to the aquatic life present in the receptor body of water under consideration. This is the general criterion to be satisfied. Compliance with the additional, specific criteria of temperature rise and maximum temperature created in the natural body of water would also be necessary. Compliance might necessitate the use of an evaporative cooling tower on the stream of spent fluid. This would accomplish three objectives:

- Lowering its temperature
- Increasing its dissolved oxygen content
- Displacing possible trace amounts of H_2S or NH_3

Potential discharge of H_2S or NH_3 into the atmosphere from the tower would be governed by the Texas Ambient Air Quality Standard of 0.12 ppm by volume, since apparently no quantitative federal standard exists.

In the case of surface disposal, the means of transporting the spent fluid to the receiving body of water must be considered. The two viable methods appear to be:

- Pumping via enclosed pipeline
- By nominal gravity flow in an open ditch system

A crude cost comparison shows that surface disposal employing pipeline transfer is at an economic stand-off with reinjection when the plantsite lies approximately 65 km (40 miles) distant from the nearest suitable body of surface water. This comparison assumes:

- A total cost of $180 per meter ($55 per foot) in moderately rural areas for a buried, 20-inch pipeline, including road and stream crossings, right-of-way, and booster stations.
- A total completed cost of $12 million for 19 reinjection wells, including pumps.

The economic distance could decrease considerably in urbanized areas and would be greater for a surface pipeline laid on grade. Aside from possible leaks and from impairment of aesthetic values along the right-of-way, no environmental problems are foreseen resulting from the pipeline itself.

An open-ditch system might be the economically preferred means of spent-fluid transport in certain cases where the following ideal conditions are approached:

- Rural environment
- Gently sloping terrain with little topographic relief
- Little likelihood of run-off flood waters greater than about 0.66 meter (2 feet) deep
- Few obstructions in the form of natural streams, irrigation ditches, floodways, or highways.

Many areas can be found in the tier of counties adjacent to the Gulf and between the Rio Grande and Calcasieu Lake where these conditions are approximated. In general, such areas extend perhaps not more than 25 to 35 km (15 to 20 miles) inland from tidewater. On the basis of the ideal conditions outlined above, a leveed, open ditch, lined with chlorinated polyethylene sheet and adequately sized to accommodate the spent fluid from the demonstration plant, might be installed at a cost crudely estimated here to lie between $30 and $45 per meter (between $10 and $15 per foot). This estimated cost range may be only a fraction of the actual cost for a ditch system in areas where conditions deviate widely from the ideal. The reasons are mainly because:

- The ditch must either follow surface contours, or else be provided with tunnels, "aqueducts", siphons, or pressured sections to preserve straight-line distances.
- Culverts or inverted siphons must be provided to preserve local natural drainage and to crossroads, irrigation ditches, floodways and other surface features.
- Right-of-way costs may be higher.

The principal ways the ditch system might adversely affect either human welfare or the environment are by:

- Addition of salt to adjacent soil through possible leaks in ditch liner, by failure of levees, or by flood waters topping the levees
- Impairment of aesthetic values
- Release to the atmosphere of possible trace amounts of H_2S or NH_3
- Creation of mists in cool weather and creation of a scaling "booby-trap" (in the event the spent fluid is not further cooled prior to discharge to the ditch).

In addition to the material emission of the spent geothermal fluid itself, there is the noise emitted by the reinjection pumps and motors. The latter will probably be multi-stage centrifugal pumps directly coupled to the motors. Characteristically, these produce a whine of high sound intensity. Since the locations of reinjection wells would be limited, almost by definition, to areas no more densely populated than suburban, the chief environmental impact of the noise would probably be its effect on livestock and the indigenous wildlife.

Cooling Tower Blowdown (Stream 32) -- The characteristics expected of the blowdown stream requiring selectivity of disposal methods are its salinity, 7500 ppm TDS, and possibly its temperature (39°C; 120°F). EPA has already promulgated new plant standards prohibiting the discharge of corrosion inhibitors. Therefore, the presence of these compounds is not expected in the blowdown. The latter flow, if discharged to the local land surface would be injurious to vegetation because of its salinity. If discharged directly to most natural streams, both the temperature and the salinity, and possibly the total quantity of heat, would degrade the water quality. If maintained as a separate stream, the blowdown might allowably be discharged into tidewater at coastal locations. Generally, what would probably be the most acceptable means of disposal would be to add the blowdown stream to the flow of spent geothermal fluid.

Cooling Tower Exhaust (Stream 33) -- It is expected that this nominally gaseous emission to the atmosphere will have the potential for creating the same general types of environmental problems confronting any other cooling tower of similar type and size. The adverse effects will be caused by the following characteristics of the exhaust stream and of the cooling tower accessories:

- The high moisture content (nearly saturated) and relatively high temperature (40.6°C; 105°F). These properties in relation to usual ambient conditions result in opaque plumes a considerable portion of the time.

- The entrained brine content (drift). This will result in a fallout at ground level consisting of the brine droplets themselves and of the fine solid particulates of the evaporated brine residue.

- Total quantity of heat present above ambient temperature.

- Noise emitted by forced-draft or induced-draft fans and motors, and by recirculating water pumps and motors.

The possible ultimate effects of each of these characteristics of the exhaust stream are discussed in the following.

The behavior of the exhaust plumes in the atmosphere will be highly variable in time, in elevation, and in horizontal areal extent, depending upon the ambient atmospheric conditions. Under ambient conditions of low humidity, high temperatures, moderate, steady wind speed, and under sunny skies, the visible portion of the plumes may typically disappear within a horizontal distance of considerably less than 30 meters (∿100 feet). At the other extreme, normally to be expected at night under "stable" conditions of moderate humidity, lower temperatures, and steady wind direction and speed, the plumes would probably merge with one another within a short distance of the stacks. The resulting combined visible plume could then persist for at least several thousand meters (∿2 miles), with its longitudinal axis at a fairly constant elevation and with increasing diameter of the visible portion. Intermediate types of plume behavior--

i.e., looping, fumigation, lofting, etc.--will also be frequent, and will correspond respectively to other types of atmospheric conditions.

The ultimate adverse environmental effects of a foggy plume are situations involving poor visibility at varying distances from the cooling tower. These include danger to aircraft operations at a possibly nearby airport, highway traffic hazards, and the creation of generally undesirable conditions for most outdoor activity. Regardless of whether or not the plume is visible, the potential effects of its high moisture content will be principally on the surface of man-made structures. Under the so-called "trapping" conditions, it will contribute modestly to the normal decay rate of wood and to the corrosion of metal surfaces. Since the demonstration plant would probably be sited in a rural area, the major effects of the moisture content of the exhaust, including any fog, would be felt principally by the outdoor structures and occasionally by the personnel of the plant itself, and at times by traffic on any nearby road during weather conditions causing a "fumigating" visible plume.

The effect of the drift on vegetation, as discussed in Roffman[33], will depend on the exact species of plant and on the proximity to the tower. The magnesium and sulfate ions present in the drift may contribute some nutrient value to certain types of cultivated crops grown in solids deficient in these two elements. It is almost always the sodium and chloride ions of windborne salts which account for most of any deleterious effects.

The long-term increase in the salinity levels of the surrounding soil will not, in general, assume the same horizontal distribution pattern as the relative drift deposition rates, but will be influenced greatly by natural topography and drainage patterns. The increase in residual soil salinity could adversely affect the growth of some nearby crops and possibly even some indigenous vegetation. The extent of this effect in the present case is not expected here to be serious.

No environmental problems other than the effects of fogging, already mentioned, are foreseen from the magnitude itself (5×10^4 kcal/sec., $\sim 723 \times 10^6$ Btu/hr.) of the sensible plus latent heat unavoidably transferred from the cooling tower exhaust to the atmosphere.

Sound levels from cooling towers, representing the combined noise output of fans, fan motors and falling water, but excluding that produced by recirculation pumps and motors, are believed to lie generally in the range between 80 and 90 db. The maximum noise intensity occurs near the tower base in the forced-draft type, and near the top of an induced-draft tower. If enclosed within the walls of a pump-house, the recirculation pumps and motors may produce sound levels approaching 100 db.

In summary, the overall environmental impact expected from the cooling-tower exhaust, as defined by the foregoing appraisal, probably will be less harsh than the majority of towers of similar size and type now in operation by private industry or public utilities.

Dehydrator Effluent (Stream 26) -- The most probable disposition of this small-volume liquid stream will be to discharge it into either the cooling tower blowdown or cooling tower make-up. No adverse environmental effects are foreseen in its ultimate disposal by either method.

Air-Cooler Exhausts (Streams 21, 29 and 30) -- The unavoidable discharge into the atmosphere of the 2.8 x 10^3 kcal/sec. ($\sim$1 x 10^7 Btu/hr) of sensible heat contained collectively in these three streams will have no adverse environmental impact other than to create higher local ambient air temperatures. The latter may result in moderately uncomfortable working conditions on nearby equipment during hot weather.

Even the best designed, properly maintained air-coolers are noisy. Sound intensities may reach 90 to 95 db near the fans and motors, and may be only slightly less at ground elevation.

Separator Condensate (Stream 17) -- No adverse environmental impact is expected from this stream. The probable disposition will be its addition to the make-up demand of the cooling tower.

Main Condenser Condensate (Stream 14) -- If used to furnish the major part of the make-up water demand of the cooling tower, this stream will not constitute an emission. Its highest grade economic use, however, may be as industrial process water or as a potable water supply to a municipality, where the revenue derived might contribute modestly to the economic success of the geopressure project. In the event of its sale, the condensate would ultimately meet the environment in at least one, and possibly a large number of emission points. The possible effects, which are here classified as indirect, are discussed in the following subsection.

Main Condenser Purge (Stream 34) -- Venting this stream is a necessity, since it provides the required purge of non-condensible gases from the main condenser. It will be uneconomical to recover its methane content. The stream actually contacts the environment as a continuously burning flare, producing water vapor and carbon dioxide as the principal materials ultimately released to the environment. Additionally, small amounts of SO_x or NO_x may also be released, but only if the source geothermal fluid contains appreciable concentrations of H_2S or NH_3. Whether or not the flaring of this stream will be in compliance with existing air quality standards will depend jointly on the actual concentrations of H_2S and NH_3 in the stream and the actual background concentrations of SO_x and NO_x of the ambient air.

Septic Tank Effluent (not indicated on Figure 10) -- This will be the clear overflow from a septic system of conventional design. The clear liquid percolates into a porous layer of sand and gravel laid one or two feet below grade. No adverse environmental effects are expected.

Aesthetics -- Aesthetically, a geopressured-electric plant will be less harsh on the existing landscape than an oil-fired steam plant. The absence of boilers will enable the installation to present a low profile. The tallest structures of the plant itself will be the cooling tower stacks, which might be no taller than about 15 meters (50 feet). The use of tall power transmission line towers will be unavoidable.

Impact of Indirect Emissions

Ultimate disposal of the approximately 7600 m^3 (∿990 yd^3) of solid wastes (drill-stem cuttings) generated during the wellfield development period will be an addition to the volume of earth fill required for the peripheral dikes surrounding the containment areas at each of the 30 well-heads.

No factual information is available concerning the probable fate in the environment of the barium sulfate contained in the relatively small amounts of drilling mud and weighting fluids inevitably spilled during a drilling operation. Although the barium ion is highly toxic to animal life, its extreme insolubility suggests that it might not enter a food chain through assimilation by plants. If ingested by higher animal forms, barium sulfate is excreted with no apparent toxic effects. It is conjectured here that the small amounts involved in possible spills would pose no threat to the environment, nor to the health of humans, livestock or wildlife.

Injury or destruction to vegetation will result from any discharge of geopressured fluid onto the land surface. During the completion and testing of both source wells and reinjection wells, some spills and initial leakage from pipe joints can be expected. If these situations do indeed occur, the amount of harm to the environment and to health will be limited to a practical extent by the use of blowout preventers during drilling and by the containment areas around the well-heads. The means of disposal of spent fluid, whether via reinjection wells or by surface methods, should be completed and operable prior to the bringing-in of a source well. The full flow of each source well can thus be accommodated during testing procedures. During plant shut-downs the disposal system will handle the full flow of the source wells.

In the event the condensate from the main condenser is sold, either as potable water to a municipality, or as process water to private industry, its ultimate discharge to the environment will be beyond the direct control of the geopressure project. Consideration should, nonetheless, be given to its copper content, conjectured to be approximately 0.05 ppm. This value, although well below the proposed federal standards[36] for public water supplies (<1 ppm), for irrigation water (<0.2 ppm), or for livestock (<0.5 ppm), might be high enough to pose a possible threat to aquatic life, particularly to fish in marine waters, where the 96-hour LC_{50} dose is apparently 0.05 ppm for most species. These situations might be realized if the total flow of condensate were to be discharged to a small, sheltered estuary or bay. If used as industrial process water, possible adverse synergistic effects in the ultimate effluent should be considered. These might result from the joint presence of the copper and a possible second contaminant acquired by the condensate in the satellite process.

Regardless of whether or not the condensate from the main condenser is used to supply the major part of the make-up for the cooling tower, the geopressure-electric plant will be a net consumer of either brackish or fresh water, although to a far lesser extent than a fossil-fueled plant of equal capacity. If the condensate is sold, the additional water requirement, equal to the entire cooling tower make-up demand, will be about 0.11 m^3/sec. (1800 gpm). This requirement will be reduced to about 7.2 x $10^{-3} m^3$/min. (115 gpm) if the condensate is used for make-up with the previously assumed concentration ratios. In the former case the $9.9 \times 10^{-2} m^3$/sec. (∿1,400 gpm) of condensate would supplant an existing or planned use of an equal amount of well water or surface water by a municipality or industry, resulting in a net ultimate water withdrawal from the environment of $2.5 \times 10^{-2} m^3$/sec. (∿400 gpm). This net water withdrawal will certainly create no problems in the case of a single 25-MW(e) demonstration plant. However, in the possible long-term picture, the potential location of several thousand megawatts of geopressured-electrical capacity in the water-short areas of the south Texas portion of the geopressured fairway, at sites directed by the location of a geopressured lens, will require long-term planning to insure the best possible use of existing water supplies. Changes in cooling tower design and operating parameters, from those assumed here, may be necessary. Some of the obvious alternatives are:

- Use of dry cooling towers.
- Use of ground water too saline for other purposes. Saline ground water aquifers are relatively plentiful in the south Texas area.
- Use of once-through seawater, or salt water cooling towers, at coastal locations.

Impact of Accidental Emissions

It is a foregone conclusion that releases of either geothermal fluid or spent fluid of greater volume than small leaks will cause damage to whatever vegetation is contacted as a result of the fluid temperature and possibly the salinity. To restrict the areal extent of the potential harm, diked containment areas, already mentioned, will be required at each wellhead. Additionally, low dikes, about 1.5 meters (∿5 feet) high will surround the entire wellfield area. Large-volume releases of either of the fluids have the potential for causing thermal burns on humans and other animal life.

The impacts of possible accidental releases of methane from the methane separation and collection systems could range from being almost inconsequential to extremely serious, depending upon the exact nature of the emergency. In the unlikely event of pipeline rupture, or similar type of failure of pressure vessels, the major effect would be the hazard to personnel. Such occurrences, although possible, are rare. There is no reason to believe their incidence will be any greater in the geopressure-electric installation than with the many existing natural gas gathering or transmission systems.

The flare on the purge stream from the main condenser may become extinguished during operational upsets or because of extreme weather conditions. During these intervals a release to the atmosphere of about 0.09 Nm^3/sec. (200 scfm) of methane will occur. Although these events will be environmentally undesirable, they are expected to be infrequent and brief, with no serious adverse impact.

In the event that the secondary fluid process, rather than the two-stage steam flash process, is the one chosen for the demonstration plant, the effects of possible emissions of isobutane should be considered. These potential emissions would include the small quantities which would escape into the atmosphere from possible undetected leaks and the large releases resulting from possible major failure of equipment. The likelihood of either of these events occurring, although very small in the absolute sense, is theoretically greater than for the corresponding releases of steam in the flash process because of the higher pressures involved with isobutane. A possible effect would be the creation of a fire or an explosion with resultant injury to personnel.

GEOLOGICAL CONSIDERATIONS

Subsidence

Land subsidence as a result of the subsurface withdrawal of gaseous hydrocarbons was noted as early as 1918 in the Goose Creek field in Harris County, Texas[38]. Active subsidence is occurring today in the Galveston Bay area of Texas as the result of the withdrawal of shallow ground water. Okumara[39] and Hirono[40] attribute subsidence in the Niigata district of Japan to the production of methane dissolved in water. Gabrysck[41] of the United States Geological Survey studied the Houston-Galveston area of Texas and notes that more than 5 feet of subsidence has occurred in some areas since 1943. This effect is principally due to the pumping of water from the Chicot and Evangeline aquifers. He concludes that records from compaction recorders in the Houston-Galveston region are insufficient to relate compaction to depth; however, most of the compaction is probably occurring near the surface because near-surface clays have been subjected to less overburden than deeper clay. These examples of subsidence are all from withdrawals of less than 200 meters depth. They may or may not be of significance for geopressured zone consideration.

There are several negative environmental effects that may be engendered by land subsidence. Kreitler and Gustavson[42] report that the area that will be inundated by hurricane tides in the Galveston Bay area has increased by 20% since 1961, principally due to subsidence caused by the withdrawal of shallow ground water. In low-lying coastal areas, a subsidence of just one-third of a meter could subject large new areas to tidal flooding. Potential flood damage, moreover, is not limited to coastal regions. Numerous inland areas of the Gulf Coast are periodically subjected to fresh water flash flooding and could be adversely affected if significant subsidence were to occur. The amount of potential damage from flooding is related to land use. Heavily urbanized areas, obviously, would suffer the most damage, while unimproved pasture land would probably suffer the least.

Major growth faults often act as reservoir boundaries; hence production from an isolated aquifer could result in a differential subsidence, or fault activation. Kreitler[42] reports that a 6-foot fault escarpment has developed in Saxet field near Corpus Christi, Texas since the onset of hydrocarbon production in 1942. Moreover, episodes of maximum fault movement seem to correlate with maximum gas production within the field. Tiltmeter measurements on the Eureka Heights and Long Point faults in the north Houston area indicate movement associated with a declining water level in the shallow Chicot aquifer. Fowler[43] has noted, in the Chocolate Bayou field in Brazoria County, Texas approximately 30 cm of differential subsidence in association with gas production from relatively shallow geopressured zones; however, no fault activation has occurred. Fault movement could cause foundation damage to homes, factories, highways, and many other types of structures. Moreover, secondary environmental damage could occur from fault movement; for example, if it were to rupture a pipeline, cause extensive damage to a railbed, or, possibly, crack the foundation of a nuclear power plant. The potential for such hazards should be thoroughly evaluated at any proposed geopressured geothermal site.

Stream drainage patterns are often controlled by local faulting, and could be affected by differential fault movements, resulting in environmental and legal problems.

What are the chances of significant subsidence and fault activation taking place as a result of geopressured production? Yerkes and Castle[44] conducted a search for documented subsidence over oil and gas fields in the U.S. and found only a few examples, mostly in California, where geologic conditions are very different from the Gulf Coast. Giertsma[45] concurs that such occurrences are the exception rather than the rule.

Giertsma[45] studied the problem extensively, and drawing from the science of rock mechanics and the previous work of Biot[46,47], Gassmann[48], Hall[49], and others have developed and refined the theory of poroelasticity. This theory states that stresses and strains in porous and permeable solid materials caused by pore pressure and pore pressure gradients can be predicted on the basis of an extension of the linear theory of elasticity, i.e. poroelasticity, provided the porous and permeable skeleton behaves like a linear, elastic body.

Giertsma[45] concludes that some or all of the following criteria must be met for significant subsidence to occur:

1. A significant reduction of reservoir pressure takes place during production.

2. Production is from a large vertical interval (continuous or stacked).

3. Fluids are contained in loose or poorly cemented rock.

4. The reservoirs have a shallow depth of burial.

The contemplated geopressured reservoirs fulfill the first three conditions, but not the last. Until field tests and measurements can be made, potential for subsidence must be evaluated from mathematical models that predict: (1) the amount of reservoir compaction that will occur, and (2) the amount of compaction that will be translated to the land surface as subsidence. There is little agreement among authors as to the best model or what values to assume for rock compressibility and the other parameters needed for the various calculations.

Almost all of the subsidence that occurs in the first few years is expected to be derived from the compression of the sandstone reservoir. After eight years, the components of sand compression and shale compaction are approximately equal; and at the end of the production period, the subsidence due to shale compaction is approximately twice that caused by sand compression.

It seems likely that some subsidence will occur; however the degree is uncertain. Herrin and Goforth[50] and Winslow and Wood[51] cite the alarming rate of subsidence caused by withdrawal of shallow ground water in the Houston area as an argument against geopressured geothermal production. As previously noted, several authors, notably Giertsma, point out that the compaction/subsidence ratio is very much dependent on depth.

One major problem that must be faced is the differentiation of subsidence and fault movement, which occurs as a natural geological process from that which is engendered by the production of geothermal fluids. Kreitler and Gustavson[42] outline a 12-point program of baseline environmental studies that should be completed prior to initiation of a test well or construction of production/generating facilities. This includes continuing leveling surveys, seismic monitoring, and strain gauge observations to determine subsidence and fault movement. Such a comprehensive study would provide enough working data to begin to assess the environmental impact of geopressured geothermal production. Many years of such monitoring will probably be necessary to accurately differentiate natural phenomena from artificially induced effects.

Earthquakes

No earthquakes have occurred on the Gulf Coast of the U.S. as a result of man's various activities, despite the fact that tremendous volumes of fluids have been withdrawn from the subsurface over a period of many years.

The one earthquake that appears in the historical record occurred near the town of Hemphill, Texas, in April, 1964. Four distinct shocks were recorded, ranging from 3.4 to 4.4 in magnitude on the open-ended Richter scale. A high level of microseismic activity continued following the shocks which diminished after a period of six months and disappeared after a total period of seven months. The quakes were shallow, in the upper few kilometers of the earth's crust, and the foci appear to have been aligned with major growth faults in the area. Herrin[50] has concluded that the quakes were a natural event, although no definitive explanation of why these faults "locked up" at that particular time has been offered. A regional gravity anomaly in the Hardeman County area suggests that typical basement tectonics may be a contributing factor.

Earthquakes are caused by the buildup of tectonic stresses within the earth's crust. Strain accumulates until it reaches a critical level, whereupon movement in the form of elastic rebound occurs. This movement generally takes place along pre-existing faults because they are zones of crustal weakness. The strain may be dissipated in slow movements along fault planes, known as creep. Or, if sufficient strain accumulates, movements of the earth may be rapid and violent; i.e., earthquakes occur.

Hubbert and Rubey[52] describe in detail the role of pore pressure in (thrust) faulting. Figure 11 shows the orientation of the principal stress on a pressurized, confined, rock specimen, based on experiments by McHenry[53] on concrete. The principal axial stress in S_1, the principal radial stress is S_3, and the principal shear stress is T. The effective shear stress, τ, is the governing force in controlling fault movements, and is a function of the effective axial and radial stresses, σ_1, σ_3, given by:

$$\sigma_1 = S_1 - p$$
$$\sigma_3 = S_3 - p$$

where p = interstitial pore pressure.

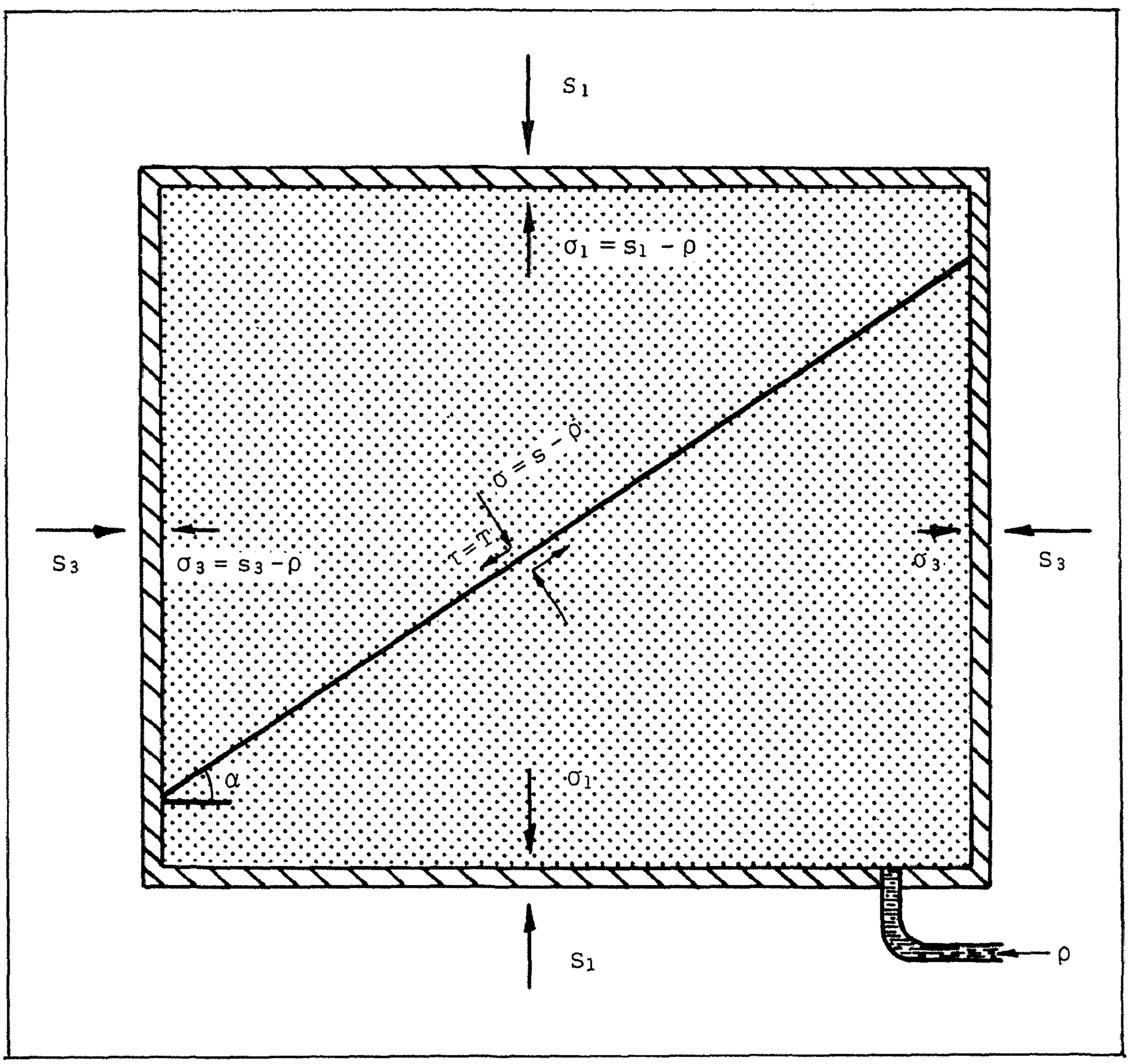


Figure 11. Total and partial stresses on jacketed specimen with internal fluid pressure.

It is readily apparent from these equations that as the pore pressure, p, becomes large, the effective confining stresses become small, thus facilitating the release of accumulated strain in the form of creep and/or earthquakes.

This effect was amply demonstrated at the Rocky Mountain Arsenal disposal well near Denver, Colorado, where after decades of quiescence, numerous earthquakes occurred between 1962 and 1965. A number of investigators, notably Evans[54], have attributed the quakes to the increase in pore pressure caused by the deep well injection into fault zones, and have correlated the frequency and magnitude of the quakes with the volume and pressure of the injected fluids during that period of time. Lomnitz[55] notes a number of earthquakes have been caused by dam construction and subsequent reservoir impoundment increasing the pore pressure and triggered by the trip-loading effect of the reservoir.

Conversely, one might expect that a significant depletion of pore pressure might cause a slowly "creeping" fault, such as the typical growth faults of the Gulf Coast, to "lock up" and accumulate sufficient tectonic strain eventually to be released in a violent earthquake.

Most evidence argues against this happening on the Gulf Coast. First, with the questionable exception of the Hemphill quakes, this effect has not been observed, even in areas where considerable pressure depletion has occurred. Second, the formations of the Gulf Coast are lithologically "soft" compared to Colorado and other areas. They have a low elastic limit and tend to deform plastically under fairly low stresses. Hence, it seems unlikely that the rocks could store sufficient strain to cause a major earthquake. Third, the sedimentary section of the Gulf Coast contains thick sequences of plastic shale and is underlain by a thick and mobile layer of salt, the Louann of Permo-Triassic age. The mobility of these formations allows them to absorb tectonic stresses by flowage, as is evidenced by the innumerable salt domes and related structures, and shale diapirs that occur on the Gulf Coast. It is interesting to note the absence of salt in the Hemphill area as a possible factor in the 1964 earthquakes.

It should be emphasized that strain accumulation and resultant earthquakes are naturally occurring geologic processes. Induced variations in pore pressure will neither cause nor prevent earthquakes, but rather may advance or delay the timing of tectonic movements which must inevitably take place. Totally aseismic areas probably do not exist; however, the possibility of a major shock occurring on the Gulf Coast is probably as remote as any place on earth.

Geopressured geothermal production is not expected to cause faults to "lock up" with subsequent release of strain through earthquakes for the reasons previously cited; nevertheless, continuous monitoring of faults should be undertaken using seismographs and strain meters. Strain meters, or gauges, are devices which are anchored on both sides of a fault and can accurately measure the accumulation of strain that occurs across that fault. Thus, if it appeared that geopressured production was causing an undue buildup of strain across a growth fault, production could be halted well before the critical level of strain accumulation is reached.

As in the case of subsidence, it will be necessary to establish baseline values for fault movement and strain accumulation before geopressured production begins, so that an accurate determination of the effects of the production can be made.

SECTION 7
MULTIMEDIA WASTE CONTROL REQUIREMENTS IN THE AREAS OF POTENTIAL USE

The requirements for controlling emissions and other environmental effects arising from the development of the geopressured geothermal potential along the Gulf Coast are not believed to be severe. The geopressured waters appear to present even fewer environmental problems than do conventional geothermal resources, which are themselves believed to offer the most environmentally "clean" alternate sources of energy.

The problems that do exist have been presented in Section 6 of this report. These problems are treated in this section (number 7) in terms of the present technology for coping with the problem, research needs, and proposed actions. These items follow.

EMISSION CONTROL

Present technology, properly employed, is capable of controlling the quantity and quality of the emissions, as well as the methods of their disposal, to meet promulgated EPA standards. In addition to the combined stream of spent fluid plus cooling tower blowdown, whose disposal by reinjection will be discussed later, the cooling tower exhaust is the only major designed emission. The present day guaranteed performance of cooling towers includes a maximum allowable drift rate commonly held to 0.005% of circulation rate. This represents a vast improvement over the 0.02% guarantee usually available five to ten years ago. This improvement is the result of advances in the design of demisters and drift eliminators. Any objectionable effects of visible plume, which might be particularly evident in urban areas during damp weather, can be either minimized beforehand, through judicious site selection and optimum orientation of the tower on the site, or alleviated by the operation of previously installed exhaust heaters. The latter adds measurably to operating costs.

Adequate instrumentation, embodying "fail-safe" interlocks, can greatly reduce the hazards of possible equipment failure by limiting the quantity of fugitive emissions escaping in the interval between time of the failure occurrence and the time of corrective action. Collectively, the common-sense type of design details can greatly reduce the potential harm to the environment resulting from possible emergency emissions. Examples would be the use of diked containment areas around each of the wellheads, and the establishment of local surface drainage in the optimum direction.

It is assumed that these geopressured waters will not contain hydrogen sulfide. Should this assumption prove erroneous, hydrogen sulfide will be an emission of consequence, primarily due to its noxious odor. Present technology does not adequately provide for prevention of this gas from the waste streams. Containment of the waters is theoretically possible but the odor does escape in actual practice. Research on ways to oxidize or otherwise destroy the hydrogen sulfide is being carried out in this laboratory as well as elsewhere. An early solution to the problem is anticipated.

REINJECTION

A commercial geopressured geothermal power plant generating 25 MW(e)/yr will produce on the order of 45,000 m^3/day of liquid wastes that will have to be disposed of. Environmental considerations indicate that deep well reinjection is the favorable method of disposal, however, the economic factors are highly variable. House et al[56] indicate that flow rates and net power output would be significantly enhanced by utilizing surface disposal. Overall economics are dependent on a number of factors, not the least of which are the price of energy and existing environmental restrictions.

The average salt water disposal well in the Texas Gulf Coast reinjects approximately 1500 m^3/day. The average waste disposal well reinjects approximately 320 m^3/day. The maximum reinjection rate for a waste disposal well is a little over 2000 m^3/day. Some wells in Louisiana are reported to be reinjecting as much as 3200 m^3/day. (Source of information: Louisiana State Department of Conservation, Texas Railroad Commission, Texas Water Quality Board.) Assuming high volume disposal wells would be utilized by a hypothetical 25 MW facility producing 45,000 m^3/day liquid wastes, approximately 30 disposal wells will be required. Cost per well is estimated to be $500,000, for a total net cost of approximately $15,000,000. This estimate does not include the cost of the high volume, high pressure pumps that will be required, nor does it include the cost of lined holding tanks or a solids removal plant to filter out SiO_2 and $CaCO_3$ precipitates. Overall total capital costs for waste disposal could easily exceed $50,000,000.

There are several requirements in planning a reinjection program. The disposal aquifers must be 300 to 450 meters below the base of usable quality water. Most water disposal is carried out at depths of 900 to 1,400 meters, hence this requirement should pose no problems. The injection aquifer must be bounded above and below by effective confining beds, aquacludes. These may be evaporites, dense limestone, or more commonly on the Gulf Coast, shale. Any faults which intersect the aquifer must not be sufficient to completely displace the aquacludes.

Injection pressure is normally limited to 0.10 kg/cm^2 per meter of depth and pressure buildup is limited to 3 kg/cm^2 increase per 1,000 meters of depth. Injectability tests must be performed prior to the issuance of a waste disposal permit to determine transmissivity and calculate pressure buildup curves from which allowable injection rates can be determined.

Records of all wells which penetrate the injection horizon within a radius of 4 kilometers of each injection well must be obtained, and each well must be squeezed and replugged in that zone to prevent possible leakage. Contamination of fresh water sands is virtually unknown where these precautions have been observed.

The two agencies in the state of Texas that are responsible for waste and salt water disposal are the Texas Water Quality Board and the Texas Railroad Commission. In Louisiana, the State Department of Conservation is responsible for waste water disposal. Their counsel and approval must be sought in designing any scheme for geopressured geothermal water disposal.

GEOLOGY

The obvious question with regard to reinjection is whether or not there are sufficient suitable potential reinjection aquifers for geothermal waste disposal for this method to be feasible. The answer is a qualified yes.

The oldest potential geopressured reservoirs on the Gulf Coast are in the Wilcox formation and are Eocene in age. These are overlaid by the Oligocene Jackson and Frio formations, into which the effluent waste of any Wilcox production would be reinjected. Unfortunately, the Oligocene sands are not well developed along this band, some one hundred miles or more inland. Some shallow aquifers do exist in this area; however, many fault blocks containing potential geopressured reservoirs will not contain adequate aquifers for waste disposal. The most promising geothermal fairways are in the Frio formation, coastward from the Wilcox. The Frio is overlaid by formations of Miocene age which contain numerous potential sands for waste disposal. These sands commonly have porosities as high as 30% and permeabilities approaching one Darcy, and are ideal disposal aquifers. The sands are often stacked; hence a number of aquifers could be utilized simultaneously to accept the large volumes of effluent. In Louisiana and certain locations on the Texas Coast and just offshore, the Miocene sands may themselves be geopressured reservoirs. These are almost invariably overlaid by shallower, hydropressured Miocene and younger sands that could be used for effluent disposal.

Obviously, it will be technically feasible to dispose of the effluent from a single, moderately sized geopressured geothermal facility by reinjection into shallower zones, although it may be economically unattractive to do so. Real problems develop, however, in projecting the large scale development of the resource. Consider that the hypothetical 25 MW(e) power plant would more than double the total amount of waste effluent now being reinjected in the entire state of Texas! This undoubtedly could be accomplished; however, it seems unlikely that the effluent from, say, a 1,000 MW(e) or more electrical generation could be practically disposed of in this manner. The environmental impact of reinjecting 2 million m^3/day, and even the physical ability to do so, remain unknown at the present time. Thus, effluent disposal may be the greatest limiting factor in the exploitation of the geopressured geothermal resource.

ALTERNATIVES TO REINJECTION

The most attractive alternative to reinjection is to find an economic secondary use for the effluent water. Dry areas such as south Texas could utilize the water directly for irrigation, if it is reasonably fresh. Moreover, because the water will contain some residual heat, it should be amenable to a self-desalination process and could provide fresh water for drinking, irrigation, and industrial processes. Other potential uses include shrimp farming and secondary oil recovery by waterflooding techniques. Waterfloods frequently have been cited as a possible mode of geopressured effluent disposal due to the very large volumes of water that are injected into the producing formations. The largest waterflood operation in the state of Texas is in the Kelly-Snyder field of Scurry County, Texas where more than 41,000 m^3/day of fresh and salt water is being injected through a total of 210 injection wells. While this is an impressive volume of fluid, a number of factors make waterflooding impractical as a method strictly for waste disposal.

The Kelly-Snyder operation and most large volume waterflood operations are of the pressure maintenance variety. Large volumes of fluid are produced concurrent with injection, from about 80% to well over 100% of the injected volume. In fact, it is often difficult for injection to keep pace with production which sometimes results in an eventual pressure decline within the reservoir. Some proportion of the injected fluid displaces the produced oil, gas, and condensate, and this is the net make-up water which must be continuously supplied to the water flood. In practice this may be as much as two-thirds of the total volume injected. At Kelly-Snyder, fresh water is pipelined from the El Capitan area and added to the produced water to supply the total waterflood needs. Two or three waterfloods the size of Kelly-Snyder would be required to dispose of all the effluent from a 25 MW(e) geopressured geothermal power plant.

The picture is not as favorable in the geothermal fairways along the Gulf Coast. Instead of highly porous and permeable formations such as the limestone reef complex (Canyon Reef) which is the producer at Kelly-Snyder, most waterfloods are performed in much tighter sandstone formations, and volumetric requirements may be diminished by an order of magnitude, or more.

The most feasible alternative to reinjection along the Gulf Coast presently appears to be pipelining or canaling to a salt water body. These techniques are discussed in Section 6 in some detail. Both methods are fully developed and can be accomplished with no additional technical research or development.

BLOWOUT PREVENTION

Problems experienced in drilling geopressured formations include lost circulation, stuck drill pipe and resultant fishing jobs, and uncontrolled wells, or blowouts. Today, however, techniques for drilling wells in abnormally pressured zones have been developed to the point that there is little chance of a blowout occurring in a judiciously planned well.

Critical to blowout prevention is a good knowledge of where the top of the geopressure occurs. Detection can begin prior to drilling. Pennebaker[57] and Aud[58] describe seismic techniques based on the reduced acoustic velocity associated with geopressure that can qualitatively and, in many cases, quantitatively define abnormally pressured zones. Various borehole logs from nearby wells can be used to further define the geopressure and predict the depth at which it will occur.

Data obtained while drilling is used to monitor a standardized rate of penetration (drillability), mud flowline temperature, shale cuttings density, volume, and size, and the presence of "trip" gas. Jordan and Shirley in a classic paper[59] describe how these data can be used to detect abnormal pressure and demonstrate that quantitative estimates of pore pressure can be made.

Good management of the drilling mud program is essential in drilling abnormally pressured zones. Due to the increased pressure gradient in the geopressured zone, much higher mud weights are required, on the order of 2 to 2.5 gm/cm^3, as compared to the approximately 1 gm/cm^3 mud used in the hydropressured zone. Heavy mud cannot be used in shallow zones because it retards drilling, spalls the bit, and can fracture the formations. Conversely, geopressures are sufficient to blow out a lighter drilling mud. Wells are therefore drilled to the top of the geopressure with a normal weight mud, cased, and cemented. Then the mud weight is increased to the proper density by the addition of heavy materials such as barite, and drilling is continued into the geopressured zone. Drilling parameters are monitored and mud weights adjusted accordingly to maintain balanced conditions within the borehole. In some cases, intermediate casing must be set within the geopressured zone.

Blowout prevention is accomplished by utilizing drilling data systems to closely monitor all aspects of the drilling operation and by installing warning devices to detect the early signs of an impending blowout. High-pressure blowout preventers, which are hydraulic or electrical devices used to close in the well in the event it begins to flow, are always used in areas known to contain geopressure. Several of these devices may be mounted in series at the wellhead, and they are considered extremely effective and reliable.

Several methods can be used to bring a flowing well under control in the unlikely event that the blowout preventers fail. One is to attempt to pump heavy mud or cement into the wellbore to shut off the flow. If this method is impossible or unsuccessful, then a second well, known as a relief well, is drilled into the well that is out of control, and heavy mud or cement is pumped from one well into the other. Many wells that blow out actually stop flowing of their own accord after a few days, as the formation heaves and eventually plugs the well bore. A hole that has blown out usually sustains considerable damage and is generally junked and a new well drilled.

Large volumes of water may be released to the land surface between the time a blowout occurs and the time it can be brought under control. In order to prevent widespread environmental damage, a diverter valve may be placed downstream of the blowout preventer which will channel the flow in a desired direction. Permits may be granted, in some cases, for emergency surface disposal into streams or canals. Obviously, this method is undesirable and should be avoided if possible. Other alternatives are to divert the flow into lined tanks or unlined pits. If unlined pits or natural basins are used, provisions should be made to dispose of the water as soon as possible by reinjection into disposal aquifers, or by other means, so that environmental damage is minimized.

SUBSIDENCE PREVENTION

Land subsidence is not expected to be a major problem created by the production of geopressured geothermal fluids for the reasons outlined in the preceding section. Nevertheless, it is necessary to consider methods to minimize any potential damage.

The surest method to prevent subsidence would be to reinject the fluids back into the producing aquifer. Formation pressures on the order of 985 to 2,110 kg/cm^3 and the very tight sand permeabilities expected in the geopressured formations would necessitate high pumps and a vast number of disposal wells, perhaps hundreds, to accomplish this type of reinjection. Add to this the fact that each reinjection well would have to be 4,500 to 7,000 meters deep and probably would cost several million dollars each; and it becomes apparent that, from an economic standpoint alone, this method is totally impractical. Evidence exists to show that it may be physically impossible, as well, to pump these volumes into geopressure using present technology. Hence, this method of subsidence prevention can be summarily dismissed as unfeasible.

Careful selection of the geothermal site will be the best method of preventing subsidence. The most critical parameter is the selection of a reservoir in a large fault block so that the compaction of the reservoir may be translated over a very large surface area. Happily, the selection of a large fault block is desirable, not only for subsidence prevention, but because it coincides with the need for very large reservoirs capable of sustaining production for a period of twenty years or more. Producing wells should be located as far as is practical from faults so that a differential subsidence or fault activation does not occur. The first plant sites should be chosen in undeveloped, somewhat inland, areas so that if subsidence does occur, damage will be minimal. Faults should be mapped using all available means, including reflection seismic techniques, to determine if any structures could suffer damage from a differential fault movement. These precautions will minimize, but probably not totally eliminate, subsidence and the resulting environmental damage. Hopefully, if these precautions are followed, any subsidence and resulting environmental damage will be minimal.

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APPENDIX
ESTIMATION OF MAXIMUM DEPOSITION RATES OF COOLING TOWER

From pp. 585-596 of "Cooling Tower Environment - 1974"[36]:

Maximum deposition rate of example mechanical-draft cooling tower:

Under slightly unstable conditions: 4×10^{-5} kg/m^3 at 230 m downwind.

Under neutral conditions: 2.43×10^{-5} kg/m^2/day at 330 m downwind.

Water recirculation rate: 12.5 m^3/sec.

TDS concentration: 10,000 ppm

$$\text{Recirculation rate of example tower} = 12.6 \times 60 \times 7.48 \times 35.3 = 199{,}700 \text{ gpm}$$

Maximum deposition rates of cooling tower considered here:

Under slightly unstable conditions:

$$\frac{4 \times 10^{-5} \times 7{,}500 \times 96{,}400}{10{,}000 \times 199{,}700} = 1.448 \times 10^{-5} \text{ kg/m}^2\text{/day}$$
$$= 434 \text{ kg/km}^2\text{/mo at} \sim 230 \text{ m downwind}$$
$$= 0.1675 \text{ µg/m}^2\text{/sec.}$$

From the Chemical Engineer's Handbook[37], the terminal velocity of (assumed) 50 µm diameter brine droplets in air is ∼0.07 m/sec. The concentration of drift particles in the atmosphere at near-ground levels will be approximately 0.1675/0.07 = 239 µg/m^3.

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16. ABSTRACT

The deep geopressured reservoirs along the Texas and Louisiana Gulf Coast are believed to offer a large potential supply of both natural gas and heat energy. Major environmental effects of development are divided into emissions and geological considerations. The potential emissions consist of brine from well mishaps, waste brine of higher salinity, cooling tower emissions, and noncondensible gases. Little or no hydrogen sulfide or other noxious gases are anticipated. Environmentally, these waters appear to be cleaner than normal convective geothermal sources.

Geological considerations are more serious. They include possible subsidence and earthquakes. The area is already low and naturally subsiding. Because the reservoirs are depletable and the waters act, at least partially, as the load-bearing element, more rapid subsidence is very possible. The great depth of the formations is one hope for avoiding subsidence.

Earthquakes are not common to the Gulf Coast, but many subsidence faults exist. Slippage might be accelerated by deep water withdrawal. Only micro-earthquakes could be expected, however.

In view of the uncertainty of extensive resource development and the relatively long time frame involved, only moderate emphasis should be placed on environmental research at this time.

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