Title

THE GEOPRESSURED GEOTHERMAL RESOURCE OF THE TEXAS AND LOUISIANA GULF COAST: A TECHNOLOGY CHARACTERIZATION AND ENVIRONMENTAL ASSESSMENT

Authors

Usibelli, A.
Deibler, P.
Sathaye, J.

Publication Date

1980-12-01

THE GEOPRESSURED GEOTHERMAL RESOURCE OF THE TEXAS AND LOUISIANA GULF COAST: A TECHNOLOGY CHARACTERIZATION AND ENVIRONMENTAL ASSESSMENT

Anthony Usibelli, Peter Deibler, and Jayant Sathaye

December 1980

William E. Siri
Program Manager

Energy Analysis Program
Energy & Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

This work was supported by the Assistant Secretary for Environment, Office of Technology Assessment, Technology Impacts Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

THE GEOPRESSURED GEOTHERMAL RESOURCE OF THE TEXAS AND LOUISIANA GULF COAST: A TECHNOLOGY CHARACTERIZATION AND ENVIRONMENTAL ASSESSMENT

EXECUTIVE SUMMARY

This report examines two aspects of the Texas and Louisiana Gulf Coast geopressured geothermal resource: (1) the technological requirements for well drilling, completion, and energy conversion, and, (2) the environmental impacts of resource exploitation. The information contained in this report comes from the literature on geopressured geothermal research and from interviews and discussions with experts. The technology characterization section of the report emphasizes those areas in which uncertainty exists and in which further research and development is needed. The environmental assessment section discusses all anticipated environmental impacts and focuses on the two largest potential problems: a) subsidence and b) brine disposal.

Technological Requirements

Nearly all aspects of geopressured well drilling and completion are similar or identical to techniques employed in conventional petroleum resource development. For those areas in which geopressured and conventional petroleum development vary, refinement of existing technique will be required. Experimentation will lead to use of the most appropriate mud and cement compositions. The greatest difficulty will be encountered in the development of monitoring devices adequate for extreme downhole pressures. Accurate and safe drilling requires simultaneously obtaining information on a range of variables. In addition, in-situ sampling techniques require further basic and applied research in order to overcome current pressure limitations. A variety of completion methods, including both water well and petroleum well techniques, will be used experimentally in the course of demonstrating resource feasibility. Additional experience will reduce the risk of blowouts and bad cementing, but as with conventional petroleum drilling, some risk will remain.

EXECUTIVE SUMMARY

Energy embodied in the geopressured resource can be exploited in three different forms: the chemical energy of methane dissolved in the brine, the thermal energy in the form of geothermal heat, and the kinetic energy of high pressure fluids. The resource of major interest, however, is the methane contained in the extracted brines. Technologically, geopressured geothermal energy conversion is a hybrid of the conventional oil and gas and the geothermal electric industries. Development of major new techniques and technologies for geopressured energy conversion is not required. High brine flow rates coupled with the problems of erosion, scaling, and corrosion, however, will require refinement of both equipment and operating procedures. Disposal of brines into subsurface aquifers (2,000 to 5,000 feet deep) will not be technically difficult, although large volumes of spent brine at high pressure require careful management and monitoring of equipment.

Environmental Concerns

Surface subsidence resulting from geofluid withdrawal and the reinjection of spent brines into subsurface formations will be the two most difficult environmental aspects of resource development. In each case, the uncertainty is high. The severe adverse impacts of subsidence, or the inability to successfully reinject huge volumes of brine, may slow or halt commercial development of the resource.

The probability of subsidence resulting from geopressured development-both its magnitude and rate-is largely unknown. Experts disagree on the adequacy of current levels of theoretical knowledge for analyzing and predicting subsidence in the necessary site-specific manner. Some factors indicate high potential for subsidence, others point to low potential. For instance, the extensive growth faulting of the Gulf Coast may help limit the areal extent of subsidence. At the same time, the undercompacted sediments of geopressured reservoirs may enhance the probability of significant subsidence.

Geopressured rock testing is almost at a standstill until new samples can be obtained and data generated. Current simulation techniques cannot be refined until more data are available. Any analogy of geopressured subsidence with subsidence resulting from the extraction of geofluids (such as oil and gas, geothermal, or groundwater) is far from precise. Its depth as well as its highly faulted sediments are unique features thought to be determinants of subsidence. Efforts are now underway to standardize the nomenclature and testing procedures used by a variety of specialists from different disciplines. Increased emphasis will be placed on extensive testing of laboratory samples. The potential severity of geopressured subsidence in the low-lying Gulf Coast indicates that research should proceed in an unhurried but deliberate manner.

Spent brine is a hot and chemically complex fluid that varies greatly in composition. Concentrations of heavy metals, organics, and trace elements frequently occur at levels far in excess of seawater concentrations and Environmental Protection Agency (EPA) toxicity standards. In an untreated form, discharge of this brine into terrestrial or aquatic ecosystems will most probably cause substantial adverse biological impacts.

At present, reinjection of the waste brine into subsurface aquifers located above the producing formation is the only disposal method under serious consideration. Undesirable communication of the brine with adjacent fresh water formations, or with the ground surface, are risks that can be minimized with proper operating procedures. Control of reinjection pressures reduce the threat of environmental disruption resulting from fluid disposal. Surface disposal of brine to the Gulf of Mexico is more problematic. Disposal of hypersaline brines into the Gulf from the Federal Strategic Petroleum Reserve (SPR) Program may provide useful data on dispersion patterns and possible impacts. Unfortunately, any disposal comparison is only partially realistic because of the different chemical and temperature characteristics of the two fluids. Brines probably cannot be dumped into the Gulf except with intensive treatment.

Air quality, solid waste, noise, fault activation, and other environmental impacts have been mentioned in association with geopressured geothermal development. In each case either: a) the magnitude of the impact is small, b) the residuals are easily controlled, or, c) the probability of occurance is so small that impacts may be considered to be of second-order importance. Residual-monitoring programs should continue for existing and new test wells to enlarge the data base. Relative to subsidence and brine disposal, these impacts should not significantly affect resource development.

No geopressured wells have been drilled, or are planned, for the offshore Gulf Coast area. However, preliminary geological mapping of the offshore resource indicates several good prospect areas. But there are environmental, economic, legal, and institutional advantages and disadvantages to an offshore development strategy. From an environmental perspective, the impact of subsidence may be reduced through offshore development. Conversely, brine disposal may be more difficult unless adequate dispersion of brines can be achieved in the deep ocean areas beyond the outer continental shelf. Research is needed in certain areas to determine if an offshore development strategy should be pursued. The aim in this report is to discuss the pertinent issues and to indicate areas of research.

Recommendations

Technological

- Joint work on in-situ logging instruments for both geopressured and conventional geothermal wells should be encouraged.
- A range of well completion techniques should be tested in order to minimize drilling and completion risks.
- Full-scale testing of commercial production facilities-- which include gas separators, hydraulic turbines, and geothermal electric units--should be conducted at the earliest possible time.

Environmental

- Laboratory research in geopressured subsidence testing should be expanded in order to better the understanding of subsidence phenomena.

- Research techniques and nomenclature should be standardized among members of various disciplines working on subsidence research.
- Monitoring and analysis of the impacts of Gulf Coast disposal operations by the SPR should be closely scrutinized by geopressured geothermal researchers.
- Offshore brine disposal should be seriously studied as an option.
- The possibility of offshore development should be critically examined. A wide range of factors must be weighed in balancing the environmental, economic, legal, and institutional advantages and disadvantages of such a strategy.

Technology Characterization and Environmental Assessment Matrices

The following two pages contain matrices, one each for the report's technology characterization and environmental assessment sections. These matrices are qualitative summaries of the subject areas considered in each section. The assigned values attempt to balance diverse opinions expressed in the literature and the non-published comments of reseachers. Nonetheless, the choice of values often remains subjective. Because of the limitations of a ranking system with only three classifications, the correct characterization of a given aspect of resource development occasionally appeared to us to fall between two of the categories. However, these matrices may aid the reader in putting various aspects of geopressured development into perspective.

Summary of Technology Characterization of Geopressured Geothermal

TECHNOLOGY	Analogy		State of the Art	Experience Level	Research		Technical Substitutes	Consensus Level
	Oil/Gas	Geothermal			Basic	Applied		
Drilling & Completion:								
Surface Equipment	1	1	1	1				1
Mud Engineering	1	1	2	2			X	2
Logging	2	2	2	2	X	X	X	
Testing	2	1	2	2	X	X		2
Casing Setting	2	1	2	2		X	X	2
Cementing	1	1	1	2		X		1
Perforation/Packing	2	1	2	2		X	X	2
Production:								
Methane Separation	2	3	2	2	X	X	X	3
Gas Processing	1	3	1	1				1
Geothermal	3	2	2	2			X	2
Binary	3	2	3	3		X	n.a.	2
Flashed	3	2	2	2		X	n.a.	2
Direct Use	3	1	1	2		X	X	2
Hydraulic Turbine	3	3	1	2		X		2
Residual Control:								
Brine Disposal	2	2	2	3			n.a.	2
Onshore-subsurface	2	2	2	3	X	X	X	2
Offshore-surface	2	3	3	3	X	X	X	1
Air Quality	2	2	2	1			X	1
Noise	1	1	1	1			X	1
Well Workover	1	2	1	2			X	1

Analogy
- 1-Direct
- 2-Partial
- 3-None

State-of-the-art
- 1-Advanced relative to anticipated needs
- 2-Partially developed relative to anticipated needs
- 3-Poorly developed relative to anticipated needs

Experience Level
- 1-Substantial operating experience
- 2-Limited operating experience
- 3-No operation experience or testing only

Research
- X-Basic or Applied research needed
- "blank"-no significant research needed

Technical Substitutes
- X-Substitutes available (several technologies or methods available to perform process)
- "blank"-no substitutes readily available

Consensus Level
- 1-Major agreement among experts
- 2-Some disagreement among experts
- 3-Wide range of expert opinion

n.a.-Not Applicable

?-Uncertain

Summary of Environmental Assessment of Geopressured Geothermal											
IMPACT AREA	Analogy			Information	Experience	Research		Magnitude	Mitigation	Uncertainty	Consensus
	Oil/Gas	Geothermal	SPR*	Base	Level	Basic	Applied	of Impacts	Procedures	Level	Level
Subsidence											
Compaction	1	2	n.a.	2	3	X	X	n.a.	n.a.	2	2
Rock Mechanics	2	2	n.a.	2	3	X	X	n.a.	n.a.	2	2
Shale Dewatering	?	?	n.a.	2-3	3	X	X	n.a.	n.a.	1	3
Fault Activation	2	2	n.a.	3	3	X	X	?	n.a.	1	2
Brine Disposal											
Offshore-surface	2	3	2	3	3	X	X	1	3	1	2
Onshore-surface	2	2	3	2	3	n.a.	n.a.	1	3	3	1
Brine Chemistry	2	2	2	2	n.a.		X	n.a.	n.a.	2	2
Subsurface Injection	2	2	1-2	2	2	X	X	2	1	2	2
Fluid Compatibility	2	2	2	2	2	X	X	3	2	2	2
Migration	2	2	2	2	2	X	X	2	1	2	2
Air Quality	1-2	2	3	1	1			3	1	3	1
Land Use	2	2	3	1	1			3	1	3	1
Solid Waste	1	2	3	1	1			3	1	3	1
Occupational	1	2	2	2-3	1	X		3	1	3	1

* Strategic Petroleum Reserve

Analogy
- 1-Direct
- 2-Partial
- 3-None

Information Base
- 1-Extensive
- 2-Moderate
- 3-None

Experience Level
- 1-Substantial operating experience
- 2-Limited operating experience
- 3-No operating experience or testing only

Research
- X- Basic or Applied research needed
- "blank"-No significant research needed

Magnitude of Impacts
- 1-Major
- 2-Minor
- 3-Insignificant

Mitigation Measures
- 1-Technology well developed
- 2-Technology partially developed
- 3-Technology poorly developed

Uncertainty Level
- 1-Major uncertainty about impacts
- 2-Medium uncertainty about impacts
- 3-Low uncertainty about impacts

Consensus
- 1-Major agreement among experts
- 2-Some disagreement among experts
- 3-Wide range of expert opinions

n.a.-Not Applicable

?-Uncertain

Key to Technology Characterization Matrix

Analogy:

This column indicates the applicability of oil and gas and geothermal technology and operating procedures to geopressured geothermal activities. A "direct" analogy indicates no substantial difference between geopressured geothermal equipment or procedure and oil and gas or geothermal operations. "Partial" indicates some differences in equipment or procedure, and "none" indicates that there are no significant similarities.

State-of-the-art

This column is an estimate of the advancement of applicable technology and practices relative to anticipated geopressured geothermal operating needs. "Advanced relative to anticipated needs" indicates that most, if not all, of the technology and procedures are well understood and easily applicable to geopressured geothermal operations.

Experience Level

This index indicates the amount of actual commercial operating experience with the indicated technology or procedure. "Substantial operating experience" means that either there have been many geopressured geothermal wells developed using the indicated technology or that there have been many years of commercial experience with directly analogous operations in the oil and gas or geothermal industries.

Research

These columns show whether or not more laboratory and field research is likely to be needed for a technology or process. "Basic" research needs are those where fundamental questions exist about the nature of a procedure, e.g. some of the theoretical foundations for well logging may be unclear. "Applied" research needs are related to engineering problems that must be solved, although the theoretical aspects of a technology or procedure are well understood.

Technical Substitutes

This column indicates whether there is more than one type of equipment or method for accomplishing a given task. For example, based upon experience in the oil and gas industry there are a variety of techniques and chemical mixes that can be used in mud engineering.

Consensus Level

This column give our estimate of the level of agreement among geopressured geothermal technology experts concerning their views of technology and procedure. "Major agreement among experts" means that we have found little or no disagreement in the published literature or in discussions on what technologies to use and how they should be applied. "Wide range of expert opinion" indicates a wide range of opinion concerning the applicable technologies or practices to be used.

Key to Environmental Assessment Matrix

Analogy

(See above)

Information Base

The information base column indicates the amount of empirical data available concerning a given phenomenon or process. "Extensive" indicates that the process is well understood and that there is much data available.

Experience Level

(See above)

Research

(See above)

Magnitude of Impacts

This column indicates the relative environmental impact of the row entry. A "major" impact would be one which has the potential for extensive disruption to the surrounding ecosystem. A "minor" impact is one that is highly localized or has little potential for effecting a larg area.

Mitigation Measures

This column refers to the level of development of the technologies and procedures necessary to lessen the environmental impacts. "Technology well developed" refers to a situation in which well developed procedures are available to lessen an environmental impact. This column does not indicate the ease of affecting the severity of the impacts.

Uncertainty level

This column indicates the amount of uncertainty present in the possible impacts. "Major uncertainty" means the level of knowledge concerning the possible consequences or even the nature of an activity is highly speculative.

Consensus level

(See above)

TABLE OF CONTENTS

I. Introduction

TECHNOLOGY CHARACTERIZATION

II. Drilling and Completion of Geopressured Geothermal Wells

III. Energy Conversion Processes

ENVIRONMENTAL ASSESSMENT

IV. Current Knowledge of the Potential for Geopressured Subsidence

V. Environmental Impacts of Geopressured Brine Disposal

VI. Second Order Environmental Impacts

VII. Offshore Geopressured/Geothermal Development

Appendix A: Non-Unique Drilling and Completion Technology

ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Environment, Office of Technology Assessment, Technology Impacts Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

INTRODUCTION

Background

Vast areas containing geopressured (i.e., in excess of hydrostatic) formations underlie coastal portions of Texas and Louisiana at varying conditions of depth, temperature, and extreme pressure (1). The geopressured geothermal resource represents three potential energy sources. These sources, contained in the extracted brine, are: 1) temperatures ranging from 200°F to 300+°F, 2) pressures from 8,000 to 20,000 pounds per square inch-absolute (psia), and 3) dissolved methane at 20 to 50+ standard cubic feet (scf)/barrel. Current interest is focused on the methane; a possibly important supplement to diminishing conventional natural gas reserves.

Technology and environmental impacts of geopressured geothermal energy are two important components of resource development The first section of this report briefly discusses the processes and technologies necessary for resource extraction and utilization. Questions such as the following are examined (2): What procedures are necessary for the successful drilling and completion of geopressured wells, and how do

---

(1) Other regions of the United States, as well as a number of foreign countries, also contain extensive geopressured formations. Only the Gulf Coast region, however, has been studied in detail, see Wallace, R.H., T.F Kraemer, R.E. Taylor, and J.B. Wesselman, "Assessment of Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin," in Assessment of Geothermal Resources of the United States-1978, U.S.Geological Survey Circular 790, especially pages 148-149.

For international information, see Fertl, Walter, Abnormal Formation Pressures: Implications to Exploration, Drilling, and Production of Oil and Gas Resources, Chapter 9, Global Occurance and Evaluation of Abnormal Formation Pressures, Elsevier Scientific Publishing Company, 1976.

(2) Because development of the geopressured geothermal resource will be similar to conventional oil and gas and geothermal development, the emphasis of this report is on processes and technologies unique to the geopressured resource. Non-unique features of geopressured resource extraction are examined briefly in appendix A as background for those not familiar with oil and natural gas drilling and completion. This report does not exhaustively characterize the technology. The geopressured geothermal industry is in its infancy and many technical questions concerning the resource remain unanswered. No commercial resource development has occurred and although one well has been drilled for the Department of Energy, testing is not yet complete.

these methods differ from those employed in the conventional oil and gas industry? Following well completion, how can useful energy be extracted, and what problems and uncertainties are there? The second major section examines the potential environmental constraints and uncertainties that may affect resource production. Most notable are the problems of ground surface subsidence and spent brine disposal.

Report Organization

The report is organized along the following lines. This introductory chapter includes brief descriptive material on: 1) Gulf Coast geology, 2) the extent of resource testing, and 3) the size and extent of the resource base.

The main body of the report is divided into two chapters: a) an analysis of the technology and processes used for the drilling and completion of wells, and for energy extraction, and b) a discussion of the environmental impacts of resource development (3). In the first chapter two different methods of methane production are examined. First, there is the more widely accepted process, in which brine and methane separation occur in facilities located at the wellhead. Secondly, there is the rapid pressure drawdown (RPD) method of methane extraction. In the latter procedure reservoir pressure is allowed to drop quickly, facilitating a preferential flow of methane relative to brine. The second process is highly controversial; its validity is based on unverified theories of geopressure formation and maintenance including the presence of both dissolved and interstitial "free gas" in the reservoir (4).

The second chapter examines subsidence and brine disposal, the two major environmental difficulties associated with resource exploitation. For completeness, other impacts likely to be of secondary environmental importance are briefly addressed. These include issues of air and water quality, noise, and surface and ecological disruption due to site

---

(3) Exploration for geopressured geothermal formations is similar to conventional oil and gas exploration. Therefore, the subject is not discussed in this report.

(4) No attempt is made to support or refute the existence of "free gas" in geopressured reservoirs. At the same time, any method that may increase overall resource production with the possibility of reduced environmental risk deserves consideration. Nevertheless, many experts feel that the RPD method has no scientific validity.

development.

In the final section of the report some of the pros and cons of offshore development of geopressured resources are briefly examined.

Gulf Coast Geology

The geology of the Gulf Coast of Texas and Louisiana has an important influence on the development of the resource. Methods and rates of drilling, well completion techniques, estimates of surface subsidence, and disposal well design are a few of the aspects of resource development that require an understanding of the region's geology. A detailed geological description is beyond the scope of this report, but the following general geologic characteristics are necessary background (5).

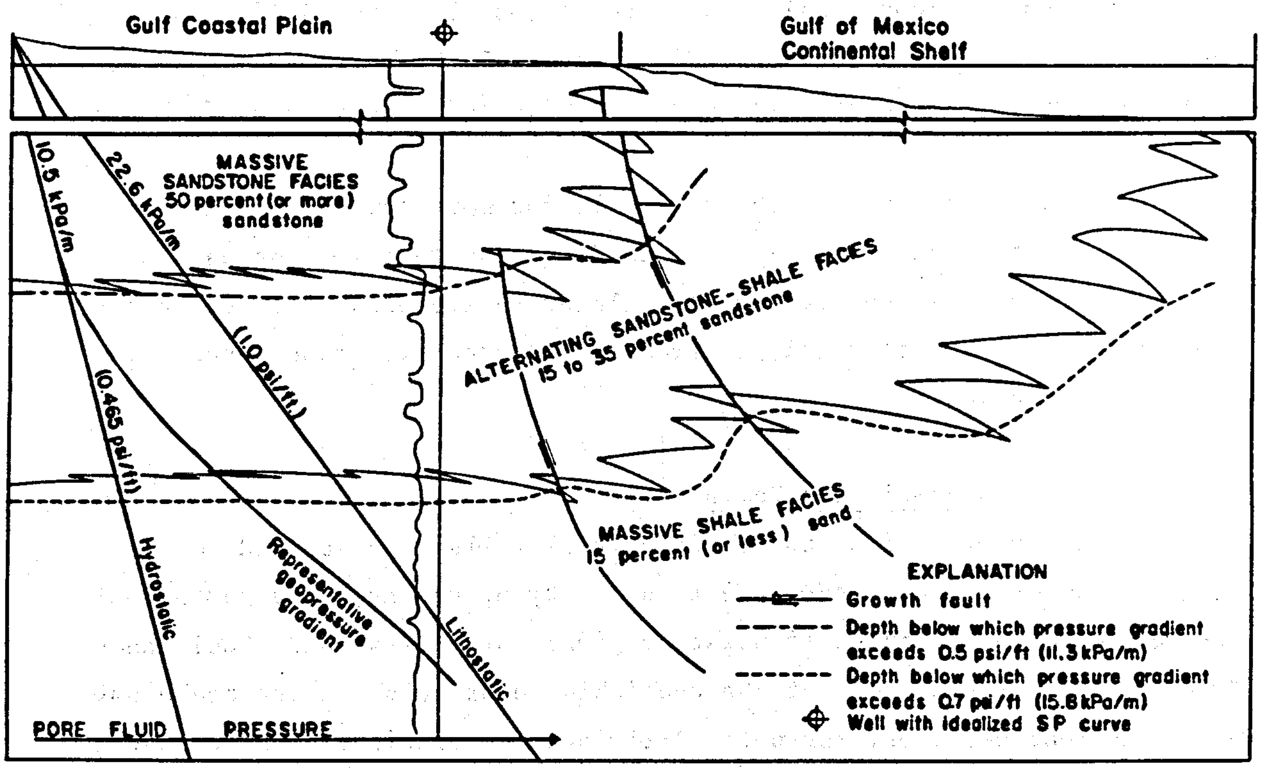
> "On the basis of sandstone percentage, three generalized depositional facies are recognizable in sedimentary beds of all ages occuring in the Gulf Coast geosyncline:
>
> 1) a massive sandstone facies in which sandstone constitutes 50 percent or more of the sedimentary volume;
>
> 2) an alternating sandstone and shale facies in which sandstone constitutes 15 to 35% of the sedimentary volume; and
>
> 3) a massive shale facies in which sandstone constitutes 15% or less of the sedimentary volume."

For rock of a given age, the sandstone facies occurs towards the north and the shale facies occur gulfward. Due to the evolution of sedimentation, these three depositional environments have gradually shifted south into the Gulf. Consequently, as illustrated in Figure 1, the volume of sandstone generally decreases vertically with increasing depth and decreases horizontally towards the Gulf of Mexico.

Fluid pressures in excess of hydrostatic are most commonly associated with the alternating sandstone and shale facies and the massive shale facies. As a rule, fluid pressures increase with increasing

---

(5) This discussion is adapted from Wallace, R. H., T.F. Kraemer, R. E. Taylor, and J. B. Wesselman,, "Assessment of Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin " in Assessment of Geothermal Resources of the United States-1978, U.S.G.S. Circular 790, pp. 133-135.



Generalized sedimentary model of the northern Gulf of Mexico basin, based on percentage sandstone and showing, diagrammatically, the relation of gross lithology to fluid-pressure gradient and growth faulting

Figure 1

Source: U.S. Geological Survey, Circular 790.

depth. Excessive fluid pressure is due to restricted expulsion of pore fluids. A portion of the overburden pressure is borne by interstitial fluids rather than by the rock matrix. Sandstone reservoirs, thought to have the greatest potential for resource development, occur within the alternating sandstone and shale facies and, to a lesser extent, within the massive shale facies.

Successive cycles of deposition and compaction have led to extensive networks of growth faults that roughly parallel the Gulf Coast and the line of deposition. Growth faults frequently have surface expression and are one mechanism for the formation and maintenance of abnormally high pressures.

Although the geology of the region is far more complex than indicated here, two concepts -- a) confined aquifers in a depositional environment and b) extensive growth faulting -- are essential for understanding the technical and environmental problems associated with resource development.

Geopressured Geothermal Test Wells

In the latter half of the 1970s several wells were spudded or re-entered in order to test the feasibility of geopressured geothermal energy production in the Gulf Coast regions of Texas and Louisiana. These wells provide most of the available information on the technical considerations necessary for well drilling, completion, and resource extraction. As of 1980, the Department of Energy's Pleasant Bayou #2 in Brazoria County, southeast Texas, was the only design well that had been drilled explicitly for geopressured geothermal sampling and testing . In addition, the DOE, under its Wells of Opportunity (WOO) program, has re-entered several conventional petroleum wells in which the presence of geopressured brines was indicated. The drilling of new design wells in Gulf Coast area and the continuance of flow testing at Brazoria are planned (6).

---

(6) The bimonthly newsletter of the Geopressured Geothermal Energy Forum, published by the Geo Energy Corporation (Suite 145, 3376 S. Eastern Avenue, Las Vegas NV. 89109), provides up-to-date status reports of DOE design wells and wells of opportunity

Resource Base Estimates

The size of the geopressured resource base is an unknown. Estimates of the total amount of methane entrained in Gulf Coast brines, without regard to technical, environmental, or economic constraints on production, range from a few hundred to about 50,000 trillion cubic feet (tcf) (7). There are no estimates of reserves in the sense that the term is normally used for assessing geologic energy sources.

Reserves may be "estimated", when there is substantial uncertainty about the numbers; "proven", when there is little uncertainty, or "recoverable", when the resource is not only proven but is recoverable under current technical and economic conditions. One estimate, by the Department of Energy's Assistant Secretaries for Fossil Energy and for Environment, places "potentially recoverable reserves" at from 150 to 2000 tcf of geopressured methane (8). The term "potentially recoverable reserves" contains considerable uncertainty as to the economic and geologic conditions necessary for future commercial production of the resource. In contrast, the proven reserves of conventional natural gas in the United States total 208 tcf, roughly a 10-year supply at current rates of consumption. It is clear that geopressured methane is potentially an important source of natural gas.

---

(7) These estimates are from a wide range of sources, one summary table is included in the DOE's Geopressured Geothermal Resources: An Unconventional Energy Source, p. 3, available through the DOE Geopressure Project Office in Houston, Texas.

(8) Unconventional Gas Recovery (Enhanced Gas Recovery), Assistant Secretary for Fossil Energy - Assistant Secretary for Environment, Department of Energy, Report DOE/EDP-0049, October 1979, p. 5.

DRILLING AND COMPLETION OF GEOPRESSURED GEOTHERMAL WELLS

Overview

Introduction

Drilling and completion activites for a geopressured well development program range from design of the drilling program to the final well completion tasks. Most of these tasks are identical to, or vary only in degree, from those for a conventional petroleum drilling program. Although the technology and techniques are often state-of-the-art, they are not unusual. The processes that are identical to conventional drilling are discussed briefly in Appendix A.

Part of this chapter is concerned with identified areas of difficulty specific to geopressured wells. Logging and monitoring of well data, mud engineering, well completion casing, cementing, perforating, and packing, are all important for most conventional petroleum drilling and completion programs (1). Because of the more hazardous pressure and temperature characteristics of overpressured zones, however, logging, mudding, casing, and cementing all take on added significance. With the possible exception of logging tools, the various phases of geopressured drilling require a refinement of existing technique, rather than new technological development. This polishing of technique will come only with further experience in well drilling.

Test wells (DOE design wells) do not vary markedly in design or technique from production wells that will be utilized in a later phase of resource development. But serious questions regarding the applicability of current technology pertain largely to production wells of 10 or 20 year lives, rather than to shorter-term test wells. The experience gained from test wells will be factored into the drilling programs

---

(1) Mud engineering and well logging are integral to any drilling program; under certain conditions, however, production casing and cementing for conventional wells are unnecessary.

of future production wells. The Federal government's role is to refine technique and encourage production of certain materials that now require special ordering. Both roles aid in risk reduction, a prime determinant of future industry involvement in resource development.

Because very few geopressured geothermal wells (test or production) have been purposely drilled to date, one cannot yet statistically compare the failure rate of geopressured wells to the failure rate for conventional oil and gas wells (2).

Only DOE design wells are explicitly considered here. Wells of Opportunity (WOO) wells are intended for short-term testing. Consequently, elaborate, long-term completions are seldom used on these wells. Specific difficulties encountered with WOO wells are mentioned, however, to illustrate the problems of the current technology.

Views on the Need for Government Refinement of Technology and Technique

The drilling and completion of geopressured wells does not require new or unusual equipment. A limiting factor in the successful drilling of deep overpressured wells may be the ability of the operator to obtain contractors of sufficient experience and expertise for crucial tasks such as cementing, mud engineering, casing selection and quality control, and logging (3).

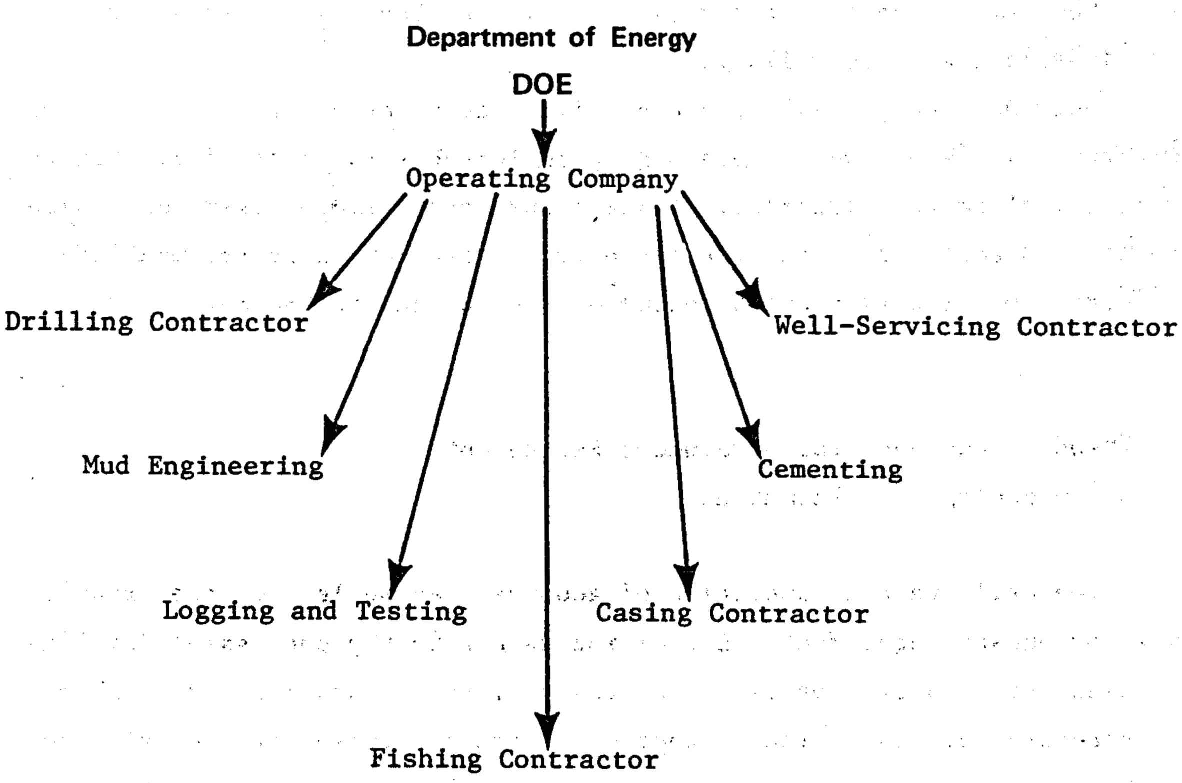
Figure 1 illustrates the organization of the drilling and completion operations. The operating company (in this case the prime contractor of the Department of Energy), subcontracts the two major tasks to drilling and well-servicing firms. Mud engineering, well testing and monitoring, cementing, perforation, and completion casing will normally all be contracted to relatively small and highly specialized firms. These subcontractors may be on the site for only a few hours, as in the

---

(2) In contrast to conventional wells that drill through overpressured zones. See the report introduction for a short review of geopressured geothermal well drilling.

(3) Special-ordering of any material, such as a high-test casing, can cause delays and contribute greatly to costs. Backlogs in materials delivery are sufficient to setback a well development schedule for weeks or months.

Figure 1



ORGANIZATION OF DRILLING AND COMPLETION OPERATIONS
FOR A GEOPRESSURED GEOTHERMAL TEST WELL

XBL 808-1835

case of cementing, or for the entire drilling period (possibly four months) in the case of the mud engineer.

Industry R&D on all phases of drilling and completion has progressed rapidly over the past few decades. There appear to be, however, at least two points of view concerning the adequacy and needed for refinement of the technology necessary for geopressured geothermal well drilling and completion. One view holds that explicit technological development is less important for successful resource development than proof of the resource. Thus as test wells are drilled technological problems will be dealt with as they arise. Keith Westhusing and Fred Goldsberry of the Doe Houston geothermal office do not anticipate major problems (in well drilling and completion) beyond those encountered routinely in industry deep well drilling (4).

An alternative point of view is that of Alex Miash of Sandia Laboratories, who is under contract to DOE's geothermal division to study drilling and completion problems. Miash believes that a demonstration of resource viability depends both on obtaining data and on decreasing the risk of well failure. He also states that there is a need for greater consistency in approaching drilling and completion problems (5). Miash points to a need for R&D to "reduce the incidence and cost" of drilling and completing wells, and cites the failure of the first Pleasant Bayou test well in Brazoria County to reach a testing and production stage. Inadequate mud logging at Brazoria led to an over estimate of the required mudweight. This over estimate in turn led to differential pressure sticking of the drill stem (6).

The first view expressed above, that no real procedural or technological problems exist, is at least partially based on an implicit assumption that industry will develop the necessary techniques and technology to handle these problems once geopressured aquifer producibility is demonstrated. Miash and others, in contrast, point to the long potential lead times for such a process. If the resource production parameters are demonstrated and a desired policy goal is the relatively

---

(4) Telephone conversations with Keith Westhusing and Fred Goldsberry, March 17 and 20, 1980, respectively.

(5) Telephone conversation with Alex Miash, March 20, 1980.

(6) The drill stem became glued to the well wall due to the differential of formation to exerted mudweight pressure.

rapid introduction of commercialization by industry, then government demonstration of reliable drilling and completion methods will aid in removing an additional level of risk perceived by industry.

Between these two nearly-polar viewpoints is the opinion of Ray Wallace, a USGS geologist and consultant to DOE's Houston geothermal office. Wallace believes that if large brine flows are necessary, existing technology and techniques can be adapted from the completion of high-flow water wells (7). Wallace's views on completion are further discussed below.

The wide range of industry views concerning the minimum requirements for demonstrating viable resource production and for diminishing risk barriers to private sector development appear to lend some weight to Miash's argument (8). Only additional experience can provide answers to these questions.

Two Possible Modes of Production

The major differences between a geopressured brine producer and a rapid pressure drawdown (RPD) producer appear in the production phase. Drilling and completion are essentially the same for the two production methods with several possible exceptions. For one, a geopressured brine producer requires relatively large diameter and expensive completion casing in order to produce 10,000 to 50,000 barrels of fluid per day. An RPD producer, in contrast, may be able to produce gas with relatively small quantities of fluid through smaller diameter casing (9). The need for well-logging instrumentation, however, may militate against the use

---

(7) Telephone conversation with Ray Wallace, March 26, 1980.

(8) See the notes from telephone conversations and interviews that form the basis of Strongin's report on industry, state government, and other interested parties' views on the minimum requirements for demonstrating resource viability. The notes and report are available from the Department of Energy, Geothermal Program Office, Washington, D.C..

(9) If in-situ production of gas is achieved through a rapid formation pressure drawdown, large diameter casing may still be required. The time period necessary to achieve the desired pressure reduction (and even the magnitude of the pressure reduction) is debatable and hence the amount of initial brine production is also uncertain. See Patent Nos. 4,040,487 and 4,042,034 by Transco, August 9 and 16, 1977, respectively.

of small diameter casing.

Sand control is essential to the successful completion and production of a geopressured brine well. Sand control may not be as important a factor in the case of RPD gas production due to the differential mobility of gas relative to fluid (10). If, however, a well is designed not only to flow brine but also to test the RPD gas theories (as in the case of the DOW Parcperdue design well in Louisiana), the stricter design considerations applicable to a fluid producer are necessary.

Institutional Problems Related to Test Well Drilling

Institutional factors can affect the success with which known technology can be applied to geopressured drilling and completion. Due both to recent FERC rulings on gas deregulation, and to Congressional debate prior to the enactment of a windfall profits tax, the level of industry drilling activity increased sharply during early 1980 throughout the Gulf Coast region. The result is a sharp decrease in the availability of heavy rigs for drilling deep overpressured wells. The stock of drilling rigs cannot be rapidly expanded in response to a sharp increase in demand. Likewise, high specification tubular goods such as completion casing that are generally available on relatively short order, is now unavailable for months ahead. As a result, design well activity have been delayed several months.

---

(10) The degree of sophistication required in downhole completion of an RPD producer would depend on the geology of the particular pay sand, and possibly on the relevant pressures and temperatures as well as the chemical constituents of the in-place brine. For descriptions of two processes for facilitating the differential production of methane from geopressured wells, see:

1) Patent No. 4,040,487, "Method for Increasing the Recovery of Natural Gas from a Geopressured Aquifer," August 9, 1977. The inventors are Cook, Geer, and Katz; the assignee is Transco Energy Corporation.

2) Patent No. 4,149,596, "Method for Recovering Gas from Solution in Aquifer Waters," April 17, 1979. The inventors are Richardson and Christian of the Exxon Production Research Company.

The equipment and materials availability problem is partially a function of the different approaches to well-planning of industry and DOE (11). Industry operators large enough to swallow the high initial investment, including the potential \$ 5 million to \$ 10 million loss for a single non-producing well, are also willing to stockpile materials to avoid delay.

Problem Areas for Geopressured Drilling and Completion

Logging and Monitoring Techniques (12)

Nearly all aspects of geopressured well drilling and completion stretch known technology to the state-of-the-art limit. However, the severe temperatures and pressures to which well-logging devices are subjected push existing instrument capabilities beyond their limits. Logging contractors have consistently experienced difficulty at geopressured well sites due to both high in-situ pressures and brine corrosion.

Anthony Veneruso of Sandia Laboratories, is now working on methods to improve instrument capabilities that fall just short of necessary specifications (13). Veneruso notes that although individual components of commercially available instruments may meet advertised specifications, the instrument comprised of the several component parts may not. This work is being done under a long-term support contract to DOE's division of geothermal energy. In addition, the DOE Houston office and the University of Texas at Austin will be sponsoring a series of workshops on geopressured logging problems beginning in July 1980 (14).

The following problems are encountered in downhole logging and monitoring:

---

(11) Telephone conversation with Fred Goldsberry, March 20, 1980.
(12) This discussion does not distinguish between geopressured wells drilled for brine production and those designed for gas production through rapid pressure drawdown. Logging problems will be encountered in either case.
(13) Telephone conversation with Anthony Veneruso, March 20, 1980.
(14) Telephone conversation with Keith Westhusing, July 8, 1980.

- The high pressures are beyond those found in either conventional oil, gas, or geothermal wells;
- Because of the pressure, obtaining adequate core samples from the wellbore is difficult following removal of the rig (15);
- Available electronic logging devices are rated only to about 150°C (302°F) (16);
- Interpretation of logging data is poor and inadequate.

In short, electronic tools require upgrading; pressure analysis tools may require basic redesign.

A variety of instruments are available for obtaining information on a wide range of parameters. Surface techniques such as acoustic logs and gravity density measurements, while essential to a sound drilling program, can only provide generalized information on reservoir parameters. Geophysical techniques frequently mask local anomalies. Additional data must be obtained from installed or wire-logged wellbore test instruments (depending on whether long-term or short-term data are required). In-situ instruments survey a far smaller volume of rock with a higher resolution.

In regard to the interpretation of well logs, Fertl notes that:

> "Seldom have questions been raised and explicitly answered, such as:
>
> 1. Which well logs are superior for quantitative pressure evaluation?
> 2. How should one quickly and efficiently recognize, select, plot, and evaluate logging parameters for in-situ formation pressure changes?
> 3. What limitations and possible pitfalls are inherent?" (17)

As with oil and gas technique in general, the science still contains an "artistic" element.

---

(15) Fluid sampling is not difficult during shut-in or production phases. See the subsidence section for a discussion of coring problems.

(16) With the recent trend towards examining lower-temperature reservoirs, on the order of 135°C (275°F), temperatures will not pose the problems for geopressured development that they do found in the geothermal case.

(17) Fertl, p.212.

The Fertl patent discusses a variety of difficulties characteristic of conventional means of well parameter measurement and prediction that render these methods inapplicable for geopressured wells (18). Wire line logs that measure electrical, acoustic, or density change characteristics in drilled formations require the suspension of drilling while measurements are obtained, a costly inconvenience. Miash of Sandia Labs,stresses the physical problems associated with obtaining accurate wire line measurements in geopressured wells. Fertl et al, explain that other methods of predicting and evaluating abnormal pressures frequently used in conventional drilling are also inappropriate for geopressured wells. Readings such as the bulk density measure of drilled shale cuttings returning from the annulus, the drill penetration rate, torque and drag of the drill stem, and mud pump pressure, all have the liability of providing post-event but not predictive information. At the point of data interpretation, the drill bit may already have penetrated a new formation.

The spectrum of techniques applied from exploration and prespudding evaluation phases to in-situ monitoring of a completed well covers five general areas:

- geophysical methods;
- drilling parameters;
- measurements of the drilling mud and drilling cuttings;
- well-logging methods;
- direct downhole pressure measuring.

The last three areas are most affected by shortcomings in the current technology. The last two are particularly tricky due to the pressure and sampling problems noted above.

New refinements in technique occur continuously. Little of this knowledge remains proprietary for long due to the contracting nature of oil and gas drilling. There are exceptions, such as mud composition, but in general new advances enjoy a rapid dispersion through the industry.

---

(18) See footnote 23 for a citation of the Fertl patent.

Fertl notes a major limitation on the intepretation of drilling data. All indicators are affected by the chemical composition of the drilling mud. Shale cutting tests, for instance, are subject to ion exchange between the cuttings, the drilling mud, and any additives in use. The difficulty, common to all oil and gas drilling, is an inability to accurately predict the amount of cation replaceability in a mixed cationic system (19). Fertl believes that the acoustic and short normal logs, both used widely in conventional drilling, are the two most valuable tools for in-situ formation pressure measurements (20).

Literature on geopressured logging begins in 1965 with Hottman and Johnson's paper. An example of the many later writings on logging techniques is a series of articles in Oil and Gas Journal describing the geopressured drilling activities of the AGIP oil firm of Italy (21).

Mud Engineering

Drilling mud serves several functions in well drilling:

- balancing annular and formation pressures;
- lubricating and cooling the drill bit;
- circulating rock cuttings to the surface.

The safest and economically optimal drilling rate is primarily a function of the mudweight. Other factors such as the weight of the drill bit and the drilling rotation speed are amenable to direct control. There is a small margin of error between an optimal mudweight that allows for controlled drilling without masking information about the drilled formation, and either an overbalance or underbalance of mudweight in relation to formation pressure. Mud overbalance or underbalance can result in lost circulation, sticking of the drill stem, or possibly a loss of well control.

---

(19) Fertl, p. 172.
(20) Fertl, p. 226.
(21) Oil and Gas Journal, "AGIP Deep Drilling Technique" series, August 21, 1978 and following issues. For Hottman and Johnson's paper, see Bibliography.

One mudding problem experienced with geopressured drilling is deterioration of the the walls of the well during drilling due to extensive contact of the drilling fluid with the easily-eroded formations. The Anahuac clay formations of southern Texas are noted for collapse and sloughing (22). Casing may have to be collared and cemented earlier than planned to protect these formations. Shale formation collapse is more of a problem than sloughing of sand formations.

Controlled drilling of the well using the proper mudweight allows sampling of shale cuttings at the surface. Fertl believes that analysis of shale cuttings and returned mud is the best indicator of formations about to be penetrated. Fertl and co-inventors have patented a technique for measuring the resistivity (or the conductivity, the reciprocal electrical characteristic) of the returning mud that yields the best advance notice during drilling of the nature of upcoming geopressured zones (23). According to the patent, resistivity or conductivity measurement of well drilling samples allows abnormal pressure prediction 200 to 1500 feet in advance of drill bit penetration.

Fertl recommends a mudweight to formation pressure differential of about 0.2 to 0.4 pounds per gallon (ppg) (24). Prediction of geopressures allows for rapid drilling up to the point of penetration. The proper mud overbalance also allows for pulling of the drill string without swabbing (25). Sticking of the drillpipe stem to the well wall can occur with either an overbalance or underbalance of mudweight.

Fertl notes, "pipe-sticking forces depend on:

---

(22) Telephone conversation with Keith Westhusing, March 17, 1980.

(23) See Patent No.3,785,446, "Predicting Occurrence of Geopressured Subterranean Zones During Drilling." The inventors are Fertl, Cavanaugh, and Hillhouse, of Continental Oil Company. The patent rights were granted January 15, 1974.

(24) Fertl, p. 233.

(25) The term "swabbing" refers to the use of rubber cups run on a wire line into the well to remove fluid from the bore. This operation is to be avoided in geopressured wells when possible due both to pressure difficulties and to downtime.

1. how long the pipe remains motionless against the formation;
2. the slickness of the filtercake;
3. permeability and;
4. thickness of zone, and, most important;
5. the differential pressure between drilling mud and pore pressure." (26)

In addition, a well kick may cause sticking of the drill stem. An overbalance in mud weight at DOE's Brazoria No. 1 well led to pipe sticking and eventual abandonment of the well.

The chemical formulation of a particular mud is devised by the mudding engineer, on whom successful well drilling heavily depends. Each mud engineer has his or her favorite formulations for use with different drilling parameters, and no two engineers will totally agree on the necessary mud composition for use in a particular instance. The range of materials used in conventional and geopressured wells is not as diverse as the 50-plus additives available for use in cement.

The DOE division of geothermal energy is working with several of the mudding firms that have been subcontracted on test well drilling operations to determine various ways that DOE can reduce the cost of mud formulations through a more thorough knowledge of the constituents and by ordering of the requisite chemicals in bulk (27). Detailed knowledge of mud mixes used at various temperatures and pressures will allow for post-drilling computer optimization. The result may be an enhanced ability to plan future wells and perhaps a significant economy, for the cost of drilling mud is not trivial . Boyd stated in 1977, for instance, that high-density muds in the 17 to 18 ppg range would cost more than $200,000 for a 15,000 foot well (28).

---

(26) Fertl, pp. 235, 237.
(27) Telephone conversation with Fred Goldsberry, March 20, 1980.
(28) Boyd, "Drilling and Completion Plans for a Geopressured Well," p. ES-2.

Completion

Casing

The completion casing:

- confines production to the wellbore,
- prevents caving and sloughing of the annular walls,
- provides some control of formation pressure,
- seals non-producing, and producible but non-targeted zones from the wellbore, and
- protects fresh-water aquifers from contamination, per state regulation.

Casing structural requirements include consideration of: a) worst-case collapse conditions, b) burst conditions, c) tensile strength, and, d) kick control (29). A major design criterion in choosing casing is the desired rate of fluid production. A number of design studies exist for both specific and generic geopressured wells (30). The information necessary for judging casing diameter can be summarized by graphing the relation of formation pressure and wellhead pressure to a variety of flow rates.

The anticipated wellhead brine temperature (largely a function of the flow rate) is an additional factor in selecting casing. Also important is information on the dynamics of downhole temperature and pressure changes over the productive life of the well. These computations are done routinely in the industry, particularly with the widespread use of computer optimization. High-temperature flow requires expansion and contraction ability in the casing material. A long string may

---

(29) Collapse occurs if external pressure in the annulus exceeds the internal pressure in the wellbore plus the collapse strength. Conversely, burst conditions occur if the internal pressure in the wellbore exceeds the sum of the external pressure in the annulus plus the designed ultimate strength of the casing. Tension strength and kick control both refer to the flexibility required for handling rapid pressure changes without either loss of circulation or loss of well control.

(30) See, for instance, "Well Completion" in the Advanced Research and Technology section of Volume 3 of the Proceedings of the 2nd Geopressured Geothermal Conference, pp. 13-24.

experience 15 to 20 feet of vertical expansion during high-temperature flow (31). The choice of casing may also be influenced by logging requirements. Larger logging apparatus can only be used in larger diameter wells.

Casing requirements and problems for overpressured wells are summarized by Fertl in the following manner:

> "...tubing strings have to be robust, strong, resistant to chemical attack by hydrogen sulfide and carbon dioxide and must provide absolutely gas tight joints even under extreme differential pressures. For the latter situation, special threaded connections, thread-sealing lubricants, and synthetic seal rings are available. Nevertheless field experience indicates that often, for no apparent reason, tubing leaks develop in the connections despite adequately torqued pipe. Investigations of deep gas wells in South Louisiana have shown that at high flow rates, the tubing string tends to develop reverse torque." (32)

As Fertl notes, however, tubing adequate for geopressured applications is available for order under both API and NACE specifications (33).

Alex Miash of Sandia adds that because of greater depth and longer drilling times in geopressured wells, drill string wear can become a serious problem. Sandia is devising casing suspension systems that reduce surface cementing and casing suspension requirements. One idea is to suspend the lower half of the casing string from supports within the well (34). If the rotation of the drill stem can be isolated to the area directly above the bit, casing wear will be reduced.

Table 1 summarizes two generic Gulf Coast geopressured well casing programs. Site-specific conditions will modify the general design.

---

(31) Thermal effects have been studied in the case of geothermal wells. Non-cemented expansion joints are commonly used for each section of tubing in order to distribute the stress of expansion equally along the casing.

(32) Fertl, pp. 267-268.

(33) American Petroleum Institute and the National Association of Corrosion Engineers.

(34) Telephone conversation with Alex Miash, March 20, 1980.

Table 1

Generic Casing Programs for Geopressured Wells in the Gulf Coast Region.

Typical Casing Sizes	Approximate Average Casing Point Depth (35) (thousands of feet)			
	South Texas	Onshore Louisiana	Offshore Louisiana	Hypothetical Gulf Coast
(1) 20"(locally plus 30")	----	----	----	----
(2) 13.375"or 10.75"	9	3-4	4	8
(3) 9.65" or 7.65"	12.5	13-15	13	15
(4) 7"liner and/or 5.5"	15	15-18	20	16.5

Cementing

Cementing:

- secures the casing in the center of the wellbore,
- provides a control substance for channeling formation fluids through perforations and into the production string,
- isolates pay zones,
- isolates potable water, and
- isolates thief zones (formations that absorb drilling mud).

---

(35) The first three wells (South Texas, Onshore Louisiana, Offshore Louisiana), are adapted from Fertl's Table 6.VI, p.260. The Hypothetical Gulf Coast well is a generalized casing program adapted from "Drilling and Completion Plan for a Geopressured Well," W.E. Boyd, in Volume 4, Proceeding of the Third Geopressured Geothermal Energy Conference, page ES-13.

Cementing of the entire annulus is not always necessary and is an expense to avoid. The second Brazoria test well has a cemented annulus; the upcoming DOW Parcperdue string will only be cemented over the bottom several thousand feet. Centralizers will be used in the upper annular space.

Prior to cementing a geopressured well, the drilling mud must be washed from the annular space. This is particularly important for geopressured wells because the chemical components of high pressure and high temperature drilling mud (usually oil or highly treated water-base fluids) are incompatible with the ingredients used in controlled set-up cement (36). Any excess fluid left over from drilling or cementing activities, may enter a vapor phase during brine production causing cement fracturing and possible casing collapse. Should this occur, squeeze cementing, an undesirable and frequently unsuccessful operation, is necessary to save the well (37). The tendency for cement to buckle increases with temperature; sloughing of shale walls may impede uniform cementing. Cement design requires avoidance of too rapid setting which is difficult with high temperatures and pressures. Uneven cement setting may result in channelling, in which fluid and vapor escape to the surface through fissures in the cement of the annular space.

Roughly 50 cement ingredients are available to help achieve the desired setting qualities (38). Retarders delay the setting process for a temperature range of approximately 75°C to 315°C. Weighting agents add the density required to balance high formation pressures. Common weight additives are barite, iron oxide, barium sulfate, ilmenite, and hematite. Fluid-loss additives preclude the expulsion of cementing liquid necessary to setting, thus avoiding a too low water-solids ratio. Dispersants reduce the viscosity of the cement slurry, allowing for turbulent flow injection with improved mud removal and cement setting. Spacer fluids physically separate cement and drilling mud and are composed of either plain water or water weighted with scouring materials such as fly ash or perlite.

---

(36) Volume 3, Proceeding:Second Geopressured Geothermal Energy Conference, p. 30.
(37) See Appendix A for a brief description of squeeze cementing.
(38) Volume 3, Proceedings:Second Geopressured Geothermal Energy Conference, p. 27.

Cementing technique now allows for a five-hour pumping process for wells with bottom-hole temperatures not in excess of 260°C (39).

Fertl notes two cementing strategies (40):

- single-stage cementing in which the liner is cemented in one operation, and
- two-stage cementing in which about two-thirds of the liner is cemented in a single operation and the liner top is then given a planned squeeze cementing.

No two cementing firms have the exact same formulation and experts disagree about various ingredients used to achieve desired setting and weighting properties.

Perforation and Packing

Appendix A diagrammatically illustrates the several options available for well completion: a) lined, b) unlined, c) slotted liner, or d) perforated liner. Boyd's hypothetical Gulf Coast geopressured well uses a perforated liner. Boyd notes that this provides the safest and most rapid means of reducing the probability of pipe sticking. Perforated liners can cause problems during the production phase, however. Sand plugging reduces fluid flows and results in downtime during well workover. Geopressured zones in the Gulf Coast are composed of relatively small grained sands so sand production may be a problem.

The best procedure for the design and installation of the production liner is a matter of some debate. Wallace suggests the use of a long interval screen completion with gravel packing, rather than a perforated liner (41). Gravel is used rather than cement in the annular space adjacent to the producing formation. The fluid flows from the formation through the gravel, through the screen, and into the wellbore. Sand production may be decreased with this method. The Dow Parcperdue Louisiana well will be a hybrid using a perforated casing with a gravel

---

(39) Ibid.
(40) Fertl, p. 264. Two-stage cementing is used in deep wells that experience wide variations in pressure.
(41) Telephone conversation with Ray Wallace, March 26, 1980.

pack at producing formation depth (42).

Conclusions

There is little variation between geopressured and conventional well drilling and completion techniques and technology. Conventional petroleum drillers experience temperatures and depths similar to geopressured conditions.

Extreme pressures, however, indicate the need for development of new in-situ logging techniques. In addition, there is a need to experiment with a variety of completion techniques that borrow from conventional petroleum, geothermal, and water well experience. There is a growing recognition of the fact that petroleum experience cannot address every aspect of geopressured well development.

No problems appear unsurmountable. At the same time, it is necessary that upcoming DOE design wells be successfully drilled in order to foster increased industry interest in the resource. Hence it is important that attention be focused on the unique aspects of geopressured drilling and completion.

---

(42) Telephone conversation with Keith Westhusing, March 17, 1980.

DRILLING AND COMPLETION BIBLIOGRAPHY

Anderson, M., "Application and Interpretation of Drill Stem Test," in *Proceedings: Invitational Well-Testing Symposium*, Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 19-21, 1977, pp. 161-174.

Baker, Leonard, Alan B. Campbell, Robert L. Hughen, "Well-Logging Technology and Geothermal Applications: A Survey and Assessment with Recommendations," Sandia National Laboratory Report SAND75-0275, May 1975.

Bellotti, P., and D. Giacca, "Seismic Data can Detect Overpressured in Deep Drilling," *The Oil and Gas Journal*, August 21, 1978, pp. 48-52.

Bellotti, P., and D. Giacca, "Simalog Detects Overpressure While Drilling Deep Wells," *Oil and Gas Journal*, August 28, 1978, pp. 149-158.

Bellotti, P., and D. Giacca, "Pressure Evaluation Improves Drilling Programs," *Oil and Gas Journal*, September 11, 1978, pp. 76-85.

Bellotti, P., and D. Giacca, "AGIP Programs Designed for Drilling Optimization," *Oil and Gas Journal*, September 25, 1978, pp. 123-132.

Bellotti, P., and D. Giacca, "Deep Drilling Operations Protect Sensitive Environment," *Oil and Gas Journal*, October 9, 1978, pp. 73-80.

Berger, Bill, and Kenneth Anderson, *Modern Petroleum--A Basic Primer of the Industry*, Oil and Gas Journal Books, Petroleum Publishing Company, Tulsa, Oklahoma, 1978.

Braden, Mickey W. Jr., and Oscar Goode Jr., "Testing of Geopressured Miocene Sands for the Dissolved Methane Resource in the Tenneco Fee "N" No. 1 Well," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Center for Energy Studies-University of Texas at Austin, GGIS--The Geopressured Geothermal Information System:Geopressured Geothermal Bibliography (Extract), prepared by Thomas Hill, April, 1980.

Considine, Douglas M., Energy Technology Handbook, McGraw-Hill Book Co., 1977.

Crook, Leo, Oil Terms:A Dictionary of Terms Used in Oil Exploration and Development, International Publications Service, New York, 1976.

Dorfman, M.H., W.E. Boyd, "Testing and Sampling Procedures for a Geopressured Well," in Proceedings: Invitational Well-Testing Symposium, Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 19-21, 1977, pp. 72-78.

Eernisse, E.P., T.D. McConnell, A.F. Veneruso, "Development of a High Resolution Downhole Pressure Instrument for High Temperature Applications," in Proceedings: Second Invitational Well--Testing Symposium, Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 25-27, 1978, pp. 41-46.

Fertl, W.H., Development in Petroleum Science, Volume 2-Abnormal Formation Pressures: Implications to Exploration, Drilling, and Production of Oil and Gas Resources, Elsevier, New York, New York, 1976.

Geer, Ernst, and Harold Cook, "Enhanced Gas Recovery from Geopressured Aquifers," presented at the 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston, Texas, October 1-3, 1978.

Geer, Ernst, and John Sharer, "Unconventional Geopressured Gas Recovery, Economics and Research," presented at the 7th Energy Technology Conference, March 24-26, 1980, Washington, D.C..

Geothermal Energy-FY 1979 Programs, FY 1980 Plans, Division of Geothermal Energy-U.S. Department of Energy, Report DOE/ET-0088, August 1979.

Geothermal Energy-Program Summary, Energy Technology Division, U.S. Department of Energy, Report DOE/ET-0101, June 1979.

Geothermal Energy, Research, Development, and Demonstration:Third Annual Report, Federal Interagency Geothermal Coordination Council/U.S. Department of Energy, Report DOE/ET-0090 IGCC-4, March 1979.

Gregory, A. Ray, and Milo M. Backus, "Geopressured Formation Parameters, Geothermal Well, Brazoria County, Texas," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Hankins, B.E., Raymond E. Chavanne, Russell A. Ham, Carroll O. Karkalits, and Joseph I. Palermo, "Results of Flow Tests of Edna Delcambre No. 1: I. Summary of Water Analysis, presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Hottman, Clarence, and R.K. Johnson, "Estimation of Formation Pressures from Log-Derived Shale Properties," *Journal of Petroleum Engineering*, June 1965, pp. 717-722.

Jones, Paul H., "Geothermal and Hydrocarbon Regimes, Northern Gulf of Mexico Basin," in Myron Dorfman and Richard Deller, Eds., *Proceedings:First Geopressured Geothermal Energy Conferences*, University of Texas-Austin, Center for Energy Studies, June 2-4, 1975, pp. 15-89.

Kenyon, W.E., "Oil and Gas Instrumentation," in *Proceedings: Invitational Well-Testing Symposium*, Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 19-21, 1977, pp. 36-43.

Petroleum Extension Service: University of Texas at Austin, *A Primer of Oilwell Drilling*, 3rd edition 1951 and 4th edition 1979.

Petroleum Extension Service: University of Texas at Austin, *A Primer of Oil-Well Service and Workover*, 2nd edition 1968 and 3rd edition 1979.

Riva, Joe Jr., "Two Views of the Production of Natural Gas from Geopressured Deposits," Library of Congress-Congressional Research Service, August 30, 1979.

Science and Public Policy Program, University of Oklahoma *Energy Alternatives: A Comparative Analysis*, Norman, Oklahoma, May 1975.

Stevens, John E., and J. Don Clark, "Completion and Testing of No. 2 Pleasant Bayou Well," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second Geopressured Geothermal Environmental/Laboratory Research Working Subgroup," Houston, Texas, Nov. 3, 1977 (published by GeoEnergy Corporation, Suite 145, 3376 South Eastern Avenue, Las Vegas, Nevada 89109).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second Geopressured Geothermal Drilling and Testing Working Subgroup," Houston, Texas, Nov. 3, 1977 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second DOE/Industry Geopressured Geothermal Overview Group Meeting," Lafayette, Louisiana, Nov. 15, 1977 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting Concerning DOE/General Crude/DOE Contractors-Plans for Brazoria Well," Houston, Texas, Dec. 21, 1977 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the Site Selection Working Subgroup," New Orleans, Louisiana, April 25, 1978 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Site Selection Working Subgroup," Houston, Texas, March 21, 1979 (published by GeoEnergy Corporation, address above)

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the DOE/Industry Geopressured Geothermal Overview Group," Houston, Texas, March 22, 1979 (published by GeoEnergy Corporation, address above)

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Drilling and Testing Subgroup," Houston, Texas, August 1, 1979 (published by GeoEnergy Corporation, address above)

Veneruso, A.F., "High Temperature Instrumentation," in *Proceedings: Invitational Well-Testing Symposium*, Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 19-21, 1977, pp. 46-52.

Wise, Robert L., Ed., *Semi-Annual Report for the Unconventional Gas Recovery Program-Period Ending March 31,1979*, (Morgantown Technical Information Center-U.S. Department of Energy, Report METC/SP-79/8, August 1979).

ENERGY CONVERSION PROCESSES

Introduction

The geopressured geothermal brines of the Gulf Coast contain three forms of potentially exploitable energy:

- chemical energy of methane;
- thermal energy of geothermal heat;
- kinetic energy of high-pressure brines.

Four energy conversion processes utilizing these sources are possible:

- separating the methane from the brine (either in-situ or above ground), and upgrading the quality of the gas to natural gas pipeline requirements;
- converting of the geothermal heat to electricity via steam production processes;
- using the geothermal heat directly; and
- transformating the hydraulic pressure potential to electricity in a turbine.

Over the last several years a number of design and feasibility studies have appeared that describe these processes (1).

This chapter describes the technologies and techniques for energy extraction from and residual control of geopressured brines. As with the previous chapter, technologies and processes similar to current practices in the oil, natural gas, and geothermal industries are described only briefly, while features unique to the geopressured resource are emphasized. As, no commercial or large-scale experimental facilities for energy production from a geopressured well have been constructed, some of the following material will no doubt require updating or

---

(1) See Southwest Research Institute (SRI), Geopressured Energy Availability, EPRI-1457, July, 1980 (work performed under contract with the Electric Power Research Institute), for a listing and partial critique of these studies. The SRI concluded that the studies were not directly comparable because of different resource assumptions and analytical methods.

modification after on-site experience (2).

Before describing these energy conversion processes, a distinction must be made between geopressured geothermal aquifers, and geopressured natural gas formations. Geopressured geothermal aquifers are overpressured water bearing formations containing methane in solution while geopressured gas formations are overpressured reservoirs containing "free" natural gas in a gas cap. Large quantities of natural gas have been extracted from these gas cap zones for many years. These wells, however, only exploit existing gas caps and do not produce large quantities of geothermal brine. When water is encountered in any significant quantities, the reservoir is termed "watered-out" and is usually abandoned. This section examines the geopressured geothermal reservoirs. These reservoirs contain large quantities of overpressured brines that are removed in order to extract heat, pressure, and most importantly, methane in solution (3).

Geopressured/geothermal energy production is, in a sense, a hybrid of technologies from oil and natural gas and those used for geothermal electricity generation. For example, brine water separators are employed widely in oil and gas fields, but the volumes of liquid produced by geopressured aquifers are vastly greater. In terms of geothermal electricity, the technologies are similar, but the fluid temperatures are much lower than sites such as the Geysers or Cerro Prieto. Geopressured/geothermal development can, therefore, adapt much of its technology from current oil/gas and geothermal operations. Nonetheless, there are sufficient differences to indicate that geopressured geothermal development will encounter unique problems.

---

(2) DOE has a number of re-entry (Wells of Opportunity) and new wells under development or contract (see Introduction). None of these wells, however, have been hooked into full-scale surface production units. The Pleasant Bayou No.2 well in Brazoria County, Texas will be the first to have such equipment, and is expected to begin flow testing in the summer of 1980.

(3) The methane production section and methane solubility section (Appendix B) describe the distinctions between solution gas and "free" gas in more detail. Production of methane from a "watered-out" reservoir, may be similar to methane extraction from an orginal geopressured geothermal aquifer, although the latter will probably be under higher temperatures and pressures.

Processes and technologies can also be expected to vary from site to site based upon the characteristics of a given well. Variations in brine salinity and chemistry, formation pressure, and temperature will affect equipment lifetimes, corrosion rates, subsidence, and other operating characteristics. Although some of these variations are described, a comprehensive site-by-site examination is beyond the scope of this report. The major emphasis is directed toward generic technological and process factors, i.e. how useful energy can be extracted from geopressured geothermal aquifers and what problems such extraction will present.

This chapter is organized into six major subsections: start-up, methane production, geothermal utilization, hydraulic conversion, residual control, and well maintenance and workover. This format instead of a detailed description of a single full-scale production facility, was chosen because of the modular nature of the energy conversion processes. This chapter thus examines the components and processes associated with production and waste control systems and tries to provide background on the technology and to point out some of the possible restraints on development of the resource.

Start-up

Following the completion of the well, (as described in Chapter II) the site must be evaluated and prepared for energy conversion. Based upon pre-drilling information, and especially data obtained during the well logging and testing phases, a determination of key reservoir parameters is completed. If methane concentration, brine temperature, brine salinity, reservoir size, porosity, and other factors are sufficiently favorable for commercial exploitation, the well is then prepared for production (4). Availability of markets for natural gas, electricity, and heat for direct applications, as well as the projected rate of return on investment, are also key factors in determining the economic feasibility of a well. However, these later factors will not be

---

(4) The parametric values which yield a commercially developable prospect are not widely agreed upon by industry. This report does not attempt to investigate this issue, except insofar as the values for various physical parameters relate to technological and process considerations

considered in this analysis (5).

Included in the preproduction phases are decisions, not only on whether to begin production, but also on what portion of the brine resource will be used. Will the well be developed exclusively as a methane source, or will geothermal and hydraulic conversion facilities be included ? Technically, there are few, if any, major obstacles to the utilization of several types of energy resources at one well. Methane separation facilities, hydraulic turbines, geothermal electricity plants, and direct use application equipment can all be integrated in the same production facility (6). Figure 1 is a schematic of one possible production facility configuration in which pressure turbines, methane separators, and flashed-steam geothermal electricity units are included at one site.

Two of the major full-range production studies often cited in discussions of geopressured geothermal production technology are those by Brown and Root, Inc. (7) and Dow Chemical USA (8). These studies have served as the base for much of the discussion and analysis of geopressured production appearing in subsequent literature. Lamb et al. have noted, however, that in the Brown and Root and Dow studies

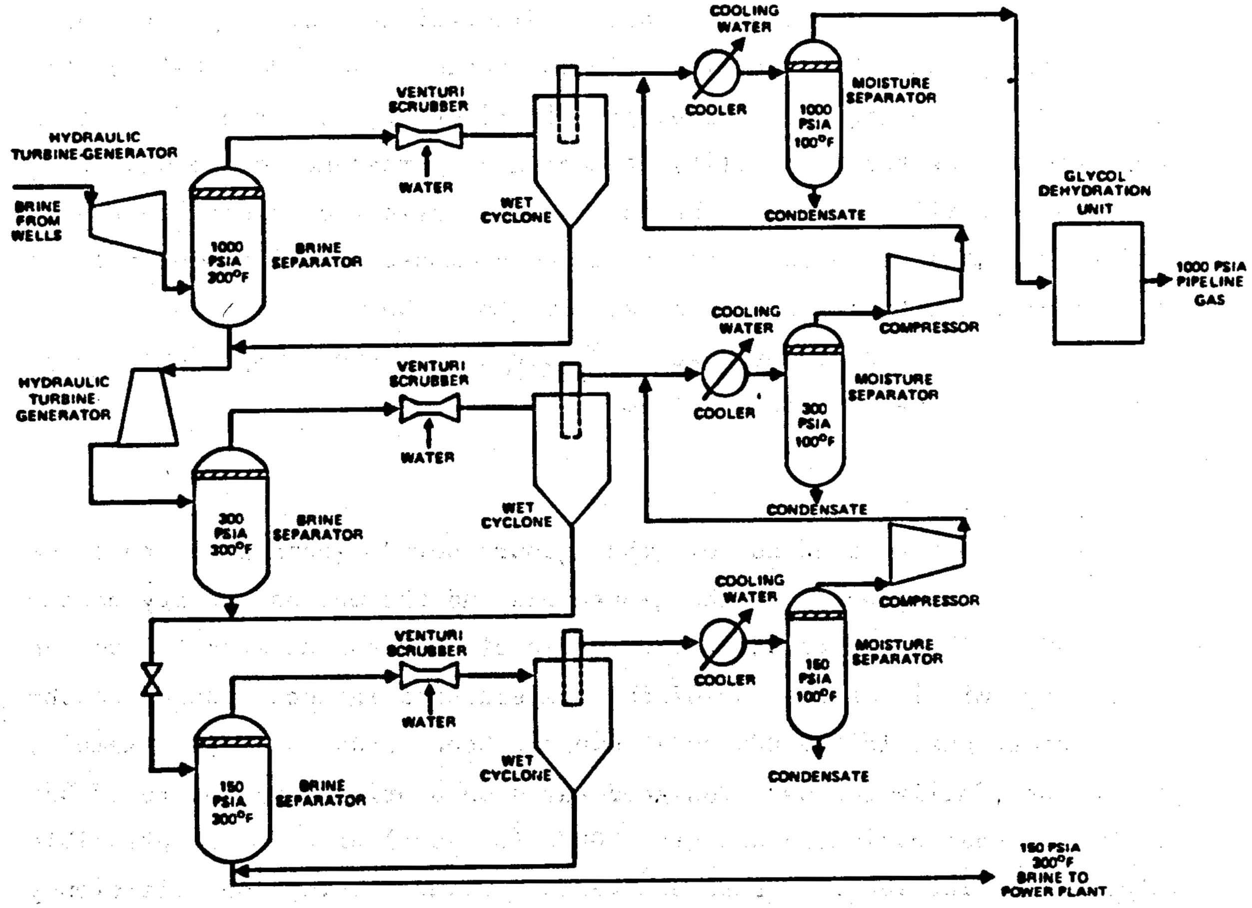
---

(5) See Strongin, Oscar Issue Paper on Geopressured Resource Development Criteria and Industry Incentives, July 26, 1979. for a discussion of rate of return on investment, economic risk, and market availability and their impacts on commercialization of geopressured geothermal resources.

(6) This does not mean that these pieces of equipment are operationally independent of each other. Process optimization for methane production, for example, may mean a less than optimal geothermal electric or geohydraulic output. In addition, the physical location of production units along the brine stream affects system output. Parker Lamb and his colleagues at the University of Texas at Austin are currently researching process optimization.

(7) Surface Technology and Resource Utilization, in Proceedings of the Second Geopressured Geothermal Energy Conference-Volume IV, Appendix A, University of Texas-Austin, February 23-25, 1976.

(8) Ibid, Appendix B.



Natural Gas Separation Process for a Flashed Steam Power Plant

Figure 1

Source: Southwest Research Institute, 1980

> "it was necessary to specify a priori all major independent parameters affecting the design such as total plant output, number of wells and their flow rates, wellhead conditions, etc. Hence, no evidence was developed which would indicate whether the proposed designs represented optimum utilization of the resource." (9)

For these reasons, the ultimate configuration(s) of a geopressured geothermal production facility remains speculative. Nonetheless, the overall design configuration presented in Figure 1, plus the facilities described in the two feasibility studies give a reasonable approximation of surface facility design. The one major modification since the publication of these studies is the decline in importance of geothermal and geohydraulic electric facilities relative to methane separation.

The following sections describe aspects of the component energy production and waste control system.

Methane Production

Several early studies of the geopressured geothermal resource placed equal emphasis on the geothermal and the methane energy potentials (10). This emphasis was the result of what now appears to be an overly optimistic estimation of the temperatures in geopressured geothermal formations. In the DOW and Brown and Root studies, for example, production facilities were designed based on a brine temperature of 350 ^{o}F. More recent estimates now give 300^{o}F (or less) as a more plausible value (11). The lower temperature means a lower conversion efficiency for geothermal electric generation, and a decline in methane solubility

---

(9) Lamb, J. Parker, Gary Polansky, and Stephen R. Bradley, "Conceptual Design Studies of Energy Conversion Plants Using Geopressured Fluids," presented at the Fourth United States Gulf Coast Geopressured/Geothermal Energy conference Austin, Texas, October 29-31, 1979 (in press).

(10) See especially the Proceedings of the Second Geopressured/Geothermal Energy Conference Volume IV, "Surface Technology and Resource Utilization, for the Dow and Brown and Root feasibility studies (Appendix A and B).

(11) The Southwest Research Institute, op cit., p. 5; estimates that the temperature gradient in the Gulf Coast varies from 1.4^{o}F to 2.0^{o}F per 100 feet of depth (moving from South Texas to Louisiana). However, they also note that, "the highest temperatures are associated with minimum sand deposition. Good reservoirs-type sands apparently seldom occur at depths greater than those at which temperatures are 300^{o}F or so."

(12). However, because the price of methane has increased dramatically over the last several years the relative price effect makes geothermal electric generation much less attractive. Hence, the present emphasis on geopressured geothermal brines as primarily a source of methane gas rather than a source of thermal or kinetic energy (13). A recent examination of the commercial feasibility of geopressured geothermal brines concluded that:

> " The current general consensus among almost all investigators is that the feasibility of geopressured resources rests on the technical and economic potential of methane extraction with thermal and kinetic energy only of marginal value." (14)

Commercial development of the geopressured brine resource as a source of methane gas involves two operations; production of the methane by surface separation or the rapid drawdown process (RDP) and dewatering and cleaning of the produced gas for introduction into natural gas pipeline systems. The latter operations use processes and facilities common to much of the "conventional" natural gas industry, while the former require techniques and technologies unique to geopressured brines. Nonetheless, neither phase appears to present any major technological problems, beyond those encountered when faced with an extremely large flow of hot high-pressure liquid.

Gas Separation Processes

---

(12) See Appendix B for a discussion of the issue of methane solubility and its relationship to brine temperature, pressure, and concentrations of total dissolved solids (TDS).

(13) Even the earlier feasibility studies considered the kinetic energy potential, represented by the high pressure of the brines, to be of minor importance. This is largely because the pressure would be expected to drop off quite rapidly (one to two years) relative to the the decline in brine temperature or methane content. See the section on hydraulic conversion below for a more detailed discussion of this phenomenon.

(14) Strongin, op cit., p 7.

There are three methods that can be used to separate methane from geopressured brines. These are:

- Pressure drop and evolution of the gas out of the brine stream;
- Gas stripping; and
- Liquid solvent extraction

Pressure drop

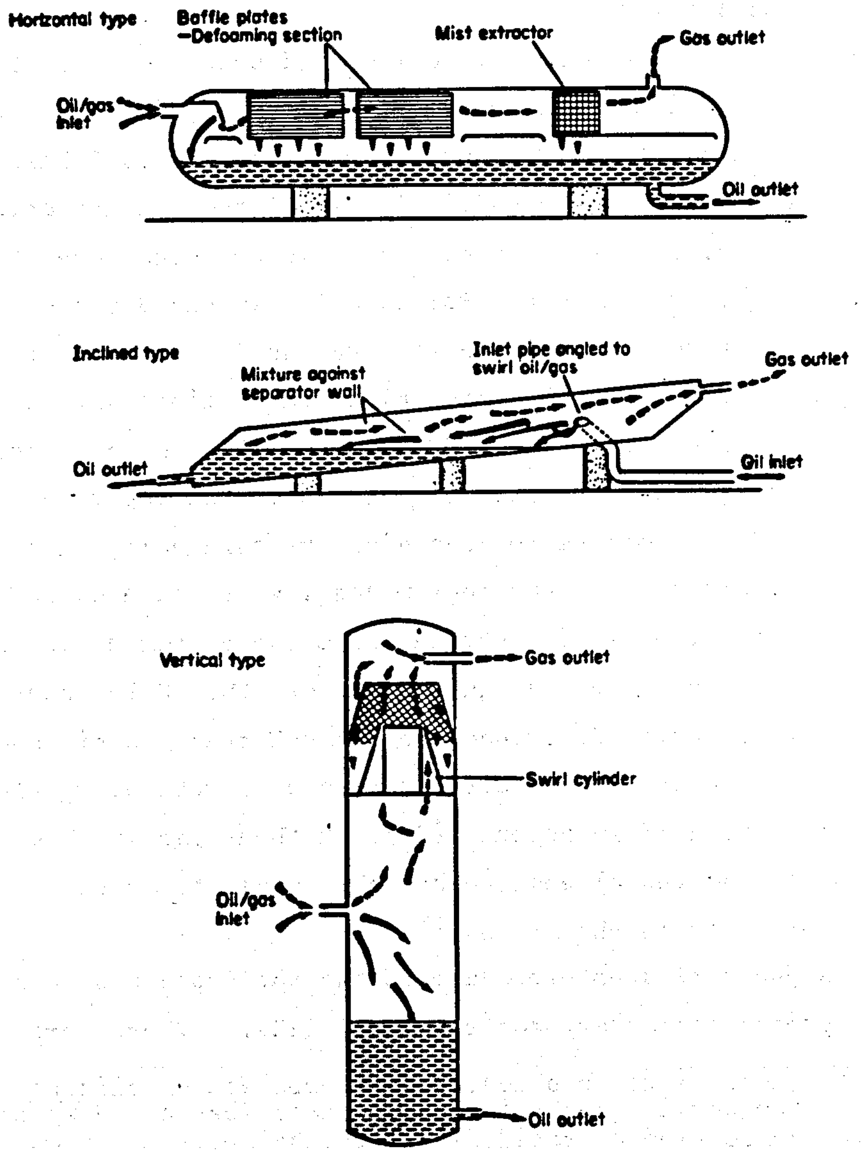
Pressure drop separation of methane gas from aqueous solutions is a relatively common practice of the oil and gas industry. Natural gas is very often found with both petroleum liquids and salt water, and separation is required before the gas is utilized (15). Figure 2 illustrates some of the types of oil and gas separation units now in use. Pressure drop production takes advantage of a basic property of methane gas in solution. As pressure decreases, the equilibrium solubility of methane decreases and some the gas moves out of solution and into a gaseous phase.

The basic design of the separator is quite simple. The brine stream enters at one end, a pressure drop occurs as the volume increases, gas is extracted from the top, and the brine stream exits at the bottom.

Surface separation of methane from geopressured geothermal brines is significantly different in scale from standard gas production processes. Both the high rates of flow and the high wellhead pressures expected in geopressured wells affect the technology and processes to be utilized. Flow rates of 40,000 or more barrels of brine per day and wellhead pressures of 3,000 to 6,000 psia can be expected at a wellsite. By contrast oil well flow rates of a few hundred to several thousand barrels per day are typical and wellhead pressures are often orders of magnitude less than geopressured values (16). Consequently, the ratio of brine produced to methane gas is much greater than in a typical oil and gas well and the corrosion, scaling, erosion, and pressure effects,

---

(15) University of Oklahoma, <u>Energy Alternatives: A Comparative Analysis</u> May 1975 p 4-12.
(16) Chenault, Roy L., "Oil and Gas Field Exploration", <u>Encyclopedia of Energy</u> 1978 p. 512 and 513.



Separators

Figure 2

Source: Crook, 1976

etc. on the separation equipment are correpondingly increased. Resolution of these problems on a long-term basis must await actual field experience, and will depend on the characteristics of a given well and its brine composition (17).

The surface pressure drop method is based upon the solubility of methane gas at various pressures. At 1,000 psia about 80% of the methane that is in solution at 10,000 psia or greater is liberated from the brine, and at 150 psia essentially all of the methane comes out of solution (18). Most of the proposed design schemes make use of a cascade series of separation units. For example, in the Southwest Research Institute design three separation units are used, one at 1,000 psia inlet pressure, one at 300 psia inlet, and a final unit at 150 psia (19). Based on a flow rate of 50,000 bbl/day, and a methane concentration of 35 scf/bbl, the respective flow rates of the separators would be approximately 1000 scf/minute for the high pressure unit, and approximately 225 scf/minute for the medium and low pressure units combined. This would be a total of 1.75 mmscf/day of methane from a single production well (20). Although no design data for the SRI separators is given, a similar unit described in the DOW study consists of a drum vessel with fluid inlet at the bottom moving at a rate of 2 ft/sec with a mean residence time of 10 seconds (21). Methane gas is then withdrawn from the top of the vessel and the brine is piped to another separator, hydraulic turbine, or geothermal unit.

A second pressure drop procedure is the the Rapid Drawdown Process (RDP). This procedure is very controversial (22). There are two RDP

---

(17) Corrosion, scaling, erosion, and temperature effects on geopressured geothermal technologies and processes are discussed in detail in the section on residual control below.

(18) Haas, John L.,"An Empirical Equation with Tables of Smoothed Solubilities of Methane in Water and Aqueous Sodium Chloride Solutions up to 25 Weight Percent, 360°C, and 138 MPa." (United States Department of the Interior-Geological Survey, Open File Report No. 78-1004). See also Appendix B of this report.

(19) Southwest Research Institute op. cit., p 62.

(20) For comparison, a single well drilled into some geopressured natural gas formations (i.e. an overpressured gas cap, not a geopressured aquifer) in Louisiana gas field can produce upwards of 20 mmscf per day. (May 2, 1980 visit to Cheveron wellsite near Baton Rouge, Louisiana)

(21) op cit., 2nd Conference Volume IV, Appendix B, p.17.

processes that have been considered: 1) rapid depressuring of a well in order to form an "artificial" gas cap as methane moves out of solution in the reservoir, and 2) production of interstitial gas that may exist in conjunction with brine waters.

One method of gas production using the RDP method has been patented by the Transco Energy Company of Houston. (U.S. Patent No. 4,042,034, August 16, 1977). The patent is based on the theory that gas can exist in three forms in a geopressured geothermal aquifer: as methane in solution in the brine, as a gas cap above the brine, and as interstitial gas occuping from 10 to 35% of the reservoir pore volume (23).

The patent describes a process of well operation in which the percentage of gas that can be recovered from a geopressured well, with an initial zone of free gas, can be increased. The patent estimates that a conventional brine flow and surface separation process would yield no more than 3% of the original gas in place in the formation. Under the Transco process the recovery factor is claimed to increase to 14% of the original gas in place. Such a fourfold increase in methane recovery would mean a substantial increase in the economic viability of geopressured resources. The patent describes the process as follows:

> "Whether or not an initial gas phase exists in a geopressured aquifer, a gas phase is created by lowering the pressure in the aquifer initially containing only gas saturated water, and then the same gas-phase saturation would exist as if it were there initially....When the gas phase starts moving towards the well bore, it is expected that the buoyant effect of the gas causes the bubbles to rise, and a movement of this type would create a higher gas saturation at some locations in the aquifer....Increased gas saturation under the layers could provide conduits for gas flow towards the wellbore."

To reach such conditions it is necessary to flow the well at a high rate (at least 15,000 bbl/day) and create a bottom-hole pressure drop of at least 25% of the initial formation pressure. Figure 3, adapted from

(22) The Parlange and the Edna Delcambre wells both exhibited methane production characteristics that form a prima facie case for the possibility of in situ separation of methane and/or the existence of "free" gas or a formation gas cap. However, neither of these wells were specifically designed to prove or even test the feasibility of in-situ or low flow gas production.
Leo A. Rogers and Philip L. Randolph have made a strong argument against the in-situ separation of gas at the Edna Delcambre No.1 well. Their analysis, which contends that the higher than expected gas to water ratio was due to leakage from adjacent formations, is found in: "Ratio of Produced Gas to Produced Water form DOE's Edna Delcambre No. 1 Geopressured-Geothermal Aquifer Well Test", presented at Proceedings: Fourth United States Gulf Coast Geopressured-Geothermal Energy Conference: Research and Development, Austin, Texas, October 29-31, 1979.

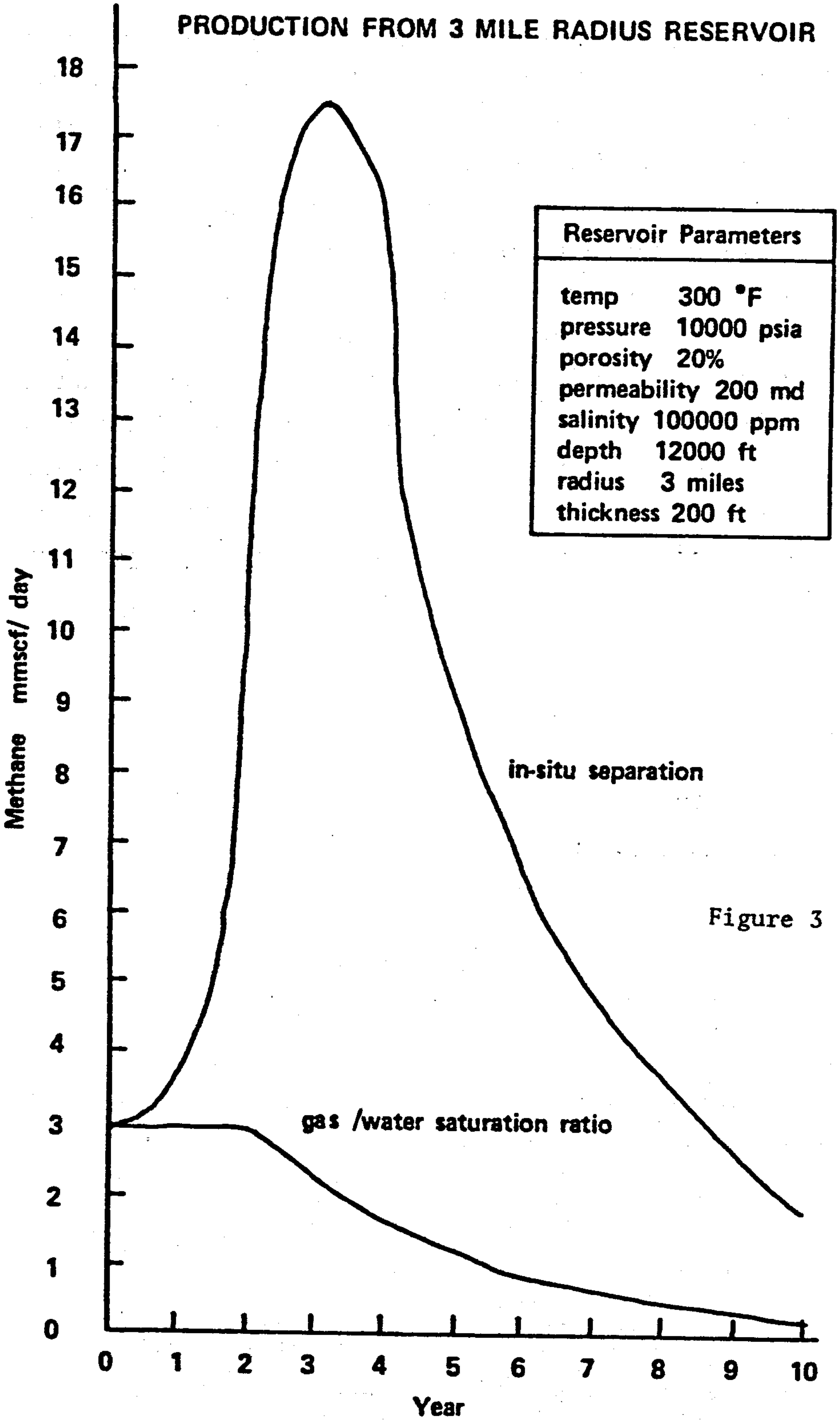


Figure 3

XBL 808-1834

Source: U.S. Patent No. 4,042,034

the patent application, displays the substantial difference in recovery factors between the conventional well and the pressure drop process. Note also that although the total amount of brine flowed in both cases is the same, the higher recovery factor of the pressure drop procedure, significantly decreases the brine-to-methane production ratio . Surface processes for the collection of the gas liberated from the well under free flow conditions are not described in the patent, but presumably they would combine conventional surface methane separators and natural gas collection units employed at "normal" gas wells.

Gas stripping

Gas stripping involves the desorption of a dissolved gas, in this case methane, by means of a stripping agent gas. The process is widely used in industry and would present no technical problem of note. Quong and his associates at the Lawrence Livermore Laboratory have investigated the feasibility of gas stripping as a means of producing methane from a geopressured brine stream while maintaining the fluid at a high pressure (24). They identified N_2 and the halogenated hydrocarbon, dichlorotetrafluoroethane (Freon 114®) as candidate stripping agents. Though technically feasible, gas stripping is too costly to be utilized at this time.

Liquid solvent extraction

---

(23) The Transco patent is for conventional geopressured reservoirs, from which natural gas has been produced to the point where the reservoir is now "watered-out." This in effect transforms the reservoir into a geopressured aquifer.

(24) Quong, R.; L.B. Owen, and F.E. Locke, "Potential Methods for Methane Extraction from Geopressured Brine at High Temperature and Pressure," UCRL-84064, Preprint, June 2, 1980.
As the title of the paper indicates, the research is directed toward separation processes that can be utilized while maintaining the brine at a high pressure. The purpose of this procedure is to decrease the pressure differential between the wellhead and the brine injection well, thus decreasing the energy required to repressure the brine for disposal. See the residual control section below.

Liquid solvent extraction is also being investigated by the research group at Livermore. The results of their work are reported in the same publication (25). The liquid solvent process is similar in principle to gas stripping except that a liquid rather than a gaseous stripping agent is used. Quong et al. describe their process as follows:

> "A high-boiling point paraffinic hydrocarbon is contacted with the brine in an extraction tower. Methane, being more soluble in the hydrocarbon, is extracted and subsequently recovered in essentially pure form by depressurization of the extract. Solvent loss is controlled by selecting a low-vapor-pressure compound." (26)

The most promising hydrocarbon so far identified is hexadecane. Unlike gas stripping it appears to be economically viable. Because it is desirabe to maintain a high pressure for reinjection, the liquid solvent extraction method merits further examination.

Gas processing

Following the brine-methane separation (by either surface or insitu processes), the gas must then be upgraded and repressurized for injection into a natural gas pipeline system. Dewatering of the gas will probably be the major upgrading process required, as excess water in pipelines can cause corrosion, decrease line capacity because of the partial pressure of water vapor, and lead to the formation of solid hydrates that plug constricted areas of the pipeline. For these reasons pipeline natural gas should contain no more than 110 to 170 ppm by weight of water (5 to 7 lbs H_2O/mmscf CH_4). Dewatering of natural gas is a standard industry practice usually employing glycol separation units that are readily available on the market. These packaged units consist of a absorber chamber where a methane gas stream and a glycol stream mix. Water vapor is absorbed by the glycol solution which then is circulated through a second loop where the water is stripped out.

---

(25) Ibid.
(26) Ibid.

A problem with geopressured brines is the potential for carry over of salt mist into the glycol separation unit, resulting in serious corrosion to the unit. In fact, SRI notes that "[m]ist elimination to minimize salt carry over is the only area [in surface separation processes] requiring [technological] development (27). This is because brine droplet sizes are not well understood and techniques and equipment requirements vary according to size. Possible pre-dehydration units could include venturi and cyclone scrubbers, but until droplet size specifications have been established specific design remains uncertain.

In addition to dewatering, it may also be necessary to remove non-condensible and potentially hazardous gases, such as H_2S, from the methane stream. Constituent analysis of completed wells indicate that these gases are minor. For example, analysis of the Edna Delcambre well showed a hydrogen sulfide concentration of 1 ppm by weight (28). If removal appears necessary the addition of an amine solution to the glycol dehydrator would probably be sufficient to clean up the gas.

Following dewatering and clean-up, the methane must be pressurized for injection into the pipeline. Pipeline pressures from 600 to 960 psig are common, with a few lines operating at pressures in excess of 1,000 psig (29). Sizing of compressors for this process may present some problems as well-head pressures decline over time, although declines below 1,000 psia are unlikely until late in the life of the well.

Availability of natural gas pipelines at or near the well site is an important consideration. No studies of the transportation requirements for geopressured natural gas appear to have been done. Nonetheless, the many oil and gas lines already in place in the Gulf Coast region should be be adequate. Natural gas distribution companies should also have an economic incentive to invest in new feeder lines if their main lines are operating at less than capacity. The more gas they can move the larger the base over which they can amortize their capital costs (30).

---

(27) Southwest Research Institute op. cit., p 70

(28) See the section on air pollutants in "Second-Order Impacts" for more detailed constituent analysis.

(29) University of Oklahoma, op. cit., p 4-23.

(30) Strongin, Oscar, op. cit.

Geothermal Utilization

As a geothermal resource, brines can be utilized both for electric generation and as a source of direct heat for process or other applications. The key factor in determining the usefulness of the brine as an energy source will be its temperature. The higher the temperature, the higher the efficiency of electricity generation and the greater its utility for direct use applications. As noted above, early studies of the resource estimated that brine temperatures would range up to 325°F or 350°F, while more recent examinations indicate that 250°F to 275°F are more realistic estimates. These lower temperatures imply that: 1) electricity generated per unit of brine input will be less, and 2) "waste" heat rejection per unit of energy produced will be greater. Production units, therefore, must be sized upward to yield the output that would be available at a higher temperature, and cooling towers or ponds would have to be designed to handle a large heat load.

Use of geothermal waters, as opposed to geothermal vapors, for electricity production does not utilize a new technology. The Wairakei field in New Zealand, and the Cerro Prieto field in Mexico are both major "liquid dominated" geothermal electric facilities that have been in operation for many years. Major differences, however, exist between these fluid-dominated facilities and those that might be developed for geopressured geothermal brines. Both the Wairakei and the Cerro Prieto units utilize much higher temperatures than those available (even under very optimistic conditions) at geopressured sites. The Wairakei field yields fluids at approximately 235°C (455°F) and the Cerro Prieto field temperatures are even higher, ranging from 250°C to 350°C (482°F-662°F). Formation pressures are also lower by an order of magnitude or more (e.g., 550 psia at Wairakei).

There are three systems that could be used for the generation of electricity from geopressured brines:

- the flashed steam process;
- the binary heat exchanger process; and
- the total flow concept.

The total flow concept is currently being researched, but remains in the experimental stage. Therefore, it is not examined further in this report.

Flashed steam

The flashed steam process is based upon the property of superheated water to rapidly change phase (flash) from a liquid to a gas under reduced pressure conditions. Thus water will remain in a liquid state at 300°F and 1000 psia, but will change into steam once the pressure is reduced to atmospheric conditions. This is the process that is currently employed at both the Wairakei and Cerro Prieto sites. In terms of an integrated geopressured production facility (e.g., kinetic, chemical, and thermal energy utilization) one or more flashing vessels would be put in line after the methane separation units. In the Dow design with an input brine pressure of 150 psia, temperature of 300°F, and a flow rate of 50,000 bbls/day, the liquid is flashed at atmospheric pressure and generates 60,000 lbs of steam per hour. This steam is then piped to a turbine with an exhaust outlet of 111°F and a pressure of 1.3 psia (31). Net output from this system was calculated to be 1.4 MWe per well.

Binary cycle

In the Brown and Root design binary system, heat from the geothermal brine is extracted by a heat exchanger and a secondary working fluid (most likely isobutane or a similar low-boiling-point fluid). This secondary fluid is then be used to drive a turbine and generate electricity. Output from a well with the same input parameters as that described above has been calculated to be 1.6 MWe (32).

---

(31) Second Conference, Volume IV, op. cit., Appendix B.

(32) However, John Hamiliton of Dow, in an interview with Oscar Strongin, notes that a binary cycle facility with fluid input at 365°F and a isobutane working fluid does not appear to be feasible as a electricity generation source. Presumably, this refers to economic and not technological feasiblity.

Cooling

Both the flashed steam and binary systems require cooling water facilities. Possibilities are a wet cooling tower, a dry tower, a cooling pond, or some combination of the latter two. Choice would be based on requirements for regulatory compliance, economics, etc. Technically, there appear to be no major differences between a cooling system designed for a geothermal electric generation plant and that designed for a geopressured geothermal electric generation plant. Only the size per unit of electricity output would have to be different due to the efficiency differences described above. In both cases (conventional geothermal and geopressured), corrosion and scaling in cooling components, especially heat exchangers, are of major importance. Mitigation strategies are described below.

Scaling, Corrosion, and Erosion

The most significant problems to be faced in geothermal electricity generation are those arising from the high pressure and temperatures. Scaling, corrosion, and erosion of equipment are all factors to be considered when designing a facility. Unfortunately, little more than broad generic statements can be made because of the site-specific characteristics of each well. Factors to be considered include brine temperature, and salinity, presence of sand in the brine, presence of corrosive gases such as carbon dioxide and hydrogen sulfide, and flow rates (33).

Scaling is largely the result of silica saturation of the brines. Deposition is most likely to occur in the expander portions of the system and throughout the cooling and reinjection systems (34). Scaling may also be a major problem if it occurs on the heat exchanger surfaces as it decreases the efficiency of heat transfer.

---

(33) 2nd Geopressured/Geothermal Conference, op. cit., Vol 4, chapter 11.

(34) House, P.A., P.M.Johnson, and D.F., Towse, <u>Potential Power Generation and Gas Production from Gulf Coast Geopressured Reservoirs</u>," UCRL-51813 May 27, 1975, pp. 18-19.

Corrosion and erosion of the turbine blades, in a flashed steam system, can result from the presence of various gases and solids in the brine. These agents include oxygen, sand, and hydrogen sulfide. Corrosion can be lessened by the use of proper alloys adapted to the given chemical and physical conditions in a well. Erosion prevention requires the use of sand settling and entrapment units and the use of erosion resistant materials. In both cases the experiences from existing geothermal facilities will provide valuable guides to mitigation strategies.

Plant Size

Large geothermal electric units (25 MWe or larger) are no longer seriously considered. Current opinion is that electricity generated from geopressure resources may only supply on-site power requirements (35). In addition, it has been noted that many of the sites, especially those in Louisiana, are often located in marshlands far from transmission lines or local markets. This may make electricity generation for inclusion in the local or regional grid system prohibitively expensive.

Direct Use Applications

Direct use applications of geothermal heat have received increasing attention in the literature over the last few years. Given the diversity of applications and the possible remote locations of wells, such applications are not considered here.

Hydraulic Conversion

The wellhead pressure of a geopressured brine stream can be used for the production of electrical energy. A hydraulic turbine or series of turbines, depending on the wellhead pressure and brine flow rate, could be used for electricity generation. These turbines would be basically centrifugal pumps designed to operate in the reverse mode and

---

(35) Strongin, Ocsar, op. cit.

connected to a generator. Output from these units under typical operating conditions in a new well, e.g., 40 to 50,000 bbl/day and a wellhead pressure of 3,500 to 4,000 psia, has been estimated to be 1.5 MWe, with a fall in this value as formation pressure declines (36).

Turbine design per se should present no major problem; however, several factors tend to decrease the long term energy potential of geohydraulic turbines. First and foremost is the decline in formation pressure that will occur with time. It is anticipated that after several years of well operation the pressure of a formation will begin to drop. How large such a pressure decline will be depends on several factors: the size of the reservoir, the presence or absence of shale dewatering, reservoir compression or other repressuring phenomena, and the likelihood of deep reinjection of brine. The significance of declining formation pressure is that turbines must be sized to accommodate maximum pressures encountered during the earliest years of well production, and, therefore, would be oversized as formation pressures begin to drop. SRI estimates that it would be economic to continue hydraulic generation of electricity until the formation pressure drops to 40% of its initial value (37). One possible solution to this problem, given that there are a number of wells in operation at various stages in their commercial lifetime, is the use of modular units that are sized for different operating pressures and that could be moved from site to site as pressures declined.

Two-phase flow may also present a difficultly in successful operation of geohydraulic turbines. As noted in the section on methane production, declining pressure of the brine solution decreases methane solubility, causing the methane to migrate out of solution and into a gaseous form. This process leads to the formation of gas pockets in the turbines (cavitation), which is known to be a potentially serious strain on operating turbines. Additionally, two-phase flow in a hydraulic turbine would decrease conversion efficiency to 50% to 75% (38).

---

(36) Southwest Research Institute op.cit., p. 67,
(37) Southwest Research Institute, op.cit., p 68.
(38) J. Parker Lamb, et al., Ibid.

Erosion of the blades may be a serious problem, especially since geohydraulic turbines will be located near the wellhead and consequently close to a possible source of sand. The magnitude of this problem is not known. At a minimum, sand settling and filtration units are required upstream from the turbine(s). Corrosion and scaling should also be considered, but their effects on the turbines have not been well established.

Residual Control

The control of residual by-products from geopressured geothermal wells will be of major importance in the overall operation of the production system. Gaseous emissions, water pollutants, solid wastes, and noise are the chief by-products of concern. Gaseous pollutants, solid wastes, and noise outputs are expected to be minimal (39). The technology required to control these residuals, if required at all, should be small, relatively inexpensive, off-the-shelf units. Consequently, control of air, solid waste, and noise pollutants are of minimal concern technologically and are not examined further in this section.

Water emissions (brines), however, present an entirely different problem, because of their magnitude relative to the other residuals produced. Vast quantities of brackish water extracted from the deep geopressured aquifers will have to be disposed of in a manner that both minimizes disposal cost and does the least damage to the surrounding environment. Disposal technology is not new, but the volume of fluid to be disposd of presents a challenge.

Brackish water is encountered in production at many oil and gas fields, and disposal of this saline water has been a normal procedure in the industry for decades. Many chemical and other industries also dispose of large quantities of brine and liquid wastes. Typically, these fluids are reinjected into the ground through disposal wells. In oil or natural gas fields, injection can occur either at a level above the production formation or directly into the original formation (40). Figure 4 illustrates the design of a typical shallow salt water disposal

---

(39) The nature and possible impacts of these elements are described in more detail in the chapter on second-order environmental impacts.

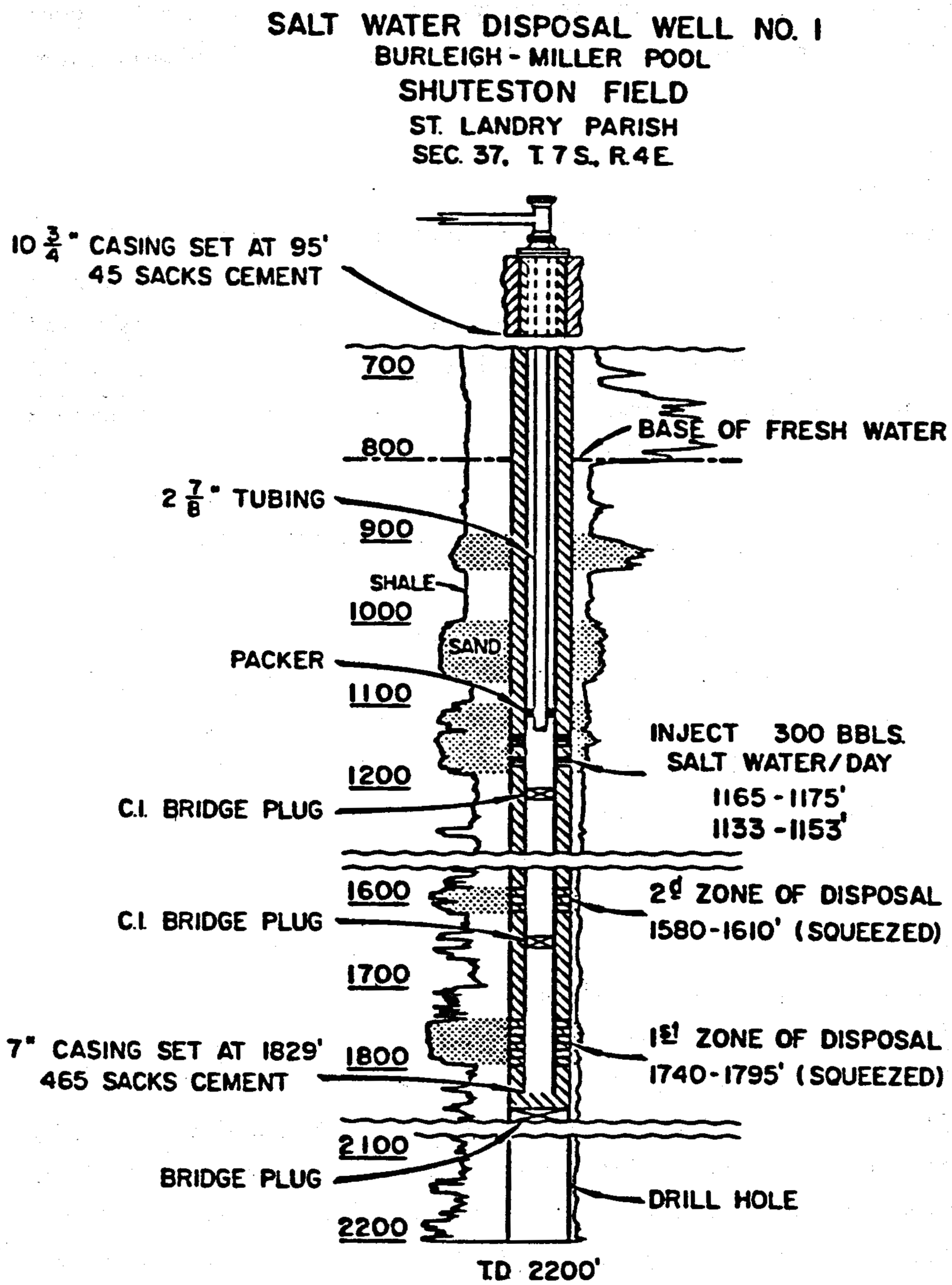


Figure 4

Source: Southwest Research Institute, 1980 well found in the oil and gas industry. Disposal of brine from a geopressured geothermal formation will be similar to oil/gas field and industrial disposal practices. The amount of brine to be disposed of, however, requires modification of these practices. The state of Louisiana, in a survey of 1,587 salt-water injection wells in use in the state in 1972, noted that the average daily injection rate was 1,306 barrels per day per well, or less than 10% of the injection rate planned for most geopressured disposal wells (41). The brine produced from a single geopressured well (up to 50,000 barrels per day) may be equal to or greater than the brine output from a large field of oil and gas wells. Over a 30-year lifetime one geopressured geothermal well operating in the conventional high flow mode may produce more than 1.5 billion barrels of water (63 billion gallons). A field of geothermal wells providing "fuel" for a single 25 Mwe electric generation plant could require from 10 to 12 production wells (42).

Provisions must also be made for brine control under emergency conditions. These can include a well blowout, the rupture of a pipeline, or the failure of the normal disposal units. In a blowout condition estimates are that a single geopressured well, depending on the formation pressure and the well casing diameter, may flow as high as 140,000 bbl/day. If the temperature of of the formation is 300°F, 16,000 barrels/day would flash to steam (43). Facilities to handle blowout or

---

(40) Considine,Douglas (ed.), Energy Technology Handbook, 1977; "Petroleum Technology," p.3-142.

(41) Southwest Research Institute, op cit., Appendix C, "Louisiana State Salt Water Disposal Regulations."
See Harold C. Corbell's article, "Salt Water Disposal Operations: North Markham-North Bay City Field, Matagorda County, Texas," in Proceedings: Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, Louisiana State University and Louisiana Department of Natural Resources, Baton Rouge, Louisiana, March 6-7, 1979, for a description of the operation of salt water disposal operations at an oil field. At present the field disposes of 60,000 bbl/day into 15 wells. The maximum injection rate into a single well is 8,500 bbl/day and the maximum pressure (under Texas law) is 400 psia.
The Conservation Division of the Lousiana Department of Natural Resources notes that the production of water in association with oil and gas varies tremendously from area to area. Some fields have no significant water production while others may have ten times a much water produced as oil.

(42) Brown and Root and Dow studies, Ibid.

(43) RPC Inc., An Analysis of the Ecological Effects of Geopressured Geothermal Development. Austin Texas, July 1979 pp 23-26.

reinjection/surface disposal facility failure will probably consist of holding ponds capable of containing, at a minimum, several days total production, i.e. one-half million barrels or more (44).

Three methods for brine control under non-emergency conditions are under consideration (45).

- Surface disposal of the brine Gulf Coast waters
- Reinjection of the brine into the original production formation
- Reinjection of the brine at a level below potable aquifers but above the production formation.

Each has been examined in the published literature. One particularly important source of information on the potential technical problems of subsurface disposal is the Proceedings of the Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, held at Louisiana State University on March 6-7, 1979. This workshop was the first, and apparently the only, attempt to address the problems of spent brine disposal in a comprehensive manner (46).

Surface Disposal

Surface disposal of spent brines, i.e., dumping into the waters of the Gulf Coast, should not present any major or unique technical problems. That is not to say, however, that surface disposal would be an inexpensive or premissible procedure. The only conceivably allowable

---

(44) 500,000 barrels or 21 million gallons represents approximately 65 acre-feet. A holding pond to contain this volume would have to be 7 feet deep and cover nearly ten acres.

(45) A fourth method, use of geopressured brines for process applications such as pulp production, has also been mentioned. In practice this method only delays the disposal process. After process applications the fluids must still be disposed of in an environmentally and economically acceptable manner.

(46) A summary of the major conclusions and recommendations developed at the workshop is given in the the paper "Subsurface Disposal of Geopressured Fluids: Potential Geological and Operational Problems with Recommendations for Disposal System Testing", by Ann L. Bachman , and C.G. Smith, presented at the Fourth United States Gulf Coast Geopressured-Geothermal Energy Conference: Research and Development, (Austin, Texas, October 29-31, 1979, in press)

method for moving the brine to the Gulf would be by pipeline, as open channels would not environmentally acceptable. Such pipelines would have to cross existing pipelines and other transportation systems that run parallel to the coast and would also have to be constructed so as not to adversely impact ecologically fragile barrier islands. In addition, the Gulf Coast is subject to extremely violent tropical storms and the line would have to be capable of withstanding such events (47).

Finally, disposal of brines in Texas and Louisiana waters would require state permits, as well as discharge permits under the Federal Clean Water Act. Piping of brine solutions into Gulf Coast waters is already occurring as part of the Department of Energy's Strategic Petroleum Reserve (SPR) Program, with flow rates of up to one million barrels per day anticipated (48). Thus surface disposal involves regulatory, institutional, and environmental questions rather than purely technical ones. The brine can be disposed of in the Gulf of Mexico; whether it will or should be permitted is the key question (49).

Adequate dispersion and dilution of the waste fluids is one major technical problem (other than pipeline construction). There is substantial disagreement about the dispersion in the Gulf Coast of SPR brines once they are released from the pipeline (50). Although geopressured brines may not be of the same density, temperature, and chemical composition, many of their dispersion characteristics may be similar. Careful modeling and monitoring of the dispersion plumes of SPR brines should provide useful information for evaluating the movement of geopressured

---

(47) Conversation with Tom Gustavson, Bureau of Economic Geology, Austin, Texas, April 28, 1980.

(48) Conversation with Al Waterhouse of the Office of Strategic Petroleum Reserves, New Orleans, Louisiana May 1, 1980 and site visit to Bryan Mound, April 30, 1980.

At present only the Bryan Mound site is discharging brines into the Gulf. Discharges are released in a batch mode, i.e. non-continuously, at the rate of 200,000 + barrels per day. The brine is pumped from the near shore site to twelve miles offshore, where it is released through a number of pipeline diffusers. The rated capacity of the line, which has not yet been reached, is more than 600,000 bbl/day.

(49) The environmental impacts of brine disposal in the Gulf are many and complex. These impacts are examined in detail in the brine impacts chapter.

(50) Conversations with Al Waterhouse, Larry de la Bretonne, and Brian Luckenow.

fluids. Information derived from this monitoring and modelling process could then be used to determine optimal diffuser design, flow rates, etc.

Deep Reinjection

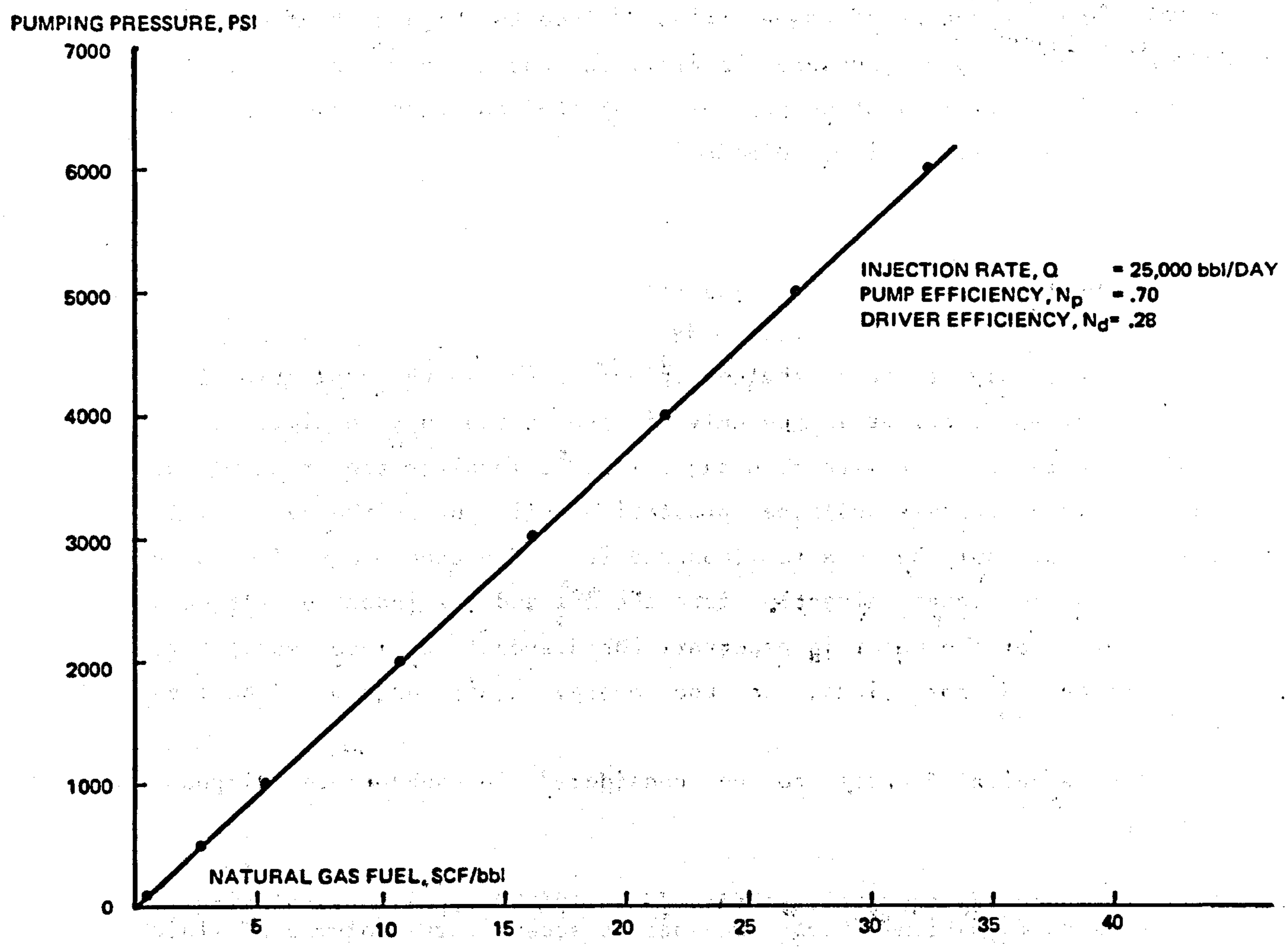
Deep injection (return of brine to its original depth) has a number of desirable characteristics.

- Reinjection back into the production formation minimizes the adverse chemical or thermal impact of the brine on groundwater aquifers, surface ecosystems, and other potentially environmentally sensitive areas.
- The brine could possibly repressure the formation and improve the ultimate amount of brine and, therefore, methane produced. (51)
- Repressuring of the deep formation might offset some of the problems of subsidence

Nonetheless there remains one major consideration which probably precludes reinjection of the brine to original depths; too much energy is required to pump the brine back into even a partially depleted reservoir. The Southwest Research Institute has investigated the energy requirements and has calculated that a well with an injection rate of 25,000 bbl/day, pump efficiency of 0.70, and a pump driver efficiency of 0.28 requires the energy inputs shown in Figure 5. In the Johnson Bayou, for example, the methane content of the reservoir is estimated to be 15 to 20 scf/bbl and the injection pressure requirements would be about 2,900 psia or 16 scf/bbl, equivalent (i.e., reinjection would require the energy equivalent of 16 scf of methane gas) (52) This would

---

(51) Sabodh K. Garg has conducted a computer simulation to determine the magnitude of recovery factor improvement from deep injection. His article "Reinjection of Fluids into a Producing Geopressured Reservoir", presented at the Fourth Geopressured-Geothermal Conference, concluded that, "reinjection can be used to substantially increase methane and brine production", and that, "[t]he attractiveness of reinjection to recover methane increases with increasing formation permeability, and decreasing formation compressibility." Under his most optimistic assumptions the estimated increase in in-place methane recovered could be as high as ten-fold. This increase is adequate to more than offset the vastly increased energy demands of higher injection pressures. If high pressure gas stripping is used, net energy yields could be expected to be even greater.



Equivalent Natural Gas Fuel Required to Pump One bbl of Spent Brine at 25,000 bbl/day Rate at Various Values of Surface Pressure

Figure 5

Source:Southwest Research Institute, 1980 also be the case with aquifers containing high concentrations of methane per barrel of brine produced, because higher solubilities are most often associated with greater formation pressures. Other factors militating against deep injection of waste brines include the high cost of drilling a well into a deep geopressured aquifer, and the requirement that the producing reservoir must be partially depleted to prevent overpressurization of the formationi by reinjection.

Shallow Injection

For the above reasons, shallow injection (above the production formation) of spent brines is the only disposal technology receiving serious consideration. As with deep injection, it involves the drilling of one or more disposal wells per production well, but unlike deep wells, drilling would only be to a few thousand feet. The technology for such wells can be taken directly from the oil and gas industry. Although repressuring of the water is necessary the disposal is into shallower, less pressured formations, so the energy requirements would be less (53).

The technical factors to be considered in subsurface disposal include:

- Existence of moderately saline (e.g. 10,000 ppm), hydrologically closed formations that are able to accept large volumes of fluid for an extended period.
- Presence of faults that could allow fluid migration into potable aquifers or that could become seismically active.
- Formation fracturing due to overpressuring.

---

(52) If the high-pressure, liquid-solvent separation process proves feasible, then the wellhead pressure drop is less than under a conventional scheme and repressuring requirements decreased. Since exact pressure drop values are not available, no quantitative estimates of lower energy requirements can be made.

(53) Exact repressuring requirements would vary from site to site, but would almost certainly be less than 1000 psia. This estimate assumes that high pressure extraction methods are not used.

- Migration of injected fluids within the formation and into other areas such as drinking water supplies.
- Compatibility of the injected brines with the rock and fluid in the recipient formation.
- Scaling and corrosion of pipes and injection equipment.
- Decline in porosity and permeability because of suspended solid, chemical precipitants, or other contamination.

Ray Wallace has investigated the availability of suitable subsurface aquifers as recipient formations for geopressured fluid disposal and concluded, along with most of the participants in the workshop, that "sand volume in the interval -2,000 to -5,000 feet is adequate in the Gulf Coast for disposal of geopressured fluids. Regional studies of the availability of aquifers for disposal are not required" (54).

There is substantial evidence of the potential for fault activation and fluid migration along fault lines resulting from injection of fluids. Whether this will occur in the Gulf Coast, with its large number of growth faults, is a matter of dispute. The high volume and possible high pressure injection rates associated with geopressured development requires that seismic monitoring should be conducted at geopressured sites (55).

A third effect of subsurface injection is the potential for fracturing of the formation. This could occur if the injection pressure of the brine exceeds the fracture pressure of the formation. This, in turn, could result in the migration of the fluid into other formations that may contain oil, gas, or potable water. However, in an examination of this problem it was noted that fracturing and subsequent fluid migration

---

(54) Raymond H. Wallace, "Gulf Coast Geopressured-Geothermal Resources as Related to Hydrogeologic Characteristics of the Subsurface System for Disposal of Spent Brines," in Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, op.cit., p.46.

(55) Environmental monitoring programs at Sweetlake and Brazoria #2 test sites include continuous seismic monitoring devices. Tom Gustavson reported the occurrence of microseismic events at the Brazoria site following shut-in tests at the site. Gustavson, Thomas C.; James Dorman; G.G. Sorrels; and Lee Wilson, "Environmental Baseline Monitoring in the Area of General Crude Oil/Department of Energy Pleasant Bayou Number 1--A Geopressured-Geothermal Test Well, 1978," presented at the United States Gulf Coast Geopressured/Geothermal Energy Conference:Research and Development, Austin Texas October 29-31.

is not likely because:

> "(1) the wells are not likely to be placed near structures like salt domes which can bound the disposal aquifer;
>
> (2) abandoned, uncased wells often plug naturally with impermeable clays;
>
> (3) fractures do not extend far upwards in the unconsolidated Gulf Coast sands;
>
> (4) [there exist] natural hydraulic gradients in the Gulf Coast the near surface;
>
> (5) operating practices can reduce the probability of overpressuring" (56).

Compatibility of the injected geopressured geothermal fluids with the formation rocks and fluids is a matter of concern because incompatibility problems may reduce fluid injection rates. Kharaka, Lico, and Carothers have examined this problem with respect to the formation of corrosive and scale products (57). They conclude:

> " The high salinity, Cl concentrations, and temperatures increase the corrosivity of geopressured geothermal waters...however [the corrosivity] probably will be controlled by reactions at cathodic sites."
>
> and with respect to scale:
>
> " reactions of these waters... indicate that oxyhydroxides of iron, carbonates of Ca, Sr, and Ba, and sulfate of Ba may precipitate from the waters during production to form scale" (58).

Finally, experience with subsurface injection as part of the Strategic Petroleum Reserve provides valuable information on decreases in formation porosity and permability. For details on this work, conducted by the Lawrence Livermore Laboratory, see: Improving the Performance of Brine Wells at Gulf Coast Strategic Petroleum Reserve Sites, L.B. Owen

---

(56) Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, Ibid, p 165.

(57) Kharaka, Yousif K., Michael S. Lico, and William W. Carothers, Predicted Corrosion and Scale-Formation Properties of Geopressured Waters from the Northern Gulf of Mexico Basin," Journal of Petroleum Technology, February, 1980, pp. 319-324.

(58) Ibid, pp. 323-324.

and R. Quong, (eds.) UCRL-52829, November 5, 1979.

Production Maintenance and Well Workover

After a well has operated for a period of time remedial work on the production equipment, the well, and even the production formation will probably be required. This is particularly the case in geopressured geothermal operations because of the extreme pressures, temperatures, salinities, and brine flow rates encountered (59). Depending on the characteristics of a given well, the combination of these factors may create chronic erosion, corrosion, scaling, and formation damage.

Since there is no long-term experience with production from geopressured geothermal wells, no operating data on production maintenance and well workover requirements are available. However, years of experience with "conventional" well operation can be extrapolated to the geopressured situation. Most commonly, the process of well workover is the job of a subcontractor expert in the field. The subcontractor's jobs, in addition to repair of surface equipment, can involve a number of well workover activities: sand removal, liner removal, casing repair, plug-back, squeeze cementing, and drilling deeper. The workover crew may also be called on to perform remedial reservoir work such as acidization or hydraulic fracturing of the formation.

Effects of sand production, including perforation clogging, pipe clogging, and well casing damage, are often the most serious impacts requiring well workover. The procedures for sand cleanout and well casing repair will be similar to those used in "conventional" oil and gas well workover, except for the need to maintain a high pressure in the well to prevent blowouts. The procedures and materials (e.g., heavy mud) that were used in the drilling and completion operations on the well should be adaptable to well workover, and therefore, should present no major technological constraints.

---

(59) The material in this section is taken chiefly from A Primer of Oilwell Service and Workover Petroleum Extension Service of the University of Texas at Austin (2nd. edition, 1971). See especially chapter 5, "Well Cleanout and Workover."
See also Appendix A "Non-Unique Drilling and Completion Technology", for descriptions of well fracturing and acidizing.

The very high flow rates, pressures, and presence of moving sands may lead to formation damage and pore closure near the wellbore. This damage would result in a decrease in the flow rate at the wellhead and a decrease in the rate of energy extraction. Acidizing (used in limestone and dolomite formations) and hydraulic fracturing (used in sandstone formations) are the main techniques for "repairing" the well formation. No mention of special formation workover problems in geopressured wells has been found in the available literature. Presumably the formation repair procedures would be similar to those used for regular oil or gas wells.

Conclusions

- The successful production of methane gas, at reasonable cost, will be the single most important factor determining the viability of the resource.
- Production of useful amounts of energy from geopressured geothermal aquifers will present technological challenges, but should not encounter major technical roadblocks.
- Production of electricity from geothermal heat and pressure will be of secondary importance in the overall energy production process.
- Disposal of spent brines in an economic and environmentally safe manner will constitute the single largest residual control problem.
- Experience from the Strategic Petroleum Reserve indicate that disposal of tens of thousands of barrels of fluid into subsurface formations will require careful monitoring and treatment of the brines to maintain injection levels for extended periods.
- Although careful preplanning is important, many problems, such as corrosion, scaling, and formation damage, will not be solved prior to large-scale production.

ENERGY CONVERSION BIBLIOGRAPHY

Bachman, Ann L.,(ed), *Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, Proceedings* (sponsored by the Louisiana Department of Natural Resources and Louisiana State University), March 6-7, 1979, Louisiana State University, Baton Rouge Louisiana.

Bachman, Ann L., and C.G. Smith, "Subsurface Disposal of Geopressured Fluids: Potential Geological and Operational Problems with Recommendations for Disposal System Testing," presented at the *Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference*, Austin, Texas, October 29-31, 1979.

Barker, Colin, "Aqueous Solubility of Petroleum as Applied to its Origins and Primary Migration: Discussion," in the *Bulletin of the American Association of Petroleum Geologists* (Volume 61, No.12, December 1977, pp. 2146-2149).

Berger, Bill, and Kenneth Anderson, *Modern Petroleum--A Basic Primer of the Industry* (Oil and Gas Journal Books, Petroleum Publishing Company, Tulsa, Oklahoma, 1978).

Blount, Charles W., Leigh C. Price, Lloyd D. Wenger, and Michael Tarullo, "Methane Solubility in Aqueous NaCl Solutions at Elevated Temperatures and Pressures," presented at the *Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference*, Austin, Texas, October 29-31, 1979.

Braden, Mickey W. Jr., and Oscar Goode Jr., "Testing of Geopressured Miocene Sands for the Dissolved Methane Resource in the Tenneco Fee "N" No. 1 Well," presented at the *Fourth Unites States Gulf Coast Geopressured/GeothermalEnergy Conference*, Austin, Texas, October 29-31, 1979.

Center for Energy Studies-University of Texas at Austin, *GGIS--The Geopressured Geothermal Information System: Geopressured Geothermal Bibliography (Extract)*, prepared by Thomas Hill, April, 1980.

Comision Federal de Electricidad, *Cerro Prieto: Underground Power*, (Rio Elba 22, Mexico, 1973).

Considine, Douglas M., *Energy Technology Handbook* (McGraw-Hill Book Co., 1977).

Crook, Leo, *Oil Terms: A Dictionary of Terms Used in Oil Development and Exploration* (International Publications Service, New York, 1976).

Fowler, William A., "Pressures, Hydrocarbon Accumulation, and Salinities-Chocolate Bayou Field, Brazoria County, Texas", *Journal of Petroleum Technology*, April, 1970 pp. 411-422.

Garg, Sabodh, "Reinjection of Fluids into a Producing Geopressured Reservoir, presented at the *Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference*, Austin, Texas, October 29-31, 1979.

Gault, Jack, James Hall, John S. Wilson, Herb Michael, Burchard P. Shepard, and Gary Underhill, "Preliminary Analysis of Electric Generation Utilizing Geopressured Geothermal Fluid," in *Surface Technology and Resource Utilization--Volume IV Second Geopressured Geothermal Energy Conference* (Center for Energy Studies, University of Texas at Austin, Austin, Texas, February 23-23, 1976).

Geer, Ernst, and Harold Cook, "Enhanced Gas Recovery from Geopressured Aquifers," presented at the *53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME*, Houston, Texas October 1-3, 1978.

Geer, Ernst, and John Sharer, "Unconventional Geopressured Gas Recovery, Economics and Research," presented at the *7th Energy Technology Conference*, March 24-26, 1980, Washington, D.C.

Gregory, A. Ray, Marianne M. Dodge, and Jan S. Posey, "Progress Report on Evaluation of Entrained Methane in Deep Reservoirs, Texas Gulf Coast," presented at the *Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference*, Austin, Texas, October 29-31, 1979.

Gregory, A. Ray, and Milo M. Backus, "Geopressured Formation Parameters, Geothermal Well, Brazoria County, Texas," presented at the *Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference*, Austin, Texas, October 29-31, 1979.

Haas, John L., "Empirical Equation with Tables of Smoothed Solubilities of Methane in Water and Aqueous Sodium Chloride Solutions up to 25 Weight Percent, 360°C, and 138 MPa," (U.S. Geological Survey, Department of the Interior, Preliminary Open File Report No. 78-1004, 1978).

Hodgson, Susan, "Cerro Prieto Geothermal Field," Geothermal Hot Line (California Division of Oil and Gas, Vol. 10 No.1, January 1980).

House, P.A., P.M. Johnson, and D.F.Towse, Potential Power Generation and Gas Production from Gulf Coast Geopressured Reservoirs (Lawrence Livermore Laboratory, UCRL-51813, May 27,1975.)

Karkalits, O. Carroll, and B.E. Hankins, "Results of Flow Tests of Edna Delcambre No. 1: II. Summary of Gas Analyses," presented at the Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference, Austin, Texas, October 29-31, 1979.

Kharaka, Yousif K., Michael S. Lico, and William W. Carothers, "Predicted Corrosion and Scale-Formation Properties of Geopressured Geothermal Waters from the Northern Gulf Of Mexico Basin," Journal of Petroleum Technology February, 1980, pp. 319-324.

Lamb, J. Parker, Gary F. Polansky, and Stephen P. Bradely, "Conceptual Design Studies of Energy Conversion Plants Using Geopressured Fluid," presented at the Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference, Austin, Texas, October 29-31, 1979.

Matthews, Charles, Existence and Flow Behavior of Gas at Low Saturations in Geopressured Formations-Final Report, Division of Geothermal Energy-United States Department of Energy, Report HCP/T2259-05, April 1979.

Petroleum Extension Service:University of Texas at Austin, A Primer of Oil-Well Service and Workover (2nd Edition 1968 and 3rd Edition 1979).

Phillips, Sidney L., Ashwani K. Mathur, and Raymond E. Doebler, A Study of Brine Treatment, EPRI ER-476 (prepared by the Lawrence Berkeley Laboratory, November 1977).

Price, Leigh, "Aqueous Solubility of Petroleum as Applied to Its Origins and Primary Migration," in Bulletin of the American Association of Petroleum Geologists (Volume 60, No. 2, February 1976, pp. 213-244).

____________, "Aqueous Solubility of Methane at Elevated Pressures and Temperatures," in Bulletin of the American Association of Petroleum Geologists, (Volume 63, 1979, pp. 1527-33).

____________, "Aqueous Solubility of Petroleum as Applied to Its Origins and Primary Migration: Reply," in Bulletin of the American Association of Petroleum Geologists (Volume 61, No. 12, December 1977, pp. 2149-2156).

Quong,R., I.R. Owen,and F.F.Locke, preprint of "Potential Methods for Methane Extraction from Geopressured Brine at High Temperature and Pressure," to be delivered at the 55th Annual Technical Conference and Exhibit of the Society of Petroleum Engineers of AIME, Sept 21-24,1980, UCRL-84064.

Randolph, Philip, "Natural Gas Content of Geopressured Aquifers," Institute of Gas Technology, Chicago (presented at the 3rd Geopressured-Geothermal Energy Conference, University of Southern Louisiana, Lafayette, Louisiana, November 16-18, 1977).

Riva, Joseph Jr., "Two Views of the Production of Natural Gas from Geopressured Deposits," Library of Congress-Congressional Research Service, August 30, 1979.

Roberts, Kenneth D., Donna C. L. Prestwood, David O.Fredrick, and John H. Vaston Jr., "Industrial Markets for the Texas Geopressured-Geothermal Resource: A Market Survey, Transactions: Geothermal Resource Council, Vol. 3, September 1979, pp. 577-580.

Rogers, Leo and Philip Randolph, "Ratio of Produced Gas to Produced Water from DOE`s Edna Delcambre No. 1 Geopressured-Geothermal Aquifer Gas Well Test," Institute of Gas Technology, Chicago (presented at the 4th Gulf Coast Geopressured-GeothermalEnergy Conference,, Austin Texas, October 29-31, 1979).

Science and Public Policy Program, University of Oklahoma Energy Alternatives: A Comparative Analysis (Norman, Oklahoma, May 1975).

Southwest Research Institute, Geopressured Energy Availability prepared for the Electric Power Research Institute, Palo Alto, California, AP-1457 (Final Report, July 1980).

Stevens, John E. and Parker Lamb, "Surface Facilities for Resource Evaluation Studies at Pleasant Bayou Test Well Facility," presented at the Fourth United States Gulf Coast Geopressured/GeothermalEnergy Conference, Austin, Texas, October 29-31, 1979.

Sullivan, Brian R., "New EPA Injection Well Rules Outlined," in Oil and Gas Journal, August 13, 1979, pp 127-128.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second Geopressured Geothermal Environmental/Laboratory Research Working Subgroup," Houston, Texas, Nov. 3, 1977 (published by GeoEnergy Corporation, Suite 145, 3376 South Eastern Avenue, Las Vegas, Nevada 89109).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second Geopressured Geothermal Site Selection Working Subgroup," Houston, Texas, Nov. 4, 1977 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second DOE/Industry Geopressured Geothermal Overview Group Meeting," Lafayette, Louisiana, Nov. 15, 1977 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting Concerning DOE/General Crude/DOE Contractors-Plans for Brazoria Well," Houston, Texas, Dec. 21, 1977 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the Environmental/Laboratory Research Working Subgroup," Houston, Texas, Feb. 23, 1978 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the Site Selection Working Subgroup," New Orleans, Louisiana, April 25, 1978 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Meeting of the Environmental/Laboratory Research Working Subgroup," New Orleans, Louisiana, April 26, 1978 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fifth Meeting of the Environmental/Laboratory Research Working Subgroup," Houston, Texas, July 18, 1978 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Site Selection Working Subgroup," Houston, Texas, March 21, 1979 (published by GeoEnergy Corporation, Suite 145, 3376 South Eastern Avenue

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the DOE/Industry Geopressured Geothermal Overview Group," Houston, Texas, March 22, 1979 (published by GeoEnergy Corporation, Suite 145, 3376 South Eastern Avenue

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Drilling and Testing Subgroup," Houston, Texas, August 1, 1979 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Overview Subgroup," Houston, Texas, May 28, 1980 (published by GeoEnergy Corporation, address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Environmental/Laboratory Research Subgroup," Houston, Texas, May 29, 1980 (published by GeoEnergy Corporation, address above).

U.S. Patent 3,258,069, "Method for Producing a Source of Energy from an Overpressured Formation," Clarence E. Hottman, June 3, 1966.

U.S. Patent 3,330,356 "Apparatus for Using a Source of Energy From an Overpressured Formation," Clarence Hottman, July 11, 1967.

U.S. Patent 4,040,487, "Method for Increasing the Recovery of Natural Gas from a Geo-pressured Aquifer," Harold Cook Jr., and Ernst Geer, August 9, 1977.

U.S. Patent 4,042,034 "Method for Increasing the Recovery of Natural Gas from a Geo-pressured Aquifer," Harold Cook Jr., and Ernst Geer, August 16,1977.

U.S. Patent 4,149,596, "Method for Recovering Gas from Solution in Aquifer Waters," Joseph Richardson, and Lawrence Christian, April 17,1979.

Wilson, John, Burchard Shepard, Sidney Kaufmann, An Analysis of the Potential Use of Geothermal Energy for Power Generation Along the Texas Gulf Coast (Dow Chemical U.S.A. for the Texas Governer's Energy Advisory Council, Project N/T-1, Austin Texas, October 1975).

ENVIRONMENTAL INTRODUCTION

The technology characterization portion of this report described geopressured geothermal development as a hybrid, combining features of both the conventional oil and gas and the geothermal industries. The environmental impacts of resource development constitute a similar hybrid. For example, site development impacts are most closely analogous to oil and gas development; thermal "pollution" problems are similar to those encountered with geothermal energy facilities; and, brine disposal problems are unique to geopressured geothermal aquifers. This chapter reviews and assesses the published work and expert opinion of individuals involved in geopressured geothermal environmental impact analysis and points to mitigation measures that may prevent some of these impacts.

The most prominent feature of geopressured geothermal energy production is the vast quantity of brine that must be extracted from the ground (1). The major or "first-order" impacts of geopressured geothermal development are direct consequences of this brine production--namely, subsidence and chemical effects of brine disposal (2). Environmental impacts resulting from air pollutant emissions, solid waste generation, and other activities will be of second-order importance.

The chapter is organized into four major sections. One examines the complex and highly controversial subject of reservoir compaction and ground surface subsidence. Another is concerned with the ecological and environmental problems arising from the disposal of "spent" brine. A third briefly summarizes second-order environmental impacts, such as air pollutant emissions. And the last investigates some of the pro and cons of offshore geopressured geothermal development (3).

---

(1) As used here the term "brine" refers to fluid or liquid extracted from geopressured geothermal aquifers. Use of the term is not intended to imply that geopressured geothermal fluid is merely concentrated seawaterr; its chemical composition can differ markedly from seawater.

(2) Production by means of the rapid pressure drawdown process (RPD), described in the technology characterization section, will not be specifically considered in this chapter. RPD will, however, almost certainly have environmental impacts less than or equal to conventional long-term high-flow production. Estimated consequences of high-flow production, therefore, should serve as an upper bound on environmental impacts.

(3) Although not entirely germane to a discussion of environmental impacts of resource development, ocean or offshore development of the geopressured geothermal energy resource is receiving greater attention among researchers in the field. Offshore development entails sufficient environmental issues to deserve inclusion.

Although some of the information presented in these sections can be applied to specific geopressured geothermal sites (especially the Pleasant Bayou No. 2 well in Brazoria County, Texas), the emphasis of the discussions is on generic, not site specific, issues (4). In addition, estimates of environmental control costs or the cost of environmental impacts to industries such as shrimp fisheries have not been included, largely because few estimates are available. No investigation of the impacts that might occur in other regions than the Gulf Coast of Texas and Louisiana--most particularly the geopressured regions of California--is included. Finally, no "most likely" resource development or environmental impact scenarios are included.

---

(4) For detailed information on specific sites the reader is refered to the bibliographies at the end of each chapter.

CURRENT KNOWLEDGE OF THE POTENTIAL FOR SUBSIDENCE

INTRODUCTION

Questions Regarding Subsidence

The potential for surface subsidence resulting from the removal of geopressured reservoir fluids is not known. Should subsidence occur, impact severity may be very high. A few important questions regarding subsidence include:

- What are the relevant mechanisms of formation compaction and how are they related to the production drive of the reservoir?
- How will compaction of the sediments in the producing formation translate through the overlying rock strata as surface subsidence?
- How meaningful is our experience with induced subsidence resulting from shallow groundwater withdrawal and oil and gas production as an analogy to deeper geopressured aquifers?
- In what specific areas of the Gulf Coast region is man induced subsidence geologically most likely to occur?
- In what areas would subsidence have the greatest environmental and economic impact?

Strictly speaking, subsidence refers only to vertical ground movement. But any of three types of ground movement may occur following production of a geopressured reservoir:

- subsidence or rebound of the surface (vertical movement only) due to reductions in fluid pressure underground;
- lateral or horizontal ground movement resulting from shifts in compacting masses;
- movement along existing growth faults with surface expression.

Subsidence may also be caused by thermal expansion or contraction of reservoir rock, although neither mechanism is considered important in the geopressured case.

Research Needs

An ability to predict the magnitude and rate of subsidence on a site-specific basis will require increased knowledge in a variety of specialized areas including:

- the flow behavior of the liquid and gas (with gas in solution or as two separate phases);
- the compressibility of geopressured brine with gas in solution;
- the chemistry of granular deformation at elevated temperatures and pressures and under conditions of decreasing pore pressure;
- the physical deformation characteristics of various types of reservoir rock;
- conceptual models that adequately address not only the static state but also the longer-term, time-dependent changes that will follow reductions in pore pressure resulting from fluid withdrawal, and;
- computer simulations that incorporate the above knowledge to predict magnitudes, and perhaps eventually, rates of subsidence.

Figure 1 illustrates the variety of scientific disciplines that must be brought to bear on the problem of subsidence (1). As an example of the broad uncertainty that now exists, the reservoir drive, an essential determinant of reservoir behavior and hence of both subsidence and resource production, may consist of:

- a "rock drive" in which the added pressure of the overburden acts as a drive mechanism for gas and brine flow;
- pore spaces filled by brine due either to expansion of fluid contained in the pore spaces following pressure reduction, or to infiltration of brines from surrounding sediments;
- brine in pore spaces replaced by gas evolved from solution or through expansion of the fluid, or;

---

(1) From Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, The Analysis of Subsidence Associated with Geothermal Development--Volume 1, September 1976, p. 1-6.

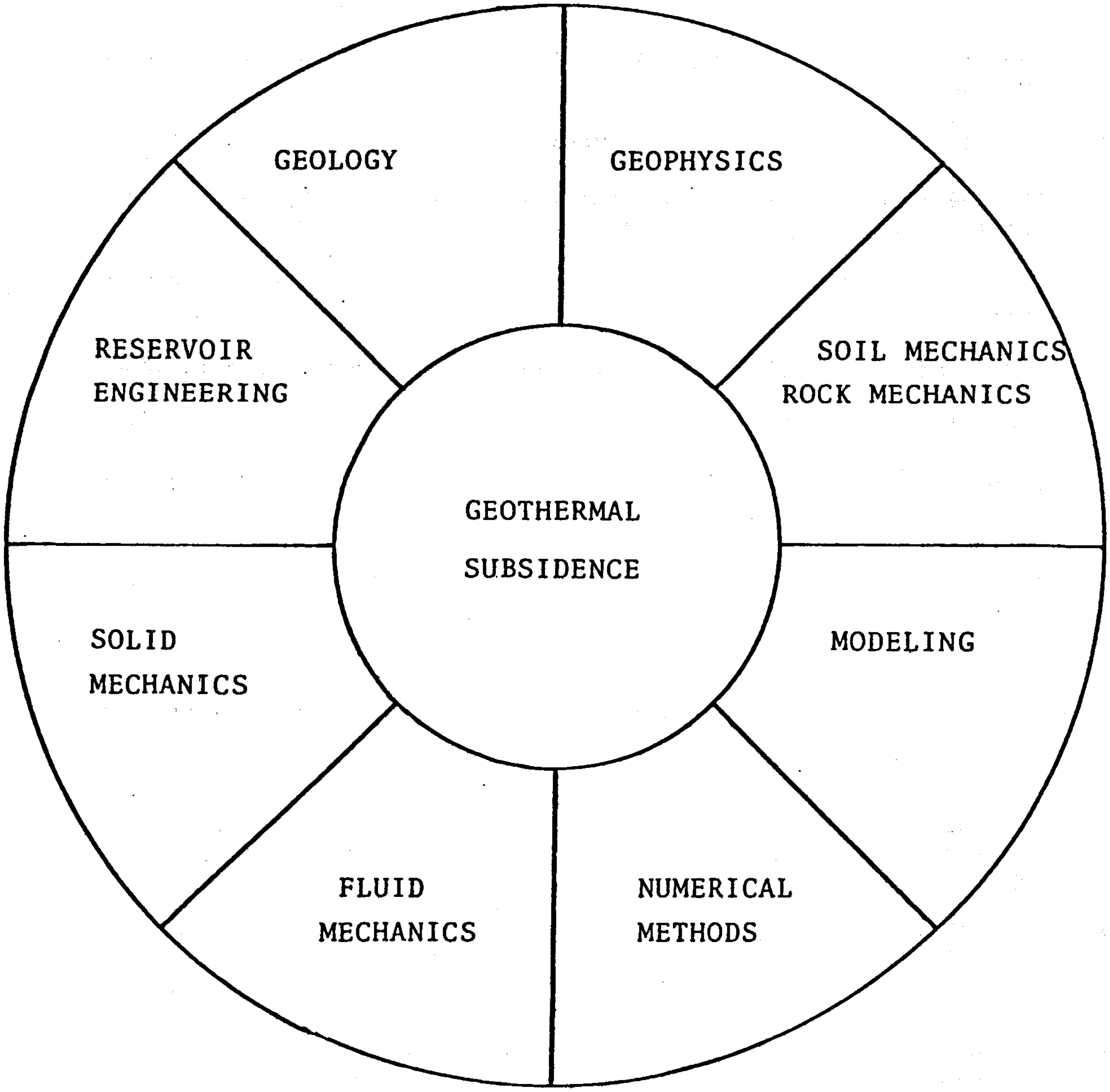


Figure 1 Geothermal Subsidence as a Synthesis Across Many Fields of Knowledge

Source: Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, 1976.

- combinations of the above.

The effect on subsidence potential of producing a geopressured aquifer under rapid pressure drawdown (RPD) conditions has not, to the best of our knowledge, been previously examined. Due to the uncertainty of subsidence, it appears imprudent to speculate on the potential for subsidence following RPD production of methane. Should increased attention be focused on RPD production methods, their potential effects on subsidence will deserve additional study.

Subsidence in the Gulf Coast

Subsidence is a gradually occurring natural process, particularly in sedimentary basins such as the Gulf Coast in which sediments compact as the pressure of overlying strata expels fluids from the formation pores. Natural, or background, subsidence in the Gulf Coast has been measured by the National Geodetic Survey for about 40 years and enough baseline data is available for most areas to allow differentiation between natural and man-induced regional subsidence. Localized rates are often more difficult to ascertain, particularly if several types of fluids have been removed from different depths. Acceleration of natural rates of subsidence in the Gulf Coast could have disastrous effects in low elevation wetlands. The DOE Brazoria well, for instance, is only five to six feet above sea level. Appreciable subsidence could increase the dangers of seasonal flooding and result in environmental and economic loss.

Subsidence Literature

<u>The Analysis of Subsidence Associated with Geothermal Development</u>, a study completed in September of 1976 by Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker of Systems Control, Inc. for the National Science Foundation, is still up-to-date and serves as a source

of much of the following discussion of compaction processes, the modelling of reservoir behavior and subsidence, and on.site subsidence monitoring. The series of Geothermal Subsidence Reports completed for the Lawrence Berkeley Laboratory serve as an excellent in-depth review of areas of knowledge and of uncertainty (2). Although intended primarily for conventional geothermal resources, these reports include frequent specific reference to the geopressured resource. The Reike and Chilingarian volume, along with the condensed version found as Chapter 2 of Fertl, provides a detailed literature review on the physical and chemical processes of sediment compaction. Updated information on subsidence research, often unpublished, can be found in the minutes of the Department of Energy/Industry Geopressured Geothermal Resource Development Program.

Organization of Subsidence Material

This chapter systematically introduces subject topics in the following order. First a truncated explanation of the concepts and processes relevant to an understanding of reservoir compaction, along with the simplifying assumptions used by theorists. What exactly does occur, and what are the limits of our knowledge of physical and chemical reservoir behavior following the removal of brine?

A brief discussion of conceptual models follows in order to illustrate the use of concepts in attempting subsidence predictions.

Next is a short description of the results of three preliminary attempts at prediction, one for a generic geopressured reservoir, and two for specific sites.

A short coverage of Gulf Coast geology as it pertains to the susceptibility for subsidence serves as a prelude to discussing historic subsidence rates for the region.

---

(2) See footnote 109 for references and accompanying discussion in the research section of this chapter.

A section on techniques for subsidence prediction and monitoring follows in which: a) analytical techniques using surface and subsurface monitoring, as well as rock testing in the laboratory and computer simulation of laboratory results and, b) analogies from subsidence caused by other types of fluid withdrawal are explained. This section ends with a description of the subsidence monitoring plans (both baseline data collection and test phase) for current and planned DOE design wells.

A section on impact severity considers environmental and economic loss that could result from geopressured subsidence in the Gulf Coast, with emphasis given to the former. The section closes with an analysis of available subsidence mitigation strategies.

The subsidence research section discusses the improvements needed in the various areas of analytical monitoring and prediction, as well as the need for standardization of nomenclature and testing procedures for geopressured subsidence research.

The conclusions stress the need for research and, above all, for site-specific data collection from design wells. Some researchers feel that, given adequate funding and rock samples for lab testing, a) verification of existing theory and b) the ability to predict magnitudes, and possibly the rates of subsidence, may not be too many years away. Others feel that the theory itself has not evolved far enough to allow for rapid development of predictive ability.

Subsidence is a technical area that borrows language from all of the disciplines shown in Figure 1. Therefore a glossary is included as Appendix C.

Theory, Conceptual Modeling, and Estimation of Compaction and Subsidence

Basic Concepts

Thompson and Gray concisely explain the geophysical aspects of geopressured reservoir compaction from a rock mechanics viewpoint (3):

> "In its most general terms the reduction of pore pressure in a geopressured reservoir will lead to an increase in the effective stress on the rock, and hence a compaction of this material with consequent reduction in permeability. Since the pressure change in the reservoir will not be uniform, and since in general the rock will be neither homogeneous nor isotropic, this compaction will be non-uniform. This increase in effective stress and the consequent compaction will induce non-uniform deformation of the immediately overlying strata which may be expected to induce shearing stresses in the rocks and, if the degree of compaction and the depth of the reservoir are of the right order, may induce surface subsidence."

Figure 2 schematically illustrates the processes described above.

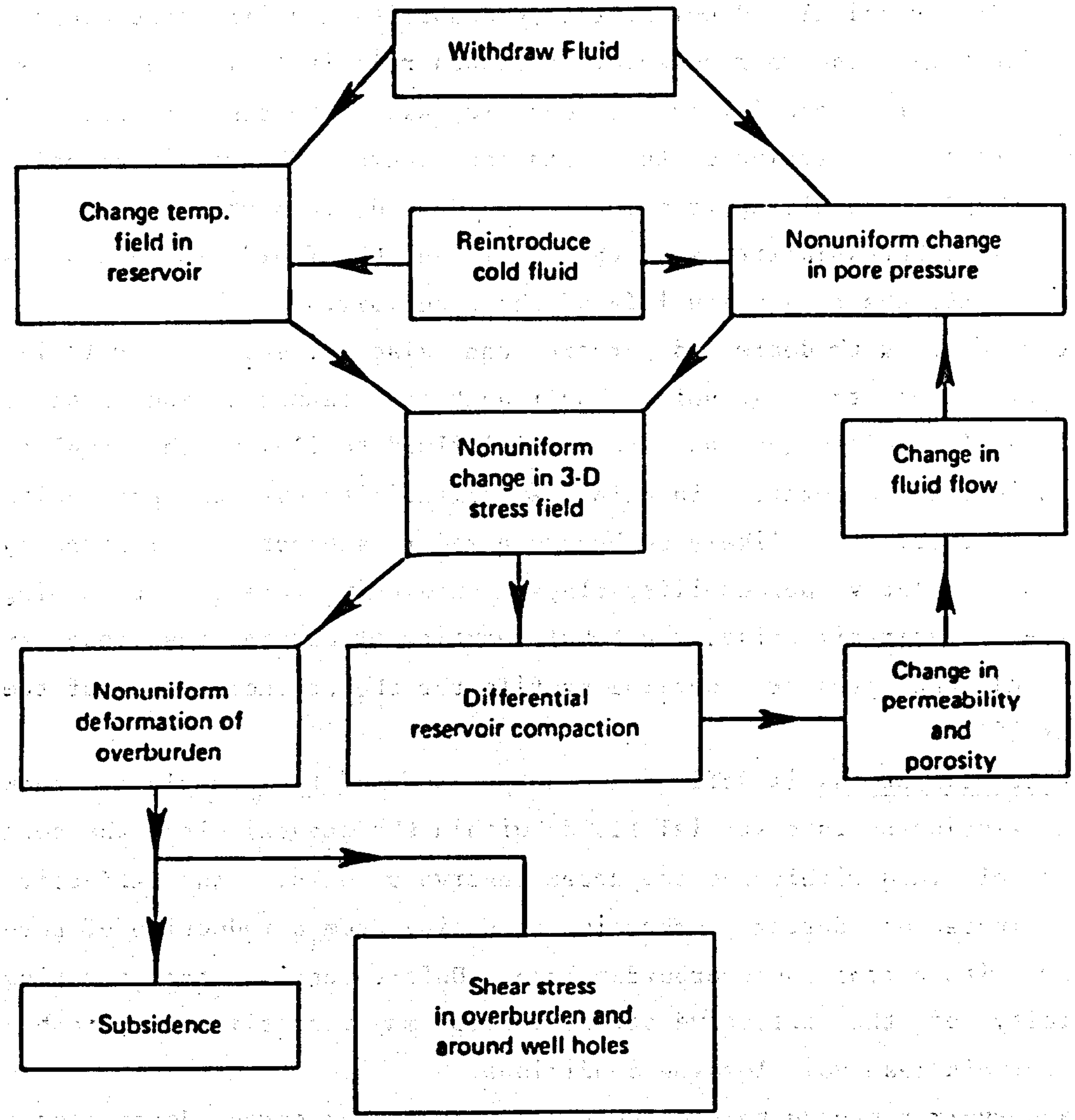
One way to gain appreciation for compaction and subsidence processes is to consider the pertinence of the following concepts to the theory of rock and reservoir behavior.

A porous medium has four essential characteristics: 1) the material is composed of both void space and solid matrix; 2) the specific surface area of the solid matrix is high; 3) diameters of individual pore spaces are small relative to the lateral extent of the reservoir, and; 4) both the absolute and relative size of the pore spaces or voids are important to an understanding of behavior (4).

Porosity and permeability are the two salient characteristics of a porous medium such as geopressured sandstone or shale. The term porosity, given as a percent or fraction, is the ratio of fluid filled volume to the total reservoir volume (fluid volume plus solid matrix volume).

---

(3) Thompson and Gray, p. 85. Figure 2 appears on p. 86.
(4) Adapted from Atherton , et al. p. 3-6. See Appendix B for definitions of terms used in this section.



RESERVOIR AND OVERBURDEN ROCK BEHAVIOR

Compaction, permeability, porosity, and other rock parameters are functions of stress state, temperature, direction, stress path, and time.

Figure 2 The effects of reservoir exploitation

Source: Thompson and Gray, 1975.

Permeability can be roughly defined as a measure of the ease with which fluids (both liquids and gases) flow through the voids of the solid matrix. Both vertical and horizontal permeability are important properties affecting reservoir behavior, although relatively little is known about the former. Porosity and permeability will both tend to decrease as mechanical compaction of the formation occurs. Changes in porosity and permeability resulting from compaction depend, in part, on the relative volume compressibilities of the matrix and the fluid. These changes will influence the production life of the reservoir.

Compaction with decreased porosity can also affect the relative permeability of the reservoir. The result is a change in the relative abilities of exsolved gas and interstitial fluid to flow to the annulus. The anticipated alteration in relative permeability over the productive life of a reservoir is likely to become a major subject of laboratory research. Relative permeability plays a predictive role in determining the type of reservoir drive, the total quantity of natural gas recoverable, and the pressure decline profile for the producing life of the aquifer (5).

Effective stress is defined as the pressure of the overlying rock strata (including interstitial fluids within the strata) minus the pore pressure of fluid within the compacted reservoir rocks. The effective stress increases during compaction resulting from a reduction of pore pressure with a constant overburden load. Unfortunately, the tempting simplicity of the effective stress concept may render it inapplicable under certain reservoir loading conditions.

Reservoir response to the increase in effective stress depends on a variety of factors, the relative importance of which is a matter of controversy. The more coarse or angularly-grained the rock material of the compacting formation, the more likely that grain deformation will occur. Porosity and permeability may both or individually be reduced, or there may be no effect on either reservoir property.

Scott has expanded the static theory of effective stress into the principle of dynamic seepage stress through studies of groundwater withdrawal-induced subsidence in California's San Joaquin Valley (6).

---

(5) See Atherton et al. Chapter 3.
(6) Ibid, pp. 4-6 to 4-7. For application of the dynamic seepage stress concept to groundwater withdrawal, see Lofgren, 1968.

This theory incorporates the dynamic aspects of compaction, as well as biaxial rather than uniaxial system stresses. The compaction of well-sorted formation grains is the result of the frictional drag of moving water.

A number of other stresses are relevant in examining compaction. The most important of these are the horizontal stresses of either a compressional or a tensional nature. The magnitude and relevance of these stresses to compaction is dependent on the nature of the load experienced by the strata laterally adjoining the reservoir.

Compressibility, cementation, and preconsolidation are three rock properties of importance to the anticipated behavior of reservoir rock experiencing reduced pore pressures. Other factors of importance include formation age and grain size (7).

Compressibility is the change in any measure of volume per unit change in the effective stress of the system (8). Both brine and rock matrix compressibilities are parameters of interest in studying compaction. Compressibilities are often represented as the slope of curves relating the void ratio to the log of the effective stress (or applied pressure). Figure 3 shows empirical results for a variety of sand and clay compressibilities.

Cementation refers to the degree of consolidation of the granular material of the porous rock. The integrity or competence of a formation rock will be directly related to the degree of cementation. A well cemented formation matrix indicates that the reduction in fluid pressure and the resulting increase in effective stress can be borne by the matrix with relatively little deformation.

The stage of advancement of this background process is determined through laboratory study of formation core samples. Loucks, Richmann, and Millikan, and Chilingarian and Rieke note the complex of factors such as the history of reservoir fluid chemistry, and the history of cementation, causing possible chemical alterations of the brine during

---

(7) Larger grains may easily undergo deformation and rearrangement; smaller grained material has a relatively lower porosity and requires a higher threshold pressure for significant granular deformation to occur. The relative age of geopressured sediments and their geographic occurrence is discussed below under Subsidence in the Gulf Coast.

(8) Atherton, et al. p. 4-13.

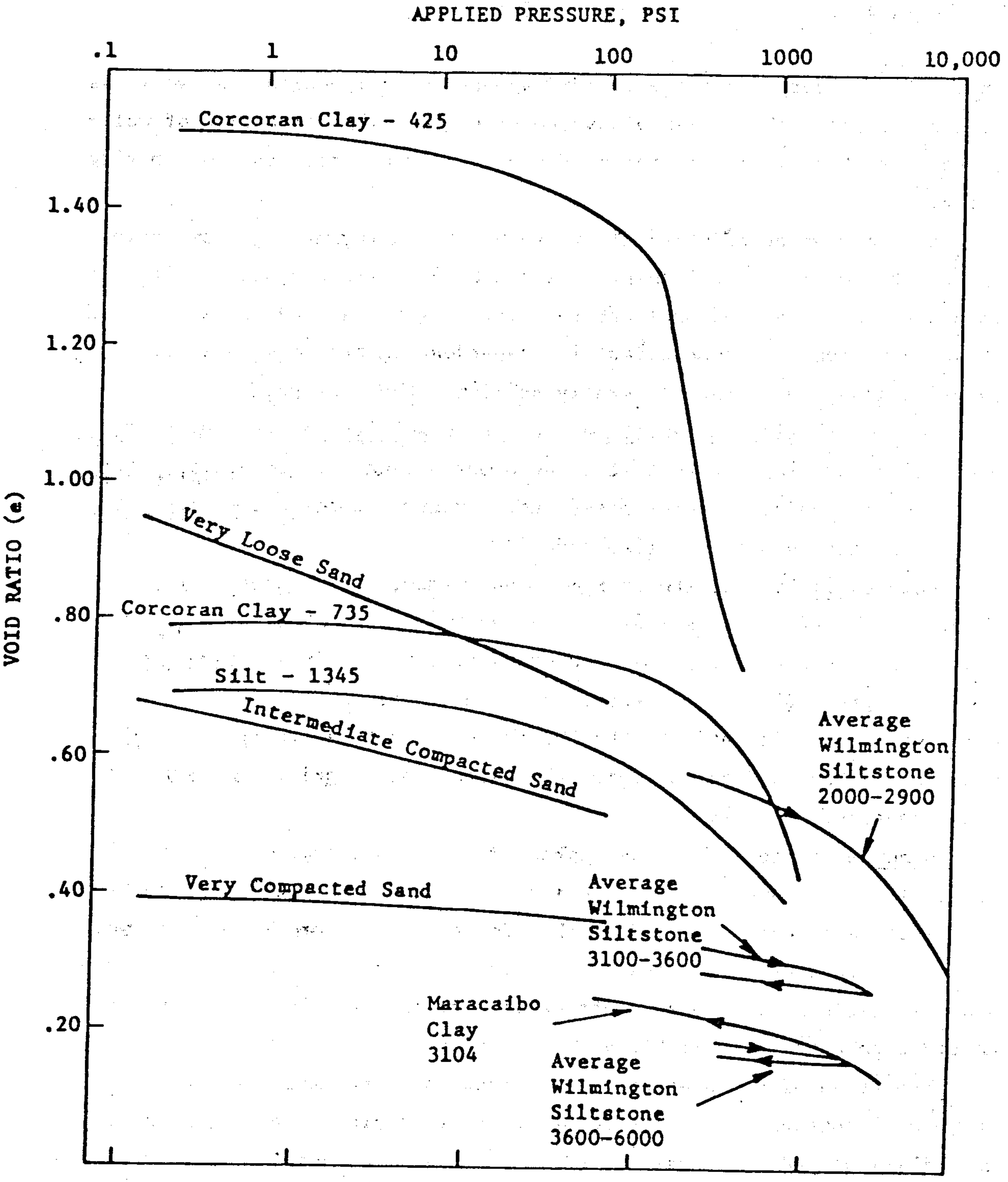


Figure 3. Compression Tests on Clays, Silts, and Sands from Wilmington, California; Lake Maracaibo, Venezuela; and San Joaquin Valley, California (Corcoran Clay). (From Allen and Mayuga, 1969)

Source: Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, 1976.

resource production (9). Some preliminary work has been done, but it is unwise to generalize from data on one or two wells as to the degree of cementation of all geopressured strata. Ken Gray notes that initial core samples from the Pleasant Bayou, Brazoria County well are more highly cemented than had been expected (10).

Preconsolidation relates the deformation properties of the matrix material of the reservoir through the theory of elastic behavior (11). Figure 4 idealizes the behavior of rock that is subjected to pressure, released, and then again loaded. The curves show the void ratio as a function of the pressure (12). Several cycles of compression are illustrated so that the maximum past intergranular pressure (preconsolidation stress) can be determined. Rock samples are loaded to failure in the lab in order to determine the onset of "virgin compression."

Elastic behavior is a component of most models of compaction and subsidence, although its applicability in cases of gradual rather than rapid loading has been questioned (13). Elastic deformation, as the term suggests, incurs compaction that is reversible following unloading. Inelastic deformation results in irreversible deformation of the matrix material. Permanent deformation will persist despite later reductions in loading pressure.

---

(9) Loucks, Richmann, and Millikan, "Factors Controlling Porosity and Permeability in Geopressured Frio Sandstone Reservoirs, General Crude Oil/DOE Pleasant Bayou Well, Brazoria County, Texas," and Chilingarian and Rieke, in Fertl, Abnormal Formation Pressures, especially pp. 67-80.

(10) Telephone conversation with Ken Gray, July 9, 1980.

(11) This discussion of preconsolidation is based on Atherton, et al. pp. 4-15 to 4-16, and on Riecke and Chilingarian, 1974, pp. 118-120.

(12) The void ratio is a means of expressing the porosity of rock material. The void ratio is defined as the volume of pores divided by the volume of solids. Thus the void ratio (e) and porosity (ϕ) are related by:

$$e = \phi/(1-\phi); \quad \phi = e/(1+e)$$

The void ratio is helpful in graphing porosity relations resulting from compaction tests because only the numerator of the fraction varies.

(13) Telephone conversation with Ken Gray, July 9, 1980. See the following subsection on problems with the theory.

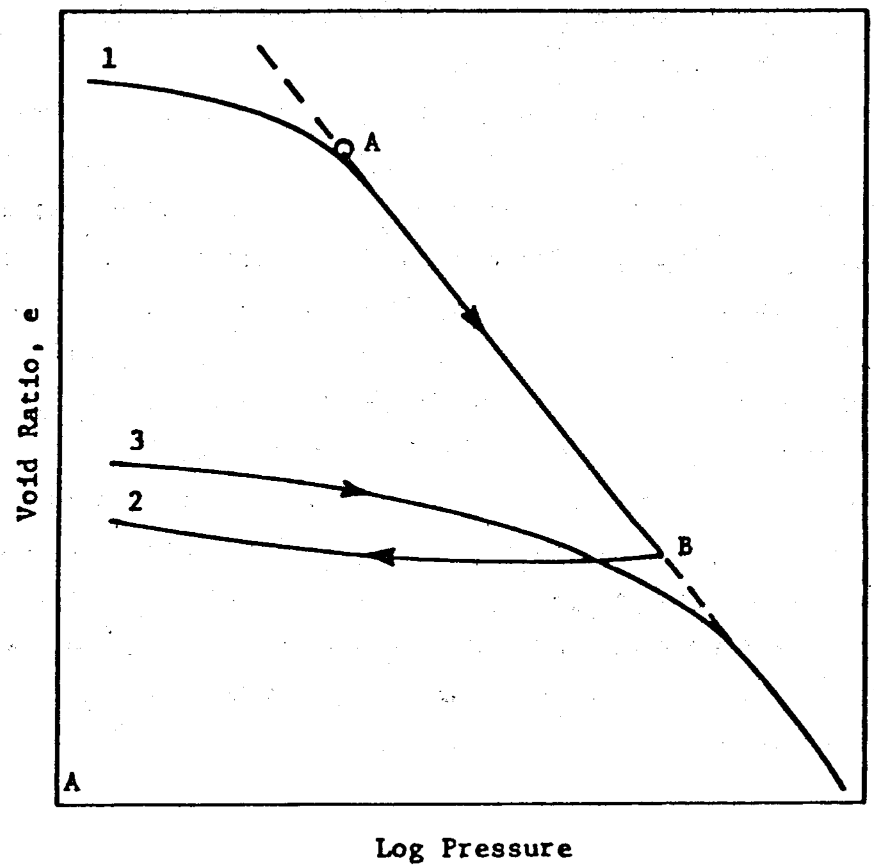


Figure 4. Schematic Variation of Void Ratio With the Logarithm of Effective Stress, (Modified after Riecke and Chilingarian, 1974)

Source: Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, 1976.

In Figure 4 elastic and inelastic behavior is illustrated with successive compression (1), rebound (2), and recompression (3) curve segments indicating that the net compression for the first cycle of loading and partial rebound equals the vertical distance between points A and B. The slight increase in the slope of curve segment (2) accompanying pressure reduction is the partial rebound from compression. The more elastic the compression behavior, the steeper the slope of this curve. Thus deformation along the line segment AB is inelastic and hence non recoverable while deformation to the left of AB is elastic and partially recoverable. The similar shapes of the loading curves (1) and (3) indicate that non-elastic deformation does not occur unless the greatest previous (preconsolidation) stress is exceeded. The onset of loading pressures above those of preconsolidation, represented by deformation along the segment AB, results in inelastic behavior and hence virgin compression yielding of the matrix material . The preconsolidation stress is empirically represented by an abrupt change in the slope of the successive compression curve as effective stress is increased beyond point B.

Problems with the Theory

This subsection relates several strands of theory to the uncertainties and gaps in present knowledge. The aim is to illustrate the range of uncertainty as well as the interrelated nature of the factors that determine the probability, type, and severity of both reservoir compaction and surface subsidence.

The theory of elasticity, the rapidity or lag effect that may characterize the onset of subsidence, and the order of the processes thought to have formed geopressured zones are all intimately connected. Elasticity theory holds that a given level of fluid pressure reduction (and correspondingly increased stress in the solid matrix of the producing formation) must occur before irreversible compaction will occur. In effect there is a threshold pore pressure level below which the resulting increased effective matrix stress will induce irreversible compaction.

Even if this region of virgin compression yielding does exist, compaction of geopressured sediments would not necessarily occur rapidly following initial reduction in pore pressure. The onset of virgin compression yielding is a function of the prior loading history of the strata of the producing zone. The greater the former stresses exceed current stresses, the greater the decline in fluid pressure that is required to initiate compaction. Conversely, if the present effective stress on the solid matrix is as great as any previously experienced, compaction may commence rapidly following fluid withdrawal. Kreitler believes that the latter situation is a correct description of the loading history of geopressured formations (14).

As Atherton notes, a prior condition of greater loading could only have occurred given either: a) a thick layer of sediment that has since been eroded from the surface, or b) the compaction of sediments at depth under full geostatic loads prior to the formation of the geopressured zones. The first is highly unlikely given our knowledge of Gulf Coast geology; the second possibility can not yet be addressed.

An additional factor in magnitude and rate of formation compaction is underburden competence. Normally-pressured strata show a decrease in porosity with depth. Figure 5 shows typical depth to porosity ratios and illustrates the sudden sharp porosity increase typical of the upper bound onset of the geopressured zone. Porosity will normally again decrease with depth through the geopressured zone, although small local porosity increases have been found over relatively small depth intervals in geopressured sediments (15).

According to Doscher et al (16):

---

(14) See Atherton et al. volume 2, pp. 2-85 to 2-86.
(15) Ibid, pp. 2-82 to 2-84.
(16) See Doscher, Osborne, Wilson, Rhee, Cox, and Kuuskraa, p. 1505.

Relationship of Depth and Porosity to Normally and Geopressured Sand and Shale Formations

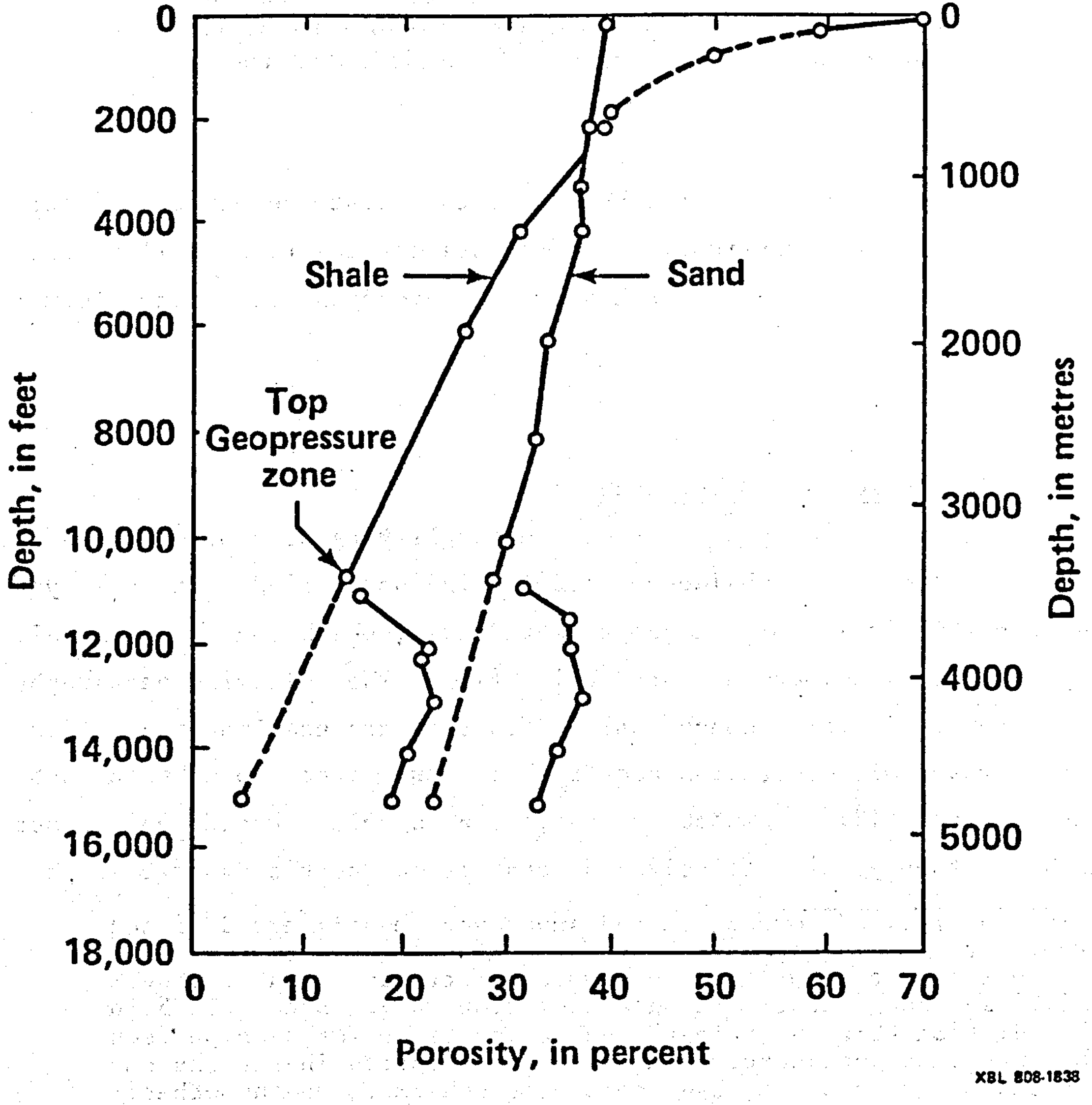


Figure 5

Source: Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, 1976

> "If the leaching [of the formation] occurred before geopressuring, it suggests that the reservoir was open to the flow of fluids after cementation had occurred and only later became sealed...Alternatively, if sealing and cementing did occur early, then the consequent solution of cement and silica could have been triggered by burial to some depth where the temperature rose to a value sufficient to activate the solution mechanism. The resulting solution of mineral constituents could have led to sufficient reorientation of the same grains so that some of the overburden pressure was transferred to the fluid within the reservoir. The compressibility of the formation would be less than usually anticipated for a geopressured reservoir..."

Thus the rate and magnitude of subsidence, the existence of free interstitial gas, and the applicability of elasticity theory may all be partially dependent on the geologic history of overpressured zone formation.

Models of Compaction and Subsidence

Because the validity of many of the simplifying assumptions used in most compaction and subsidence models is unverified, it is as yet unclear, particularly for the geopressured case, which conceptual model, if any, will provide accurate prediction (17). The following paragraphs briefly review several conceptual models that are used together, first to derive reservoir compaction coefficients, and then to obtain subsidence figures (18). Compaction models are usually based on either Terzaghi's theory of effective stress or on Scott's dynamic seepage

---

(17) The majority of compaction and subsidence models are designed to replicate the geophysical processes resulting from the relatively shallow withdrawal of groundwater, petroleum, and geothermal fluids (the latter without exsolution gas). See Table 5 in the "Prediction through Analogy" subsection below for a comparison of the important subsidence-related characteristics in representative cases of groundwater, hydrocarbon, geothermal, and hypothetical geopressured fluid withdrawal. For listings and discussion of computer simulations as well as theoretical presentations of compaction and subsidence computations, see Miller, Dershowitz, Jones, Myer, Roman, and Schauer, Simulation of Geothermal Subsidence, 1980, and Proceedings: Second International Conference on Land Subsidence, 1975.

(18) Computational, as opposed to conceptual, models are discussed briefly in the simulation subsection of this report that appears under Techniques for Subsidence Prediction and Monitoring.

stress theory. The subsidence and compaction models presented below, for convenience, are based on the former, analytically simpler model. Two frequently used methods for calculating compaction using a minimum of reservoir data are discussed.

Most models of reservoir compaction and of subsidence begin with a common set of simplifying assumptions (19). It is customary to assume that (20):

- the reservoir shape can be approximated by a disk of a given height (reservoir thickness) and diameter (average of the areal extent of the reservoir);
- the reservoir material is homogenous;
- isotropy (elastic properties of the matrix independent of direction) exists throughout the reservoir; and
- linear elasticity (strain is a linear and single-valued function of stress; i.e., loading and unloading curves are identical and are straight lines).

Kreitler and Gustavson's compaction estimates are based on two frequently used compaction computations (21). One approach is based on the specific storage of the reservoir rock (22). This value is estimated empirically and then used with the formation thickness and the anticipated pressure decrease to arrive at a formation compaction estimate. The second method is based on the change in porosity of the reservoir rock resulting from fluid withdrawal (23).

---

(19) This discussion of models is adapted from Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, 1976, with footnoted inclusions from Thompson and Gray, 1976, Van Til, 1979, and others.

(20) Thompson and Gray, p. 88.

(21) See the subsection entitled <u>Estimates of Geopressured Subsidence</u> for Kreitler and Gustavson's subsidence results.

(22) The first method of compaction evaluation uses the following formula with the specific storage coefficient value from Papadopulos, et al., 1975:

$\Delta m = Ss\,\Delta h\,m$ = change in clay thickness

Ss = specific storage
Δh = pressure decline.
m = clay thickness

(23) The second method estimates compaction through the long-term decrease in reservoir porosity:

$$\Delta m = \Delta\phi\, m$$

$\Delta\phi$ = change in porosity.
m = clay thickness.

This parameter can be estimated given information on the anticipated pressure decline and the initial overburden pressure gradient. As with Kreitler and Gustavson's results, the magnitude of pressure decrease is varied so that a range of compaction figures are derived, each linearly associated with a different rate of reservoir drawdown.

Geertsma developed the <u>uniaxial compaction coefficient</u>, an expression that summarizes several important parameters (24). This coefficient may be overly simplified for geopressured use, however. The assumption of elastic behavior results in computing vertical stresses as three times the horizontal stresses (25). Elastic behavior may be more representative of shallow rock, such as at the Groningen Gas fields of Holland for which the coefficient was first developed (26).

Gabrysch developed a concept for relating compaction of shallow groundwater aquifers to surface subsidence (27). Whether this model can be usefully applied to deep overpressured formations is questionable. The model relates past subsidence to the decline pressure head of the reservoir, and to the percentage of clay in the producing zone in order to derive an empirical relationship for subsidence prediction. Gabrysch

---

(24) For an explanation of the uniaxial compaction coefficient, see Thompson and Gray, pp. 88-89. Vertical compaction estimates are based on:

$$w = c_m h \Delta_p,$$

in which c_m is the uniaxial compaction coefficient, given by

$$c_m = (1-\beta)(1-2v) \div 2\mu(1-v), \text{ with}$$

β = the ratio of the rock matrix to the rock bulk compressibilities

v = the bulk shear modulus (a collection of properties that define the shearing action of the rock as a whole)

μ = the bulk Poisson's ratio.

The uniaxial compaction coefficient has dimensions of psi^{-1}; pressure units cancel yielding a magnitude of vertical compaction distance. Poisson's ratio is an elasticity constant.

(25) This crucial assumption is embodied in Poisson's ratio.

(26) Geertsma, "Land Subsidence above Compacting Oil and Gas Reservoirs," 1973. Thompson and Gray, p. 94, also discuss the possible inapplicability of Geertsma's formulation for geopressured.

(27) Gabrysch, "Land Surface Subsidence in the Houston-Galveston Region," 1970; also 1975 and 1977 papers.

simplifies the overburden characteristics so that compaction and subsidence consitute a direct and rapid response to pore pressure declines. While this may describe the behavior of groundwater aquifers, greater analytical complexity is required to describe subsidence above a geopressured reservoir.

An important factor in geopressured subsidence in the Gulf Coast, faulting, is excluded from these conceptual models (28). The role of faulting in determining the magnitude and the shape of the surface subsidence expression is not well understood.

Estimates of Geopressured Subsidence

Three groups of researchers have used combinations of the existing compaction, overburden, and subsidence models to predict vertical ground movement above either specific or hypothetical Gulf Coast geopressured reservoirs. These estimates are subject to wide ranges of error and should not be used as the basis for subsidence policy. As the researchers themselves are quick to admit, the main value of these estimates is in exploring the sensitivity of the results to various assumptions concerning rates and magnitudes of reservoir compaction and the relation of that compaction to surface subsidence.

The earliest estimates appear to be those of Papadopulos, Wallace, Wesselman, and Taylor in 1975 (29). These USGS researchers assess two different production rates of pressure drawdown to derive "crude estimates" for subsidence above a hypothetical "representative" geopressured reservoir. The estimates represent upper bounds. Assumptions common to both sets of estimates are that: a) there is full reservoir compaction (the full decrease in effective stress resulting from pore pressure reduction is translated into deformation of the solid matrix), and b) that this compaction of the reservoir is expressed 1-for-1 as surface subsidence.

---

(28) See the discussion of simulation in the Techniques for Subsidence Prediction and Monitoring section.
(29) See "Assessment of Onshore Geopressured Geothermal Resources in the Northern Gulf of Mexico Basin," in U.S.G.S. Circular 726, pp. 136-138.

Under Plan 1, fluid is removed from the reservoir using several wells at a combined rate of 0.15 m^3 per second (about 81,000 barrels per day). Over 20 years the average subsidence ranges from 5 to over 7 meters for Plan 1. Under Plan 3, in which fluid withdrawal rates are restricted, the average subsidence at the surface is 1 meter. (Plan 2, production with an intermediate rate of reservoir pressure reduction, was not used for subsidence calculations).

In 1976, Kreitler and Gustavson estimated the subsidence that might occur at the Armstrong field, a fairway in Kenedy County, Texas (30). Compaction is first calculated with two different methods using a range of pressure decline values. With the first compaction calculation, Kreitler and Gustavson's order-of-magnitude estimates for three wells range from lows of 1.6, 2.6, and 3.4 meters at a pressure decline of 100 psi, to 16, 26, and 34 meters at pressure declines of 1000 psi. Reservoir clay thicknesses for each well are 70, 113, and 146 meters, respectively. The magnitude of compaction and the pressure decline are linearly related (31).

The second compaction computation, using a different method, yields far lower figures. With identical clay thicknesses, the compaction figures are 0.7, 1.1, and 1.5 meters at a pressure reduction of 100 psi. At 1,000 psi the comparable figures are 3.5, 5.7, and 7.3 meters (32).

The authors use Geerstma's theory of poroelasticity to translate reservoir compaction into subsidence. Geerstma's percentages are used to relate subsidence to the depth and type of overburden (33). The figures for subsidence for each of the wells (again the same clay thicknesses and the same range of pressure declines), for compaction methods 1 and 2, respectively, range from: 0.6 to 5.9 meters and 0.3 to 1.3 for the first well; from 1.0 to 9.6 meters and 0.4 to 2.1 meters for the second well; and from 1.3 to 12.6 meters and 0.6 to 2.7 meters for the third well (34).

---

(30) See Kreitler and Gustavson, pp. 25-32. Also the Models Compaction and Subsidence section of this report, particularly footnotes 22 and 23 for the details of these two computations.
(31) Ibid, Table 1, p.28.
(32) Ibid, Table 2, p.30.
(33) Geertsma, 1973, p. 740.
(34) Kreitler and Gustavson, Table 3, p. 31.

Kreitler and Gustavson express no concern about the use of Geertsma's poroelasticity theory, and Gustavson has recently stated that the theory is still the best available for estimating subsidence (35). In regard to the wide variation in compaction estimates attributed to each method, Kreitler and Gustavson comment:

> "A more accurate estimate for reservoir compaction will be known only when mudstone compressibilities can be determined experimentally with actual core material... The different approaches, however, suggest that some mudstone compaction should be expected when pore pressures are lowered significantly within the reservoir" (36).

A third set of subsidence estimates has recently been made for the Lawrence Berkeley Laboratory by Earth Sciences Associates (ESA). These unpublished, hand-calculated subsidence estimates for four geopressured aquifers are part of an exercise intended to determine the magnitude of problems now encountered by researchers estimating subsidence (37). This effort includes an attempt to identify those compaction and subsidence concepts that are most pertinent to geopressured subsidence assessment. The results are only preliminary.

The Phase 1 report of EDAW-ESA identifies four geopressured prospect areas intended to be representative of the range of reservoir, overburden, and surface characteristics likely to be found in the Gulf Coast. The reservoirs include two in Texas, the Austin Bayou Prospect (Brazoria Fairway) and the Cuero Prospect (DeWitt Fairway); and two in Louisiana, the Gladys McCall Prospect and the S.E. Pecan Island Prospect (38).

The subsidence estimates of ESA were derived using: a) a compaction model similar to method 1 of Gustavson and Kreitler that relates sandstone compressibility and pressure decline to compaction, b) Terzaghi's

---

(35) Meeting with Peter Deibler and Tony Usibelli, April 28, 1980.

(36) Kreitler and Gustavson, p. 30.

(37) Telephone Conversation with Linda Lee, ESA, July 17, 1980.

(38) See EDAW-ESA, 1980, p.1. Also Newchurch, Van Sickle, Bachman, Bryan, Harrison, Muller, and Smith, "A Comparison of Six Geopressured Geothermal Prospect Areas in the Louisiana Gulf Coast Region on the Basis of Potential Environmental Factors," 1979. This paper discusses the potential for impact, should subsidence occur, at the S.E. Pecan Island Prospect.

theory on the compressibility and de-watering contribution of the shales within and adjacent to the reservoir strata, and c) Geertsma's poroelasticity theory to translate compaction into subsidence. ESA found conceptual problems in applying the second and third models. It is questionable whether Terzaghi's theory of the behavior of strata within several hundred feet of the earth's surface is applicable at great depths; poroelasticity theory assumes linear elastic behavior that may not be characteristic of rock behavior in overpressured zones.

Subsidence estimates are calculated for two sets of assumptions. First, assuming relatively low compressibilities for both the reservoir rock and the adjacent shales, subsidence ranges from about 0.02 to 0.2 meters for the four prospect areas. The second set of assumptions, sandstones of low compressibility but highly compressible shales, yield subsidence figures ranging from about 0.1 to 1.3 meters. A third set of assumptions based on highly compressive sandstones and shales should be considered until early experimental results indicating low sandstone compressibility can be verified (39).

All of ESA's estimates are substantially below those described above. These estimates will now be used as the basis for designing a research program for in-situ and laboratory analysis aimed at answering such questions as whether: a) shale dewatering is relevant to reservoir compaction, b) the poroelasticity theory is applicable to geopressured, and c) subsidence effects will take place rapidly upon fluid withdrawal or if substantial lag times may be involved (40).

Subsidence in the Gulf Coast

Gulf Coast Geology and its Relation to Subsidence Potential

---

(39) Telephone conversation with Linda Lee, ESA, July 17, 1980. Measurement of Brazoria cores tested in the lab by Ken Gray of the University of Texas indicate compressibilities lower than anticipated.

(40) Telephone Conversation with Linda Lee, ESA, July 17, 1980

The sedimentary depositional processes of the Gulf Coast encourages natural subsidence. Rivers provide millions of tons of silt per year, increasing the total depth of sediments, increasing loading pressures, and causing compaction. The Gulf Coast geosyncline is up to 60,000 feet in depth; compaction and diagenesis leach fluids from the deeper sediments and, unless counterbalanced by the deposition of new sediment, surface subsidence results. Syndepositional growth faulting increases with the most southerly sediments. Figure 6 illustrates the extensive growth faulting zones that parallel the Gulf Coast (41). The upper boundary of the geopressured zone usually increases with the age of the sediment. Wallace notes that the potential for subsidence is greater in the Miocene formations of the Louisiana geopressured zone than for the older formations underlying the onshore area of Texas (42).

While assessing the causes of subsidence in the Gulf Coast in an effort to establish a baseline collection of data prior to geopressured fluid production, Newchurch et al. note that vertical movement in coastal Louisiana can be attributed to:

- regional subsidence from sedimentary loading associated with downwarping, compaction processes, and tectonic processes;
- subsidence from shallow withdrawal of hydrocarbons and groundwater;
- local subsidence resulting from shallow salt and sulfur mining;
- subtle and frequently undetected subsidence resulting from hydrocarbon and formation water production from deep but normally pressured reservoirs, and;
- subsidence resulting from volume reduction of soils due to oxidation, dehydration, and erosion (43).

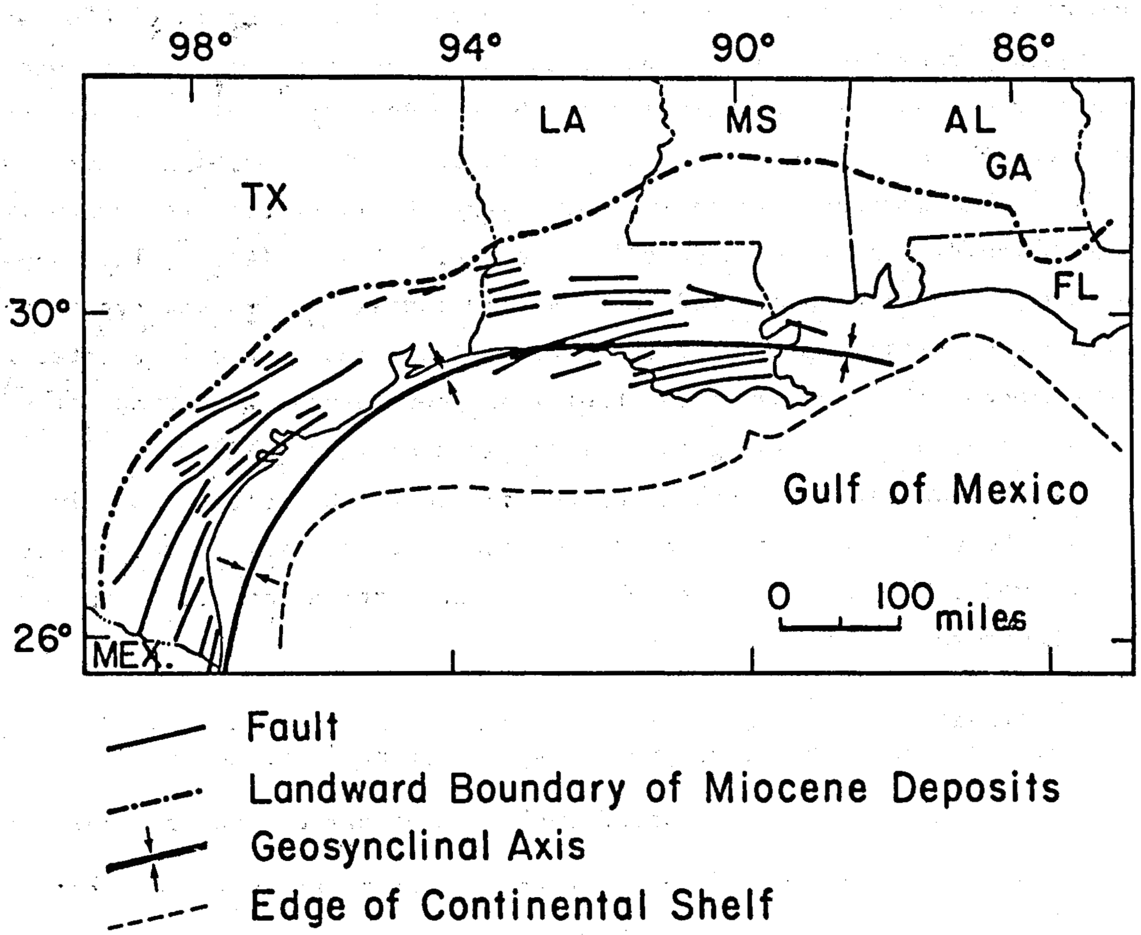
---

(41) For brief overviews of Gulf Coast geology and theorized processes for geopressure formation, see: Newchurch, Bryan, Harrison, Muller, Wilcox, Bachman, Newman, Cunningham, Hilding, and Rehage, in UCRL-13913, pp. 77- 88, and; Atherton et al. Volume 2, pp. 2-71 to 2-87. This discussion is based on these two sources, as well as Jones' paper in the First Geopressured Geothermal Conference Proceedings, and the geology overview section of this report.

(42) See Wallace's comments in Strongin, Final Report - Issue Paper on Geopressured Resource Development Criteria and Industry Incentives, 1979.

(43) Newchurch, et al. (see footnote 41 for the full reference), pp. 91-92.

Figure 6 MAJOR REGIONAL FAULT ZONES IN NEOGENE DEPOSITS, NORTHERN GULF OF MEXICO BASIN (modified from Murray, 1961)



Modified from Jones and Wallace, 1974

XBL 796-1801

Figure 6 Major Regional Fault Zones in the Neogene Deposists, NOrthern Gulf of Mexico Basin (modified from Murray, 1961)

Source: Grimsrud, Truner, and Frame, 1978.

Local and regional shear faults, along with impermeable caprocks, are thought to form the boundaries of the confined geopressured aquifers. If these faults have surface expression, they probably play a major role in determining the volume of the overburden that directly loads the reservoir, as well as the subsidence profile at the surface. Shear faults may be responsible for lateral shifts so that the subsidence bowl may not be directly over the reservoir. Angular faulting may also result in a complex interbedding of overlying formations that, due to increased structural integrity, may limit the magnitude and extent of direct compaction of the overlying formations. See Table 5 in the subsidence analogy subsection of this report for a comparison of relevant factors. The presence of the faults, however, may increase subsidence potential but localize the effects by bounding the dimensions of the subsidence bowl.

It has been suggested that the cemented caprock at the top of the geopressured zone may be of sufficient thickness and integrity to significantly limit the portion of reservoir compaction translated to the surface. Little is known about this caprock or of its ability to inhibit subsidence (44).

Historical Rates of Subsidence

Preliminary mappings are available for rates of regional Gulf Coast subsidence resulting from the combined effects of the non-geopressure geothermal processes listed above. Figure 7 maps the elevation changes. Figure 7 indicates background subsidence (both natural and man-induced) of up to 5 mm/yr in both the New Orleans area of Louisiana and the Houston-Galveston area of Texas (45).

The collection of extensive baseline subsidence data for the areas surrounding drilled and planned geopressured wells is just beginning. Data collection is scheduled to commence in late 1980 or early 1981 for the Parcperdue, Sweet Lake, and LaFourche Crossing prospects of Louisiana (46). Baseline monitoring prior to spud-in and during testing

---

(44) Atherton, et al. Volume 2, p. 2-86.

(45) See the following subsection, Prediction through Analogy, for a brief discussion of the groundwater withdrawal-induced subsidence of the Houston-Galveston area.

(46) See the discussion below in the Subsidence Planning for DOE Wells subsection.

PRELIMINARY RATES OF ELEVATION CHANGE
(From Holdahl and Morrison, 1974).
Units for Contour Levels are mm/yr.

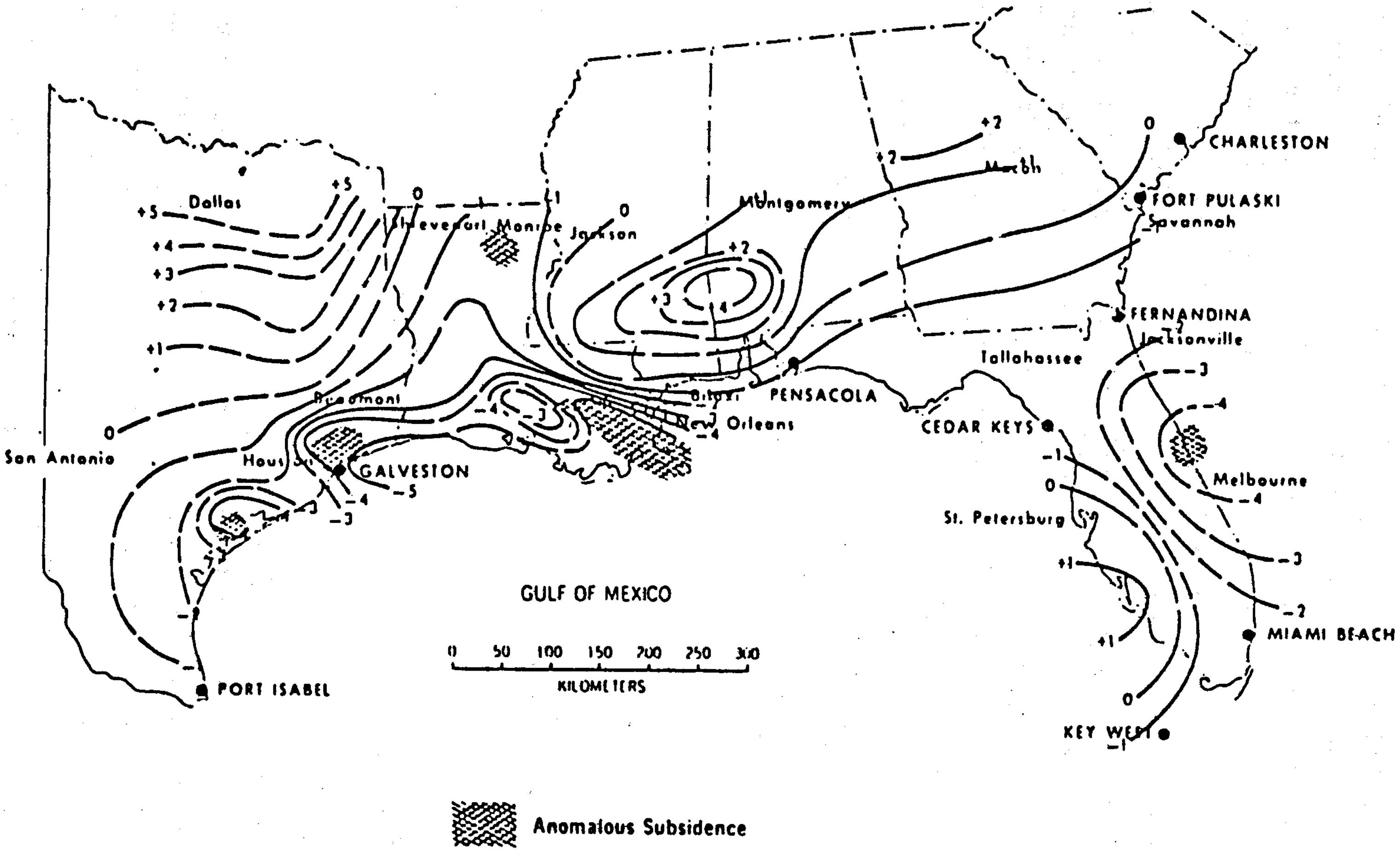


Figure 7

Source: Newchurch, Bryan, Harrison, Muller, Wilcox, Bachman, Newman, Cunningham, Hilding, and Rehage, 1978.

phases, has been done in the area of the Brazoria well (47). "Natural subsidence", a term used here to indicate all background vertical movement, whether geologic or man-induced occurs at a mean rate of 8.8 mm/yr (0.029 ft.) in the vicinity of the Brazoria well. First-order leveling surveys indicate that a range in total subsidence of from 0.119 to 0.373 meters (0.391 to 1.224 ft) has occurred in the well vicinity between 1942 and 1978.

Techniques for Subsidence Prediction and Monitoring

Introduction

There are at least two approaches to subsidence evaluation. The first, the analytical approach, has four phases : (1) geophysical methods for surface monitoring at pre-production, production, and post-production phases of development; (2) subsurface monitoring of the drilled wellbore through logging and sampling; (3) laboratory testing of in-situ core samples with interstitial fluid intact through the replication of downhole conditions; and (4) computer simulation of reservoir compaction properties and subsidence.

The second approach, evaluation by analogy, consists of examining other instances of subsidence known to have resulted from fluid withdrawal in an effort to discern pertinent comparisons to the geopressured case. Unfortunately, any direct analogy of geopressured subsidence to subsidence above groundwater, oil and gas and fluid-dominated geothermal aquifers is questionable at best. Analogous situations of subsidence have helped, however, by fostering the development of a body of theory, that although possibly inapplicable in a number of aspects to the geopressured case, does serve as a basis for delineating future research. The study of analogous subsidence situations is also relevant in that comparison may help to identify factors of importance in geopressured subsidence.

---

(47) See Gustavson, Dorman, Sorrells, and Wilson, "Environmental Baseline Monitoring in the Area of General Crude Oil/Department of Energy Pleasant Bayou Number 1 - A Geopressured Geothermal Test Well, 1978."

Analytical Techniques

Surface Monitoring

Van Til enumerates six reasons for a surface monitoring program, although they apply equally well to all aspects of the analytical evaluation of subsidence. Site-specific subsidence analysis may be undertaken for any of the following reasons (48):

1. To evaluate potential subsidence impact on surface and subsurface environmental features such as streams, bayous, wildlife habitats, and the integrity of freshwater aquifers.
2. To evaluate potential subsidence impact on man-made structures, including irrigation and drainage canals, on-site plant facilities, and transportation systems.
3. To aid in the development of subsidence monitoring techniques, in studying the relation of rates and magnitudes of fluid withdrawal or of reinjection to subsidence, etc.
4. To verify the adequacy of engineering design features or production control and field development programs intended to minimize the effects of subsidence.
5. To satisfy legal requirements for monitoring and evaluation.
6. To collect evidential data for enforcement of subsidence monitoring and control regulations.

Activities that should be considered in planning a surface subsidence monitoring program include (49):

---

(48) Adapted from Van Til, Guidelines Manual for Surface Monitoring of Geothermal Areas, pp. 3-4. Although specifically designed for liquid-dominated and vapor-dominated normally pressured geothermal reservoirs, this manual appears to be a good starting point for evaluation of geopressured development in the Gulf Coast.

(49) Ibid, pp. 6-18.

- Preliminary Investigation
    1) basic data gathering
    2) initial site inspection
    3) field investigation
    4) report of preliminary investigation
    5) plan for additional information

- Design of Monitoring System
    1) defining the site
    2) regional survey network
    3) local survey network
    4) special monitoring
        a) extensometers
        b) tiltmeters

- Monitoring Operations
    1) construction
    2) scheduling
        a) pre-production phase (baseline)
        b) production phase
        c) post-production phase
    3) measurements
    4) data handling.

The preliminary investigation stage is largely self-explanatory. The low elevations and the consequently high potential for salt water intrusion (given surface subsidence) are major considerations for Gulf Coast geopressured development. Design of monitoring activities have been completed for the Brazoria well and will soon be completed for the current Louisiana prospects (50). The prospect areas are tied into the regional survey network of benchmarks that either have been recently, or are now being, resurveyed by the National Geodetic Survey.

A first-order leveling survey is completed for the vicinity of the wellhead. Tables 1 and 2 list the accuracy requirements for first-, second-, and third-order horizontal and vertical control surveys, respectively. In areas other than the Gulf Coast, second-order accuracy might be adequate. Despite the added expense and the slower retrieval of information, first-order leveling will be used for geopressured well testing. Surveying procedures are well established and documented and are not covered here (51).

---

(50) See the subsection Subsidence Planning for DOE Wells below.
(51) See Van Til, pp. C-3 to C-17 for surveying details.

Table 1. (a) Summary of Standards for Horizontal Control Surveys - Triangulation

Survey Classification	First Order	Second Order	Third Order
Base Line Measurements	1 in 1,000,000	1 in 900,000 (Cl. I);	1 in 500,000 (Cl. 1);
Standard Error		1 in 800,000 (Cl. II)	1 in 250,000 (Cl. II)
Triangle Closure			
Average, not to exceed	1.0"	1.2"(Cl. I); 2.0"(Cl. II)	3.0"(Cl. I); 5.0"(Cl. II)
Maximum, seldom to exceed	3.0"	3.0"(Cl. I); 5.0"(Cl. II)	5.0"(Cl. I); 10.0"(Cl. II)
Closure in length,			
Should not exceed	1 in 100,000	1 in 50,000 (Cl. I); 1 in 20,000 (Cl. II)	1 in 10,000 (Cl. I); 1 in 5,000 (Cl. II)

(b) Summary of Standards for Horizontal Control Surveys - Trilateration

Survey Classification	First Order	Second Order	Third Order
Minimum Angle in Geometric Configuration	25°	25° (Cl. I); 20° (Cl. II)	20° (Cl. I); 15° (Cl. II)
Length Measurement	1 in 1,000,000		

Source: Van Til, 1979.

Table 2. Summary of Standards for Vertical Control Surveys*
(After Moffitt and Bouchard, 1975)

Survey Classification	First Order	Second Order	Third Order
Related Uses	Control network; regional tectonic movements	Subsidence monitoring networks	Supplementary subsidence measurements
Instruments	Automatic or tilting levels with parallel plate micrometers; invar scale rods	Automatic, tilting, or geodetic levels; invar scale rods	Geodetic levels and rods
Maximum length of sight	50 meters (Cl.I); 60 meters (Cl.II)	60 meters (Cl. I); 70 meters (Cl. II)	90 meters
Maximum closures (K = Distance in kilometers)	$3mm\sqrt{K}$ (Cl.I); $5mm\sqrt{K}$ (Cl. II)	$6mm\sqrt{K}$ (Cl. I); $8mm\sqrt{K}$ (Cl. II)	$12mm\sqrt{K}$

---

*Standards subject to change. Before using, check current publications,

Source; Van Til, 1979.

Van Til details the advantages of certain monitoring tools and describes desirable instrument features for geothermal or geopressured leveling (52). Vertical leveling tools include the precision level with optical micrometer and split bubble spirits. Monitoring of horizontal movements requires direct tape measurement, triangulation, or electronic distance monitoring (EDM) instruments. EDM devices are becoming increasingly popular because of their accuracy and ease of use (53).

Photogrammetry, used mainly in aerial photography, does not yield the required accuracy of a first-order leveling. But old aerial photographs taken with this method, when compared to recent aerial photographs, can illustrate topographic changes such as the appearance of new faults.

Extensometers and tiltmeters are used in high accuracy monitoring (54). Extensometers measure the change in distance between two closely-spaced points (between 10 feet and 100 feet apart) and are frequently used to measure shear movement across faults.

Tiltmeters are single-point-station tilt monitoring instruments that use a variety of sensors to transmit raw data, in the form of micrometer readings versus time, for remote readout. Both portable and permanent devices are available; the former is more popular but the latter is being tested for use in DOE geopressured well areas. Tiltmeters require a redundancy in the recording of data so that local anomalies can be averaged for mapping area-wide isotilt contours. Tiltmeters are accurate to approximately two seconds of arc. The Brazoria tiltmeter is a prototype using three organic fluids for enhanced sensitivity (55). The device will be permanently installed on steel pipes that are driven to 30 feet or refusal in the soil. Special design measures have been taken to avoid vertical stressing of the buried pipe

---

(52) Ibid, Appendix D.

(53) Ibid, see p. D3 for a description of EDM instrument use.

(54) Ibid see p. D4, and pp. D8 to D17 for descriptions of these devices. Borehole extensometers are used for subsurface monitoring as explained in the following subsection. The term "tilt," as used in ground movement studies, is discussed in the following section on the severity of subsidence impacts.

(55) Gustavson, Dorman, Sorrells, and Wilson, "Environmental Baseline Monitoring in the Area of General Crude Oil/Department of Energy Pleasant Bayou Number 1 - A Geopressured-Geothermal Test Well, 1978."

during soil wetting and drying cycles.

The scheduling of monitoring operation must be flexible but allow for an adequate period of baseline data collection. Production (or testing) and post-production measurements will include periodic releveling, probably on an annual basis, or more frequently if subsidence occurs.

Subsurface Monitoring

One of the volumes in the Lawrence Berkeley Laboratory's Geothermal Subsidence Research series details the capabilities of existing instruments and the research needed for accurate borehole measurement of overburden strata compaction (56). The research section of this report lists the research recommendations of the LBL consultants. Subsurface monitoring is not covered in great detail here because the expense of a research program to develop these devices is probably not warranted at this stage in the assessment of the geopressured resource. This research may be undertaken for other geothermal resources, however. Advancements made in such a program should be applicable, with modification, to geopressured if commercial development appears feasible.

Geothermal wells, and geopressured wells in particular, present very hostile environments for long-term, in-place instrumentation. The special component design characteristics required for scaling, corrosion, temperature, and pressure analysis have benefited from jet engine and space vehicle development.

Borehole extensometers measure changes in vertical distance and borehole inclinometers measure changes in horizontal displacement. The former is generally a permanently installed mechanical device while the latter is usually a probe. Both extensometers and inclinometers consist of five components (57):

---

(56) O'Rourke and Ranson of Woodward-Clyde Consultants, Instruments for Subsurface Monitoring of Geothermal Subsidence, July 1979. This report forms the basis for this subsection.
(57) Ibid, p. 1.

1. the borehole
2. markers
3. a sensing device and read-out
4. a logging system
5. an azimuthal orientation device (inclinometers only)

The operation of an instrumentation system is dependent on the integrity of each of these components. O'Rourke and Ranson concentrate on extensometers because a) vertical movement is more important to measure, and, b) the technology needed for adequate inclinometer measurements for geothermal wells is either state-of-the-art or not yet available.

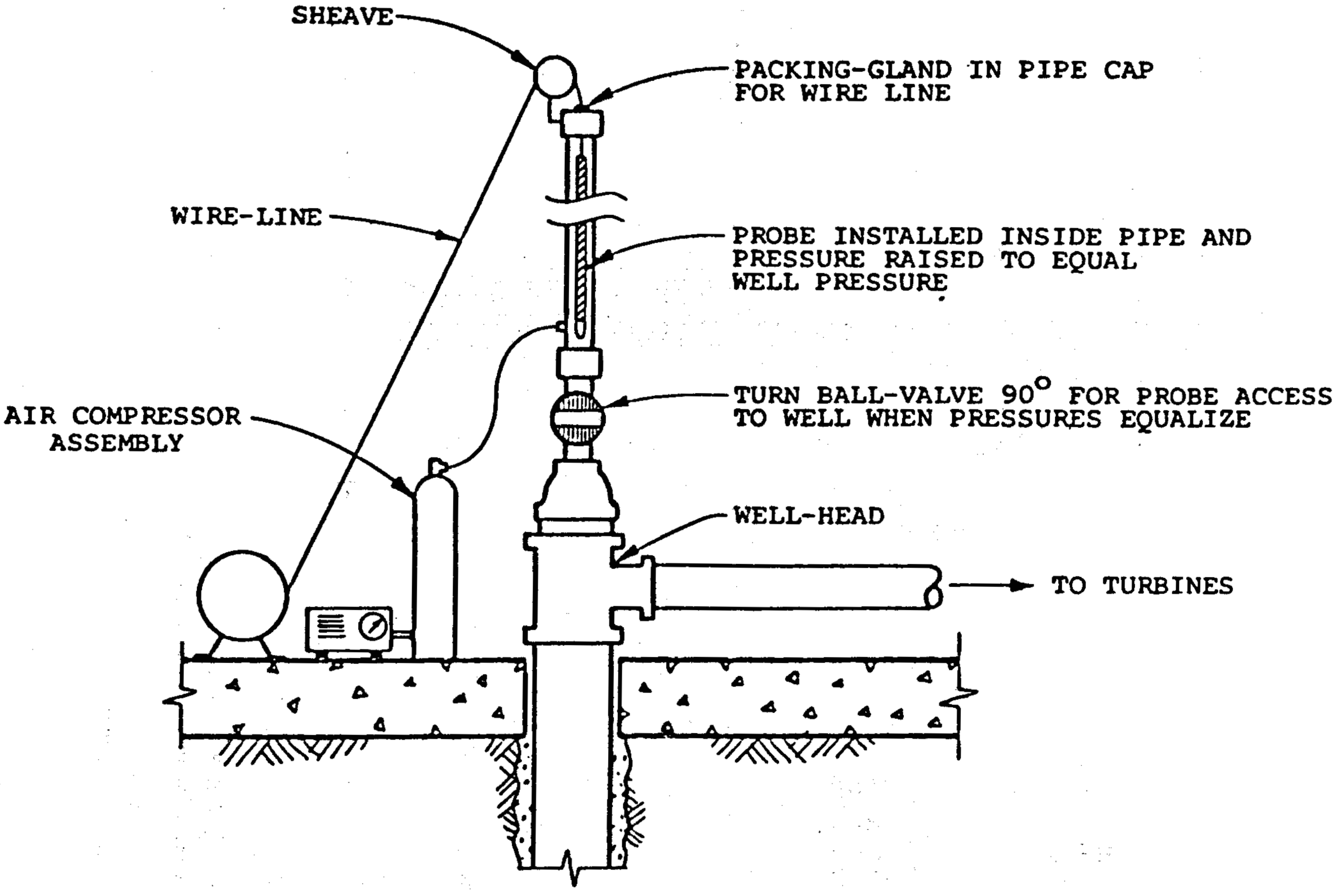
In order to place subsidence-measuring instruments at a geopressured site, the borehole will have to be cased. Markers are used to measure vertical and horizontal displacement. In the design of current geopressured wells, radioactive bullets are used for vertical measurement; horizontal movement is not measured. The sensing device is the crucial component of the instrumentation measuring the spacing between markers. It is lowered into the hole and then retrieved. The logging system complements this device. Following a survey of available extensometers and inclinometers, O'Rourke and Ranson found none to be adequate for geothermal use without modification (58).

Geophysical logging and casing markers both have limitations in current monitoring arrangements. Logging gives only averages of overburden compaction and cannot provide a subsidence profile. Thus geophysical logging alone cannot identify the compacting strata. Casing markers do yield a profile, but their accuracy may be degraded by slippage between the casing and the annular wall, or between the casing and the surface.

Figures 8 and 9 illustrate several recommendations for handling these problems with casing markers. (59). Figure 8 shows an access gland for the use of probes with permanent surface instrumentation that minimizes down time during measuring. Figure 9 illustrates the placement of an outer string of auxiliary tubing used exclusively for instrumentation. In addition, O'Rourke and Ranson recommend the use of slip couplings and corrugated casing, both of which allow for thermal

---

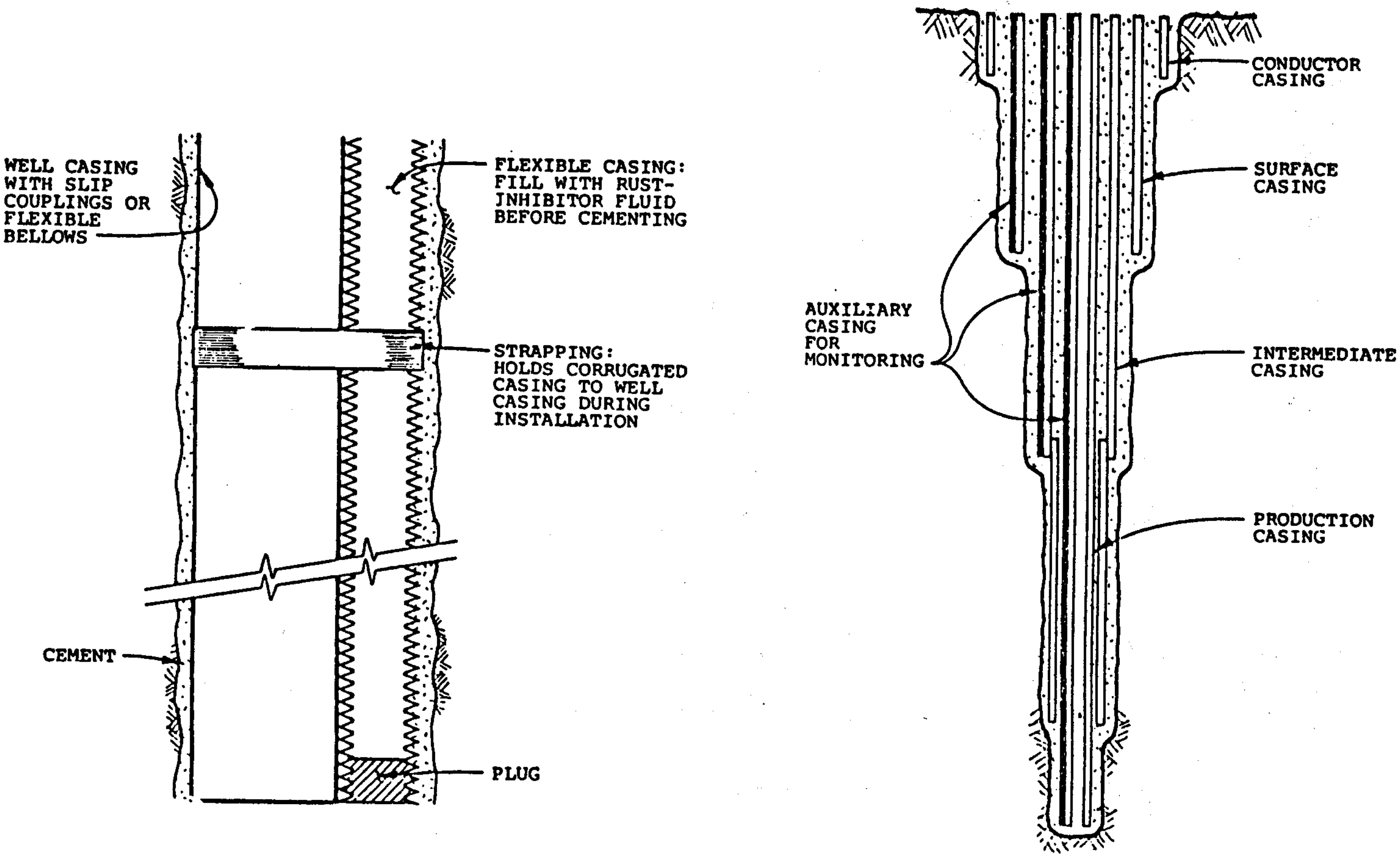
(58) Ibid, p.6.
(59) Ibid, pp. 49, 50.



NOTE: ALL EQUIPMENT EXCEPT PROBE IS LEFT AT WELL HEAD.

Figure 8 - ACCESS GLAND FOR SETTLEMENT PROBE

Source: O'Rourke and Ranson, 1979.



a) SCHEMATIC OF INSTALLATION

b) USE OF MULTIPLE AUXILIARY CASING

Figure 9 - AUXILIARY CASING INSTALLATION
Source: O'Rourke and Ranson, 1979.

expansion and contraction of the production string without buckling. The casing integrity will be increased, and marker readings will have a higher assurance of accuracy.

The Woodward-Clyde report details improvements required to overcome corrosion, scaling, temperature, and pressure problems, and recommends materials for geothermal instrumentation use. Tables 3 and 4 list the recommended accuracies for vertical and horizontal measurements downhole (60).

Laboratory Study

Laboratory testing consists of studying the lithology of downhole samples as well as the physical and chemical characteristics of in-situ fluids. It is important to know how both the solid matrix and the brine will react to reduced pore pressures and increased effective stress. Geopressured laboratory techniques have just reached the point at which in situ conditions of temperature and pressure are routinely replicated with downhole samples (61). Ken Gray of the University of Texas at Austin has done the bulk of the rock testing for the geopressured program. Gray describes his laboratory:

> "The testing apparatus is called the simultaneous properties system. The pressure vessel takes the cylindrical samples between platens; pore pressure and confining pressure can be independently controlled up to about 50,000 psi. Deformations, p and s wave velocities, permeabilities, and pore volume changes are measured" (62).

Gray found lower than expected compressibility figures for in-situ samples from the Brazoria well. The ratio of the matrix compressibility to the bulk compressibility was higher than expected, on the order of 1 in 10 or 1 in 15. Thus the total volume change accompanying compaction

---

(60) Ibid, pp. 7-9, and 32, and pp. 20,21 and 32, respectively.
(61) See the Laboratory Testing subsection of the subsidence research section for more detail on the labs involved and their plans for future work.
(62) See United States Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Drilling and Testing Working Subgroup," August 1, 1979, pp. 65-68.

Table 3. Specifications for Monitoring Subsurface Vertical Displacements.

TYPE OF GEOTHERMAL RESOURCE MEASUREMENT CAPABILITY	VAPOR-DOMINATED	LIQUID-DOMINATED	GEO-PRESSURED
MAXIMUM DEPTH OF MEASUREMENT	3 km (6 km)	3 km (6 km)	(6-7 km)
MAXIMUM TOTAL COMPACTION	0.3 m (0.6 m)	4 m (6 m)	(5-7 m)
DESIRED MAXIMUM VERTICAL INTERVAL BETWEEN MONITORING POINTS	30 m, increasing to 80 m outside reservoir	30 m, increasing to 80 m outside reservoir	(30 m, increasing to 80 m outside reservoir)
ACCURACY OF MEASUREMENT OVER FULL DEPTH OF INSTALLATION	±3 mm	±30 mm	(±30 mm)
ACCURACY OF MEASUREMENT OVER 30 M INTERVAL	±0.5 mm	±5 mm	(±5 mm)
MINIMUM FREQUENCY OF READINGS	weekly for 1st month; monthly for 1st year; then semi-annually	weekly for 1st month; monthly for 1st year; then semi-annually	(weekly for 1st month; monthly for 1st year; then semi-annually)
MONITORING PERIOD	15 yrs (50 yrs)	15 yrs (50 yrs)	(15 yrs)

TYPE OF GEOTHERMAL RESOURCE ENVIRONMENTAL CAPABILITY	VAPOR-DOMINATED	LIQUID-DOMINATED	GEO-PRESSURED
TEMPERATURE	285°C (300°C)	300°C (375°C)	(375°C)
PRESSURE	35 kg/cm^2	300 kg/cm^2 (600 kg/cm^2)	(800-1,000 kg/cm^2)
SALINITY	0.01%	3% (20%)	(3%, increasing to up to 20% above reservoir)
DISSOLVED SOLIDS	0.2%	30%	(more than 30%)

Note: Long-term values in parentheses

Source: O'Rourke and Ranson, 1979.

Table 4. Specifications for Monitoring Subsurface Horizontal Displacement.

TYPE OF GEOTHERMAL RESOURCE MEASUREMENT CAPABILITY	All Cases
MAXIMUM ANGULAR ROTATION OVER DEPTH	1°
MAXIMUM LOCAL ANGULAR ROTATION	10 deg
ACCURACY OF ANGULAR ROTATION MEASUREMENT	40 sec
Note: depth, frequency, monitoring period and environmental capabilities same as Figure 3.	

Source: O'Rourke and Ranson, 1979.

appears not to result from pore volume decrease.

Values for bulk compressibility as a function of the hydrostatic stress are measured by both p and s wave travel times and by strain gauges attached to the sample. Porosity is determined by two methods that are usually in close agreement: a) volume change using strain gauges, and, b) actual fluid ejected from the core or added to a previously drained sample. Testing of core samples from the Brazoria well indicates that the uniaxial compaction coefficients are surprisingly low (63). Because lab work is at an early stage, the planned activities are described under research.

Computer Simulation

The following paragraphs discussing simulation draw on the Golder Associates report and on a paper presented at the Fourth Workshop on Geothermal Reservoir Engineering (64). The first report simulates the Austin Bayou as an exercise in testing the sensitivity of various parameters. The Systems, Science, and Software (SSS) paper also simulates the Austin Bayou Prospect, but with the intention of obtaining preliminary subsidence results. The intention here is not to provide an exhaustive review of existing models, but rather to illustrate the state-of-the-art in modeling--its strengths and weaknesses. The Golder Associates volume provides listings of geothermal reservoir and deformation models with comments on usefulness (65). Two companion volumes provide a mathematical presentation of the simulated compactions and an in-depth evaluation of six subsidence models now available (66). The Pinder volume (also Golder Associates) provides a more comprehensive coverage of the current limits of geothermal reservoir modeling (67).

---

(63) See Ken Gray's comments, U. S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Drilling and Testing Working Subgroup, August 1, 1979, pp. 65-68.

(64) See Miller, Dershowitz, Jones, Myer, Roman, and Schauer, Simulation of Geothermal Subsidence, 1980, and; Garg, Riney, and Brownell, "Preliminary Reservoir and Subsidence Simulations for the Austin Bayou Geopressured Geothermal Prospect," 1978.

(65) See Tables la and 12, pp. 17, 151.

(66) Miller, Dershowitz, Jones, Myer, Roman, and Schauer, Physical Processes of Compaction - Companion Report 1, 1980, and, Detailed Report on Tested Models - Companion Report 2, 1980.

(67) See Pinder, State-of-the-Art Review of Geothermal Reservoir Modelling, 1979, in particular Table 2a and accompanying text, p.124.

Research needs and recommendations for model development presented by Miller et al. are covered at a later point (68).

Miller et al. include an idealized case study of the Austin Bayou Prospect. "(The) purpose is to study modeling, not to study the Austin Bayou. We have tried to make the model realistic only to the extent that it is <u>similar to</u> [original emphasis] a real Gulf Coast geopressured geothermal system" (69). This study of modeling assumptions and sensitivities focuses on (70):

- The application of different flow models for geothermal reservoirs
- The importance of flow/deformation coupling
- A comparison of different types of constituent relationships
- The importance of dimensionality
- The implementation and accuracy of models incorporating only a portion of the total system
- The effects of faults in regions of geothermal production
- The sensitivity of surface subsidence to variations in material elastic properties
- The effects of geothermal spent fluid reinjection.

The production scheme consists of three wells, each draining two zones for a total reservoir production of 45,000 bbls/day. Each producing zone is 60 feet thick. Three mixes of overburden constituency were used: a) unconsolidated clay and shale, b) 65% shale and 35% sandstone, and c) 10% sandstone (71). The model uses elastic compaction behavior, Geertsma's subsidence formulations, and generalization of the reservoir shape as a disk for one-dimensional modeling of compaction and subsidence. two- and three-dimensional simulation techniques are used to couple reservoir flow-to-deformation activity, with elastic behavior again assumed.

---

(68) See the <u>Computer Simulation</u>, subsection under Subsidence Research.

(69) See Miller, Dershowitz, Jones, Myer, Roman, and Schauer. The quote is from page 102.

(70) Ibid, p. 107.

(71) Ibid, pp. 105, 107.

One three-dimensional model, NFOLD, is considered to be the only available fault simulation model. Further development of the model is recommended; its subsidence results are suspect because the horizontal effects of pore pressure decreases are excluded from the model. However, the results indicate that faulting is relatively unimportant in the expression of subsidence at this particular prospect. This finding should not be generalized to other geopressured prospects (72).

Among the case study conclusions (73):

- Lack of physical data is the limiting factor in model accuracy
- The basic physical processes of subsidence appear to be well understood and correctly modelled
- The dimensionality of the model (one- , two-, three-, or axisymmetric) is an important factor in model usefulness
- Knowledge either of reservoir pressure and temperature decrease or of the rate of fluid withdrawal are important
- Accurate knowledge of stress-strain relationships is "somewhat important" at Austin Bayou (due to shale nonlinear behavior)
- Reservoir depth relative to extent is important
- Temperature effects are unimportant in the geopressured case
- The use of stress-dependent permeability has a modest effect on the rate of pressure decline and little effect on compaction
- Reinjection of fluids into the overburden will do little to retard or halt subsidence
- Geothermal subsidence models are needed that can handle two-phase flow with less complication. Figures 10 and 11 illustrate sources of error and the degree of uncertainty attributable to various factors in the modeling process.

Garg, Riney, and Brownell have also simulated the compaction and subsidence behavior of the Austin Bayou Prospect (74). The authors estimated the reservoir properties (in lieu of unavailable test data),

---

(72) Ibid, pp. 109, 112.

(73) All conclusions but the last two, pp. 143-144. Conclusions regarding reinjection, pp. 139, 142. Two-phase modeling is discussed on pp. 118-119.

(74) See Garg, Riney, and Brownell, "Preliminary Reservoir and Subsidence Simulations for the Austin Bayou Geopressured Geothermal Prospect," 1978.

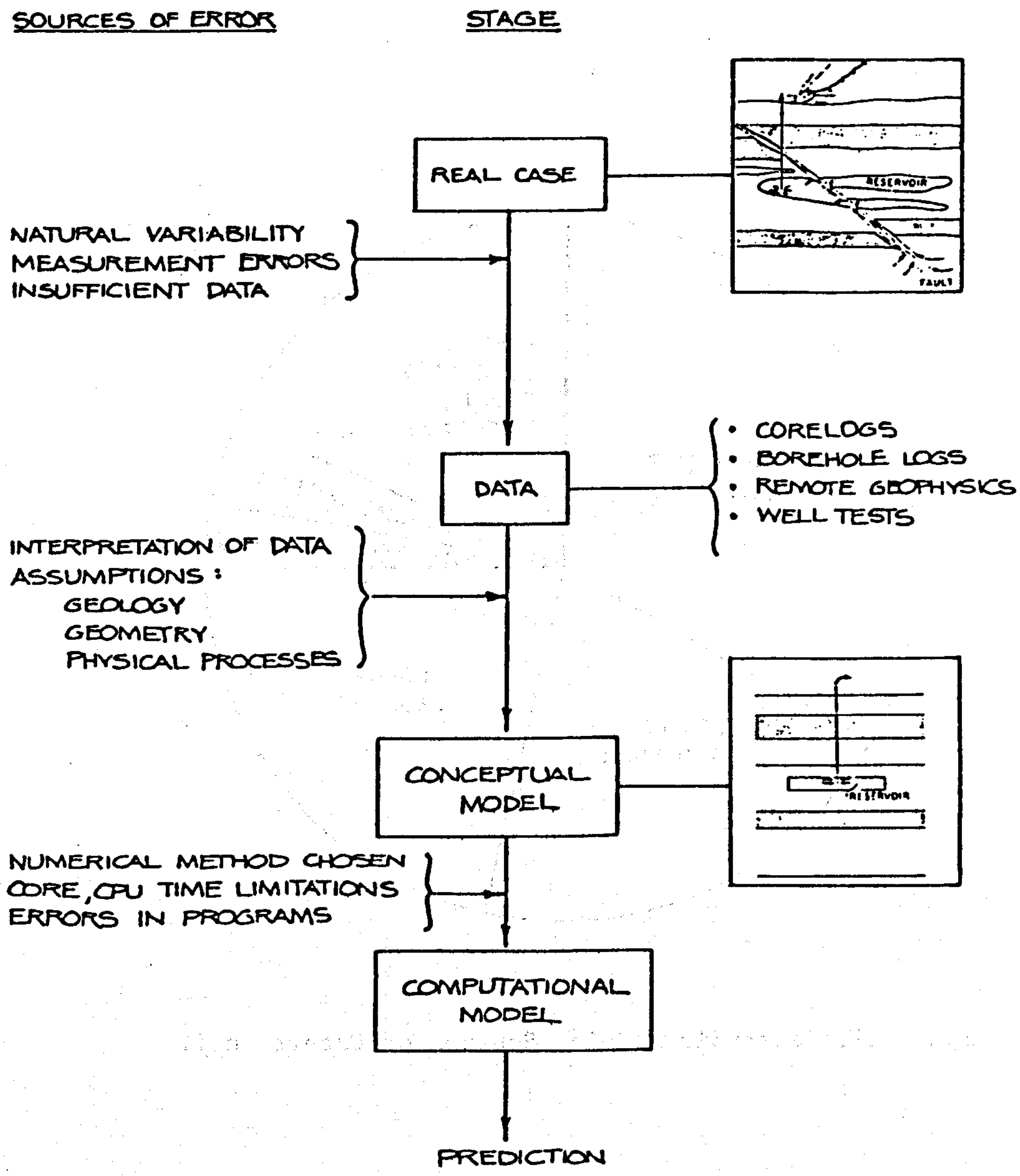


Figure 10. Geothermal Subsidence Prediction Process.

Source: Miller, Dershowitz, Jones, Myer, Roman, and Schauer, 1980.

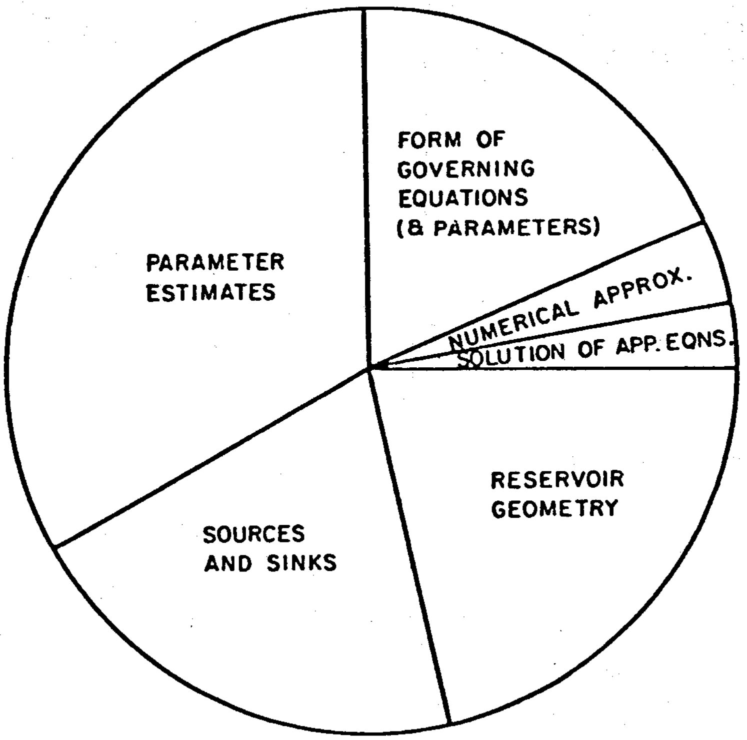


Figure 11. Reservoir Models: Sources of Uncertainty.

Source: Miller, Dershowitz, Jones, Myer, Roman, and Schauer, 1980.

and used hypothetical formulations for the stress-deformation behavior. The effort was designed to "assess the sensitivity of reservoir behavior to variations in estimated sandstone/shale distribution, shale compressibility, and vertical shale permeability" (75). (75)

The model includes two-phase flow and vertical as well as horizontal permeabilities for both the shales and sandstones. These factors may be very important and they are frequently not included in simulations. The results of the time-dependent pressure decline, "illustrates the influence of fluid influx [i.e., dewatering] from the adjoining shales" (76). The authors note that dewatering should have little effect on the time scale pertinent to well testing, but will probably be of importance during the productive life of a commercial geopressured reservoir.

Surface subsidence results are based on assumptions of: a) reservoir solid matrix competence, b) partially unconsolidated overburden, and c) linearly elastic behavior of overburden and underburden strata. Subsidence results are obtained for three choices of rock elastic properties. For each case, at time (t) = 30.3 years, the maximum vertical movements are about 20, 29, and 43 cm, respectively. Maximum horizontal displacements are 30, 47, and 59 cm (77).

Garg, Riney, and Brownell stress the preliminary nature of their results and the need to replace estimated and assumed properties with data obtained from well testing at Austin Bayou.

These two simulations of reservoir compaction and subsidence for the Austin Bayou Prospect give indications of anticipated subsidence behavior, but all conclusions must be qualified. The Golder Associates report does not provide compaction and subsidence results, apparently because of the goal of the experiment of testing various assumptions with full freedom to model. The initial results of the Garg, Riney, and Brownell model would appear to indicate that subsidence may be in excess of a foot. This may be a manageable magnitude depending on the topography and hydrology of the specific area and on whether effects will be

---

(75) Ibid, p.280.
(76) Ibid, p.281; bracketed comment added by present authors.
(77) Ibid, Figure 7, p. 285.

relatively localized.

When the input data is more substantial and the modelers more certain of constituent expressions, modeling of the Louisiana prospects should be attempted. The geologic and surface conditions may indicate a greater potential for objectionable subsidence effects in the low-lying wetlands of Louisiana than in many areas of coastal Texas.

Prediction through Analogy

Man-induced subsidence has occurred around the world as a result of subsurface removal of fluids and solids. Examples of fluid removal with resulting subsidence are groundwater withdrawal and geothermal fluid withdrawal, as well as oil and gas production in relatively shallow fields. The rates and total magnitude of fluid withdrawal are lower in the case of petroleum but often higher in groundwater and geothermal instances. But because the depths are all considerably shallower than will be the case for geopressured brine production, subsidence from water and petroleum withdrawal may bear little analogy to the geopressured case. Nevertheless, past instances of subsidence may be helpful in studying geopressured subsidence because a body of theory, albeit as yet unverified, has been devised and the necessary disciplinary knowledge developed to commence subsidence studies.

A number of relevant factors in three well-known and somewhat extreme instances of subsidence (one each for groundwater, geothermal, and petroleum production) are compared to a hypothetical Gulf Coast geopressured well in Table 5. This comparison illustrates areas in which the analogy of other forms of subsidence with geopressured may be appropriate, and others where it almost certainly is not. The following paragraphs refer to Table 5.

Area of subsidence. It is not possible to predict the area of surface subsidence above a compacting geopressured reservoir. Faulting and reservoir depth may act to minimize the extent of the surface expression. Some experts believe that faulting will effectively segregate subsidence within relatively small areas.

Table 5. Comparison of Factors in Three Subsidence Cases to Conditions at a Hypothetical Gulf Coast Geopressured Well[1]

Factor	HOUSTON/GALVESTON TEXAS (groundwater)	WILMINGTON, CALIFORNIA (petroleum)	WAIRAKEI, NEW ZEALAND (geothermal)	HYPOTHETICAL GULF COAST (geopressured)[2]
area of subsidence	10^4 km^2 (1969)	>65 km^2 (1970)	65 km^2 (1974)	?
maximum subsidence	1 to 2 meters	8.8 meters	4.7 meters	?
maximum horizontal movement	not measured	3.7 meters	0.8 meters	?
depth of reservoir	50 to 600 meters	600 to 2300 meters (most production from 600 to 1100 meters)	150 to 1360 meters (most production from 180 to 300 meters)	3500 to 5800 meters
maximum reservoir thickness[3]	≤ 550 meters	500 meters (major production zones)	120 meters (major production zones)	150 meters (maximum anticipated)
porosity	not reported	20 to 35%	extremely variable due to cementation	10 to 30%
permeability	not reported	100 to 1500 mD	100 mD	10 to 30 mD
confined or unconfined reservoir	unconfined	unconfined	unconfined	confined
maximum in-situ pressure reduction	10 kg/cm^2 (142 PSI)	77 kg/cm^2 (1100 PSI)	25 kg/cm^2 (355 PSI)	240 to 420 kg/cm^2 (3400 to 6000 PSI)[4]
maximum rate of fluid withdrawal	8.7×10^9 m^3/day (5.5×10^6 bbl/day)	2.2×10^4 m^3/day (1.4×10^5 bbl/day)[5]	1.3×10^4 m^3/day (8.2×10^4 bbl/day)[6]	1.9×10^4 m^3/day (1.2×10^5 bbl/day)
total fluid withdrawal	4.3×10^9 m^3 (2.7×10^{10} bbl) 8 year period	2.2×10^8 m^3 (1.4×10^9 bbl) about 35 years[7]	9.3×10^8 m^3 (5.9×10^9 bbl) 18 year period	1.4×10^8 m^3 (8.8×10^8 bbl) 20 year period
reservoir geology	Unconsolidated sand and clay of Pleistocene to Miocene(?) age.	Unconsolidated to semiconsolidated sand with interbedded clay and marine shale. Miocene to Pleistocene age.	Pumice brecchia with sandstone and minor siltstone; medial rhyolite sill of Pleistocene age.	Undercompacted clay, shales and sandstone of Miocene age. Reservoirs are separated by regional growth faulting.
age of reservoir	0.1 to 22 (?) million years.	2.0 to 22.0 million years.	0.1 to 2.0 million years.	about 10.0 to 22.0 million years.
overburden thickness	50 to 600 meters	600 to 2300 meters (mostly 600 to 1100 meters)	150 to 1360 meters (mostly 180 to 300 meters)	3500 to 5800 meters
composition of overburden	Unconsolidated and clay of late Cenozoic age.	Unconsolidated sand, shale, claystone and siltstone of Pliocene and Pleistocene age.	Tiffaceous shale and sandstone with interbedded tuff and conglomerate of Pleistocene age.	Unconsolidated alluvium underlain by sandstone, shale and siltstone of late Tertiary and Quaternary age.
injection practices	Reinjection into producing zone.	Reinjection into producing zone.	As of 1975, reinjection of hot water into the producing formation was being considered.	Reinjection of spent brines into overburden strata.

Table 5 (continued)

1. Sources of data and descriptions of geology and production history include: Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, 1976; Grimsrud, Turner, and Frame, 1978; Papadopoulos, Wallace, Wesselman, and Taylor, 1975; and Viets, Vaughan, and Harding, 1979.

2. This hypothetical geopressured-geothermal reservoir is assumed to have the following physical properties:

   Disk shape,
   volume of 4.2 km^3 (1 $mile^3$),
   thickness of 150 meters.
   areal extent of 5900 meters.

   These figures are consistent with average reservoir properties given in Southwest Research Institute, 1980. The range of porosity and permeability figures are also drawn from this source.

3. These are upper-bound figures. The producing zones are not each likely to be this thick. For the first three cases, production may have occurred from a variety of zones within the total reservoir thickness. For geopressured geothermal, 150 meters (500 feet) is an optimistic goal in choosing pay sands (see Southwest Research Institute, 1980.)

4. This range of pressure reductions is derived from the production assumptions of Papadopulos, Wallace, Wesselman, and Taylor, 1975.

5. These figures are for oil only, although natural gas and brine condensate were also removed.

6. Production at Wairakei is about a 1 to 4 ratio of steam to water by weight. In converting to volume of fluid removed, the assumption of pure water is made. This assumption probably leads to a small overstatement of produced fluid.

7. Oil and natural gas only, brine condensate not included.

Maximum subsidence. This factor is the most important unknown. Geopressured subsidence can not meaningfully be compared to the depth of subsidence from other forms of fluid withdrawal because the relative importance of the various factors influencing subsidence is not well understood.

Maximum horizontal movement. This factor is highly site-specific and may depend largely on local faulting and the type of reservoir and overburden materials experiencing compaction.

Depth of reservoir. The propensity for overburden deformation (assuming a single slab of material) varies as the cube of the thickness of the overburden. The depth of geopressured reservoirs may act to minimize both the magnitude and rate of subsidence. A few experts point to this thick land bridge as a reason to anticipate only small magnitudes of geopressured subsidence.

Maximum thickness of reservoir. The assumed maximum thickness of a single geopressured zone is comparable to the Wairakei field and is less than a third of the reservoir thickness found at Houston-Galveston and Wilmington. Relatively thin productive zones, a negative aspect economically, may minimize subsidence.

Porosity. The relatively low porosity of geopressured zones may aid in reducing reservoir compaction.

Injection practices. Reinjection into or below the producing zone is thought to be the best strategy for inhibiting subsidence. The economic and energy costs of deep reinjection for the geopressured case will almost certainly require that shallow reinjection be used. This strategy may of may not be helpful in impeding the rate or magnitude of subsidence.

Composition of overburden. The three sedimentary overburdens are of similar general composition. All three are undercompacted. In the case of geopressured, undercompaction and thickness of overburden tend to counteract one another in determining the magnitude of subsidence.

Permeability. The lower permeability characteristic of geopressured zones may affect subsidence either positively or negatively. Compaction may occur more slowly if lower permeabilities preclude rapid reductions in pore pressure. Conversely, low permeabilities may reduce the rate at which fluids from adjacent formations, if present, can replace the produced fluids. Hence the effect that permeability may have on reservoir compaction is closely related to the unverified theory of dewatering from adjacent shale bodies.

Confined or unconfined aquifer. Because geopressured aquifers are believed to be confined, all of the overburden pressure is borne by the rock matrix and the pore fluids. If these aquifers are part of larger systems confined over a greater area, however, the influx of fluids from adjacent formations following the production of reservoir fluids may reduce the magnitude of reservoir compaction. Again the unverified concept of shale dewatering is crucial to reservoir behavior under confined conditions.

Maximum in-situ pressure reduction. The total pressure reduction experienced in a geopressured aquifer is far greater than for the other three cases. This factor, taken alone, enhances the probability of significant reservoir compaction. Not enough is known to weigh the relative importance of this factor.

Maximum rate of fluid withdrawal. This value is comparable for the geopressured, petroleum, and geothermal cases. The groundwater withdrawal rate is very roughly five times greater than in the geopressured case. The rapid rate of withdrawal is believed to be an important contributor to subsidence at Houston-Galveston.

Total fluid withdrawal. The value of analogy for total fluid withdrawal is difficult to assess. At the Wilmington field the total quantity of fluid produced was about 50% higher than for a hypothetical geopressured well, but this withdrawal occurred over a longer time period. Over a comparable time period, the Wairakei withdrawal is six to seven times greater than the geopressured quantity is likely to be. Finally, groundwater withdrawal occurred over a short time period and totaled about 30 times the anticipated geopressured withdrawals.

Reservoir geology. Geopressured geology is most similar to the sedimentary characteristics of Houston-Galveston and Wilmington. The igneous geology at Wairakei is not useful for analogy. Given similar levels of undercompaction in the three sedimentary cases, extensive growth faulting in the geopressured case may enhance the probability of subsidence while limiting the subsidence to a smaller areal extent. If geopressured undercompaction is greater, however, the propensity for reservoir compaction may be increased.

Age of reservoir. As a rule, the older a reservoir the greater the previous compaction of overlying sediments. The Wairakei case is not helpful here because of differences in geology and age. Because of the wide variations in age reported for Houston-Galveston and Wilmington (both well documented instances of subsidence), it is difficult to compare the role of this factor in causing or exacerbating subsidence in the three sedimentary cases.

Overburden thickness see Depth of reservoir.

Subsidence at the Chocolate Bayou Prospect in the vicinity of the Brazoria well has been studied as being a possible analogy to geopressured subsidence in south Texas (78). Unfortunately, the data yield an ambiguous history of subsidence. Although some hydrocarbon production from overpressured zones occurred and included the removal of relatively small quantities of brine condensate, shallow oil and gas production, groundwater withdrawal, and poorly documented irrigation of rice lands

---

(78) See Grimsrud, Turner, and Frame, Areas of Ground Subsidence Due to Geofluid Withdrawal, 1978, pp. V-1 to V-77. The results of this study are summarized in a presentation by Barbara Turner. See United States Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fifth Meeting of the Environmental/Laboratory Research Working Subgroup," July 18, 1978, pp. 5-13 (with figures in the back).

tend to obscure the portion of the subsidence that can be fairly attributed to each of the causes. In addition, hydrocarbon production has consisted predominantly of gases rather than liquids.

Only one first-order leveling line traverses the field, and this is over the West block, a portion of which has experienced petroleum production at fairly substantial depths, but not from geopressured zones (79). There is a divergence between theory and the observed subsidence that appears attributable to groundwater withdrawal. Using a rule-of-thumb formula for subsidence attributable to withdrawal (a ratio of subsidence to groundwater aquifer head loss of 1 to 100), subsidence from groundwater should be only 0.5 feet of the total maximum observed West block subsidence of 1.8 feet. Instead, the subsidence contribution of groundwater withdrawal appears to be between 0.5 and 1.5 feet (80).

Major faults are mapped at depth and their traversal of petroleum production zones is well documented. Whether these faults have surface expression, a factor that could strongly affect the observed subsidence, is unknown (81). Grimsrud, Turner, and Frame state that no data was encountered on the mineralogy of the Frio shale sequences that are interbedded with the producing sandstones of Chocolate Bayou. These shales are not usually found in conjunction with reservoir rocks in the Gulf Coast and have not been well studied (82).

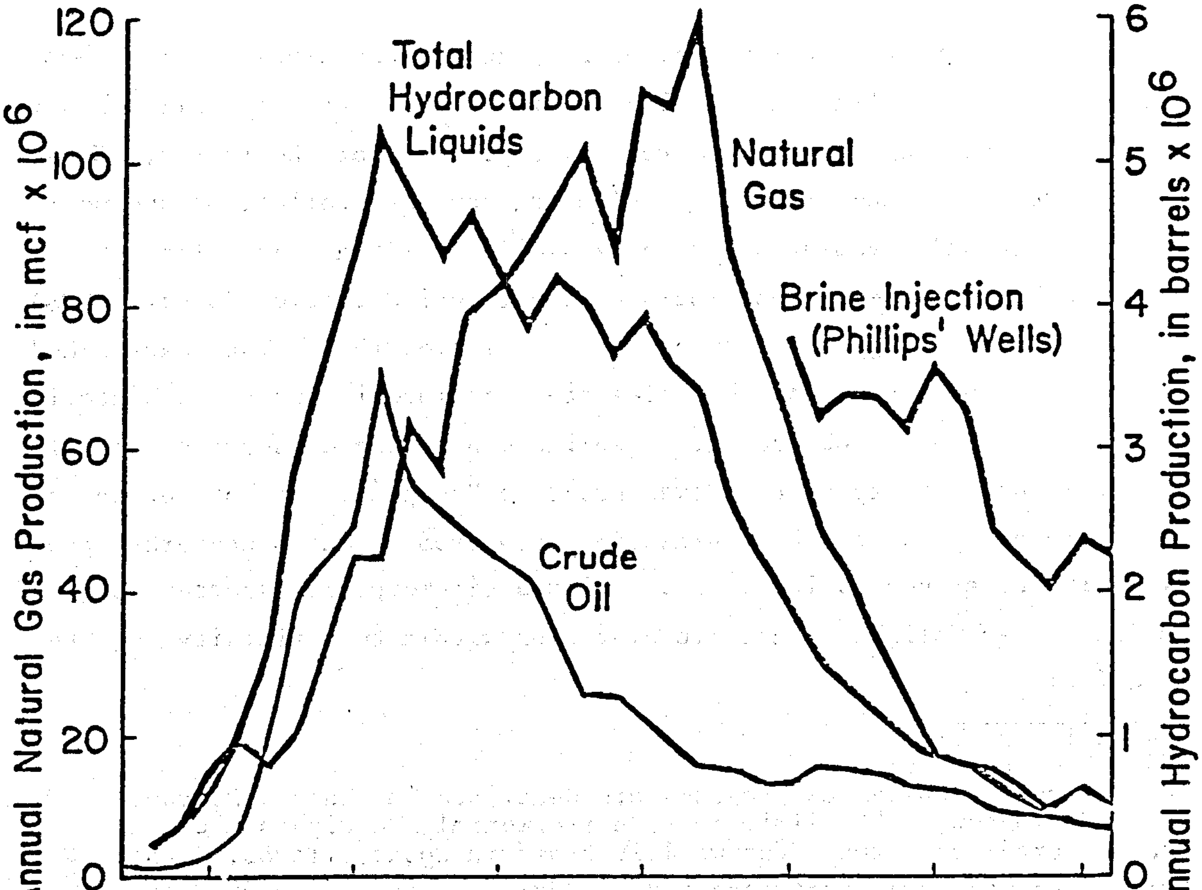
The above uncertainties appear to make it difficult to draw any conclusions about subsidence at the Chocolate Bayou field. Figure 12 illustrates the complex production history of the field. In addition to fluid and gas removal, brine injection also occurred. Data on this reinjection is available only from 1965, although the practice began much earlier (83). The South block, absent of benchmarks, is composed entirely of abnormally-pressured producing zones.

A point in favor of correlating subsidence to injection/withdrawal is that the data for natural gas production from the West block is inclusive for both gas and condensate; extrapolation of brine production

---

(79) See DOE/Industry Minutes, p. 6.
(80) Ibid, p. 12.
(81) See Grimsrud, Turner, and Frame, p. V-12.
(82) Ibid, p. V-28. Loucks and others are now investigating the Frio sands.
(83) Ibid, p. V-43.

Figure 12



PRODUCTION HISTORY OF CHOCOLATE BAYOU FIELD (Hydrocarbon production from Texas Railroad Commission; Salt water disposal from Phillips Petroleum Company)

Source: Grimsrud, Turner, and Frame, 1978.

to reinjection prior to 1975 is probably feasible. Grimsrud et al. note that "If extraction of oil, gas, and brine from the field has contributed to subsidence, then the fact that subsidence rates are still increasing suggests that there is probably a lag time of at least several years between extraction of deep fluids and the appearance of subsidence effects" (84). Rice farming is responsible for undetermined quantities of groundwater withdrawal from poorly-specified locations. Petroleum production occurred from twenty different pay zones ranging in thickness from 10 to 200 feet (85).

Subsidence Planning for DOE Wells

Baseline and production monitoring plans are complete for the Brazoria well and baseline data collection is either currently taking place or will shortly begin for the three wells planned for Louisiana; Sweet Lake, Parcperdue, and Lafourche. Planning for data collection and monitoring of ground movement activity is similar for the four wells (86).

The Brazoria well plans included a National Geodetic Survey (NGS) first-order leveling that transects the well area (87). The background rates of subsidence in the area are described in the above Historic Rates of Subsidence subsection. Baseline monitoring data are now available for the vicinity of the Texas Brazoria Prospect, but not for any of the Louisiana prospects. At Brazoria, data from seven benchmarks provide 15 reference points, and a liquid tiltmeter is expected to give notice of very slight changes in elevation within the vicinity of the site (88).

---

(84) Ibid, p. V-68.
(85) Ibid, p. V-19.
(86) Brazoria subsidence programs are described in: White, McGraw, and Gustavson, "Preliminary Environmental Analysis of a Geopressured-Geothermal Test Well in Brazoria County, Texas," and; Gustavson, Dorman, Sorrells, and Wilson, "Environmental Baseline Monitoring in the Area of the General Crude Oil/Department of Energy Pleasant Bayou Number 1 - A Geopressured Geothermal Test Well, 1978." Full plans for monitoring of the Louisiana wells have not yet been published. For information on the Parcperdue plans, see Louisiana State University - Louisiana Department of Natural Resources, "Environmental Monitoring Plan: Parcperdue Test Well, Number 1."
(87) Wise, Semi-Annual Report, p. 354.
(88) See Gustavson, Dorman, Sorrells, and Wilson.

Newchurch, et al. find that of six Louisiana prospect areas the Sweet Lake and Lafourche sites have the lowest vulnerability to land use and ecosystem damage should subsidence occur during well testing (89). These two prospects are upland, although rice farmlands near Sweet Lake could be affected by appreciable vertical movement and alterations in the salinity of waters should subsidence occur.

The monitoring plans for the Louisiana wells are not all published. The plans are similar for each of three wells, however, although experimental liquid tiltmeters will only be installed at Lafourche. Carver and Van Sickle both note problems with liquid tiltmeters due to their excessive sensitivity to background disturbances (90).

The Parcperdue subsidence monitoring plan calls for (91):

1. Baseline studies consisting of:
   a) about 16.5 miles of precise first-order leveling to determine relative surface elevations
   b) an examination of historic leveling data and topographic maps to determine subsidence history in the vicinity of the well
2. Test phase monitoring consisting of:
   a) first-order releveling surveys at 12-month intervals to detect subsidence or movement along faults during production.

No plans have been made for monitoring a production well. The design of such a program, should the resource prove commercially attractive, will benefit from the results of the test well monitoring programs.

---

(89) See Newchurch, Van Sickle, Bachman, Bryan, Harrison, Muller, and Smith, "A Comparison of Six Geopressured-Geothermal Prospect Areas in the Louisiana Gulf Coast Region on the Basis of Potential Environmental Impacts."
(90) Telephone Conversation with Dale Carver, July 2, 1980; and Virginia Van Sickle, meeting with Peter Deibler and Tony Usibelli, May 1, 1980.
(91) Although not specified, extensometers will probably be used to gauge fault movement at the surface. See Louisiana State University - Louisiana Department of Natural Resources, "Environmental Monitoring Plan: Parcperdue Test Well No. 1."

Severity of Subsidence Impact

Introduction

It is difficult to identify, much less quantify, all economic and environmental impacts of ground subsidence. The extent of environmental and economic damage may be highly site-specific and dependent on topography, extent of human development, and local flora and fauna. Gathering the sparse available data on environmental and economic damages at sites of known geofluid-withdrawal subsidence is one focus of the Lawrence Berkeley Laboratory's (LBL) Geothermal Subsidence Research program (92). Viets, Vaughan, and Harding selected six case study areas representing subsidence worldwide. Four of these are among the most extreme instances of man-induced subsidence: Wairakei, New Zealand (geothermal); Wilmington, California (petroleum); and the San Joaquin Valley, California, and Mexico City (both groundwater). All have experienced vertical movement of five to nine meters (93).

he LBL study attempts to identify both the quantifiable and unquantifiable costs in each case. An important point to note is the frequent coincidence of environmental and economic costs, such as in the case of flooding damage. The direct effects of flooding remedied through disaster relief funding is known and quantifiable; the loss of wildlife habitat, subsequent alterations in regional biota, and the effects of saline intrusions are not quantifiable. Some costs, such as damage to sewer installations, may be purely economic. Other costs, such as altered hydraulic salinity gradients (if there is no effect on commercial species), might be considered strictly environmental costs. The distinction of environmental and economic costs, because of man's reliance on natural systems, is necessarily ill-defined.

The following sections generalize the different forms of surface disruption that can result from subsidence, identify the known costs in non-geopressured incidents of subsidence that might be relevant to the geopressured case, and identify sources of the biological and ecological

---

(92) Viets, Vaughan, and Harding, Environmental and Economic Effects of Subsidence, 1979.
(93) Ibid, p. II-3.

information necessary for conducting regional and site-specific studies of the environmental impact of geopressured subsidence in the Gulf Coast. The Houston-Galveston subsidence resulting from groundwater withdrawal, one of the six case studies in the Viets, Vaughan, and Harding volume, is referred to below as a rough comparison for cost information. Although not fully applicable to geopressured fluid withdrawal, Houston-Galveston may be the most geologically and geographically pertinent instance considered by Viets, Vaughan, and Harding (94).

Viets, Vaughan, and Harding note a number of difficulties in studying known subsidence including (95):

- Lack of data on the geographical distribution of the damage within the subsidence bowl,
- reservoir operators, at least prior to the early 1970's, had little incentive to study or evaluate the occurrence of subsidence unless structural damage to on-site buildings occurred, and
- the connection of fluid withdrawal to surface movement is not unique, as other geophysical processes (natural subsidence, growth faulting, tectonics) can produce similar results.

Figure 13 illustrates possible direct and indirect effects of subsidence resulting from fluid withdrawal (96). Primary subsidence phenomena can produce environmental and economic costs directly without aggravating other hazards. Conversely, primary phenomena may increase the probability of damage resulting from other natural and man-made hazards. It is essential to recognize the temporal aspects of subsidence; the relation of fluid withdrawal to subsidence, and of subsidence to appreciable damage, are both important. Subsidence in the Texas coastal plains, for instance, may have relatively little immediate effect. The effect might become apparent when flooding damage during the next severe hurricane is worse than that experienced in the past. The possibility of a delay between physical ground movement and

---

(94) For more information on the Houston-Galveston case, see the analogy subsection of the "Techniques for Subsidence Prediction and Monitoring" section above. Note the ways in which groundwater subsidence and ground movement induced by geopressured brine removal may be very different.

(95) Viets, Vaughan, and Harding, p. I-6.

(96) Ibid, p. I-3.

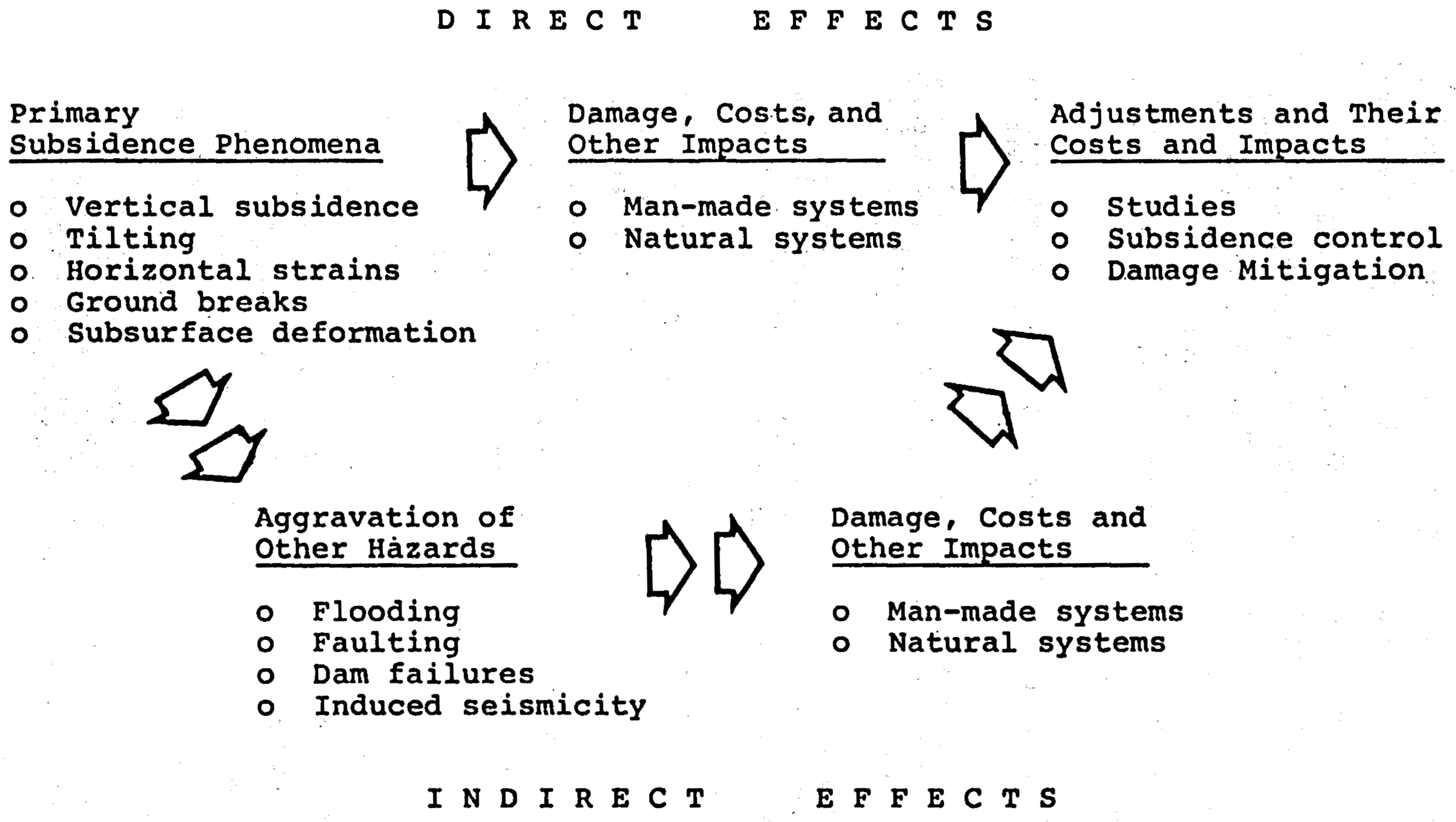


Figure 13

Concepts Used in Examining Subsidence Effects.

Source: Viets, Vaughan, and Harding, 1979.

environmental and economic effects should be recognized.

Environmental Effects

The angle of tilt relative to the horizontal in different portions of the subsidence bowl, as well as the maximum depth and area of the bowl, are important parameters in assessing the extent of surface disruption (97). Figure 14 shows a generalized subsidence bowl, relates compressional to tensional strain, and demonstrates the use of the inflection point to calculate the tilt (98). The horizontal stresses at the surface are tensional at the periphery, and compressional at the center of the bowl. In some instances, the absolute amount of vertical movement may not be as important as the tilt of the bowl in determining the severity of structural damage to buildings or the disruption of levees, streams, and other hydraulic systems. For a generalized bowl shape, the larger the subsided area, the less the tilt will be. Thus subsidence may have a relatively mild impact over a larger area, or a more severe impact over a smaller area. Because subsidence bowls above geopressured reservoirs of relatively small areal extent (compared to groundwater aquifers, for instance) will probably be correspondingly small in area, the degree of tilt may be the major determinant of impact severity. Horizonal tensional stress along the sides of the bowl, aggravated by high tilt, may result in fissuring. Faults, with or without previous surface expression, may experience shearing movements.

The reported environmental damage for the Houston-Galveston area resulting from groundwater withdrawal can not be stated as a quantifiable cost. The damages are similar, however, to those that might occur along the Gulf Coast were subsidence to follow the removal of geopressured fluids. Damages attributable to vertical movement alone included:

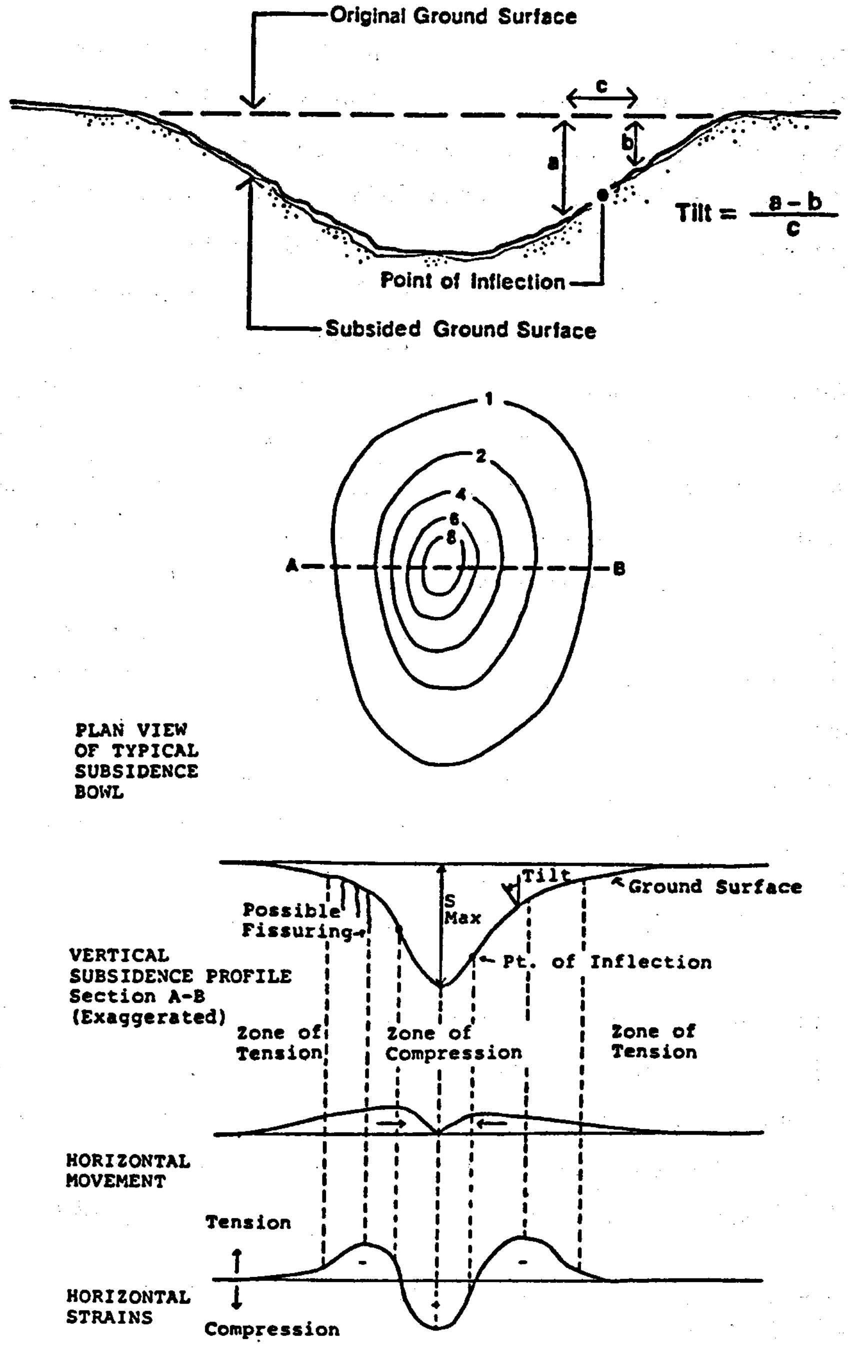
- increased risk of flooding, particularly inundation of escape roads during hurricanes;

---

(97) The tiltmeter, a device used to measure angular tilt at specific points of an area of potential subsidence, is discussed earlier in the analytical techniques section.

(98) Viets, Vaughan, and Harding, portions of pp. II-3 and II-8.

Figure 14



RELATIONSHIP OF TYPICAL SUBSIDENCE PHENOMENA

XBL 808-1833

Source: Viets, Vaughan, and Harding, 1979.

- modification of natural vegetation due to altered salinity gradients, and;
- the submergence of river mouths that transform deltas into bays of greater salinity.

Although not specifically mentioned, and perhaps not observed, an alteration in the balance of animal species is likely to have occurred, with some species better able than others to tolerate increased salinity.

Altered patterns of drainage are common in cases of surface tilt. Natural rates of sedimentation and erosion are altered with an increased potential for disruption of irrigated crops such as rice.

Several sources of baseline information, written specifically for the geopressured resource, provide a first step in the evaluation of subsidence impact on local biota. In a volume completed for the Fish and Wildlife Service, Gustavson, McGraw, and Tandy survey the ecological systems of the Gulf Coast, cataloging birds, mammals, and unique, rare, or endangered species. A similar study completed for the Department of Energy by the Louisiana State University concentrates on the natural systems of the Louisiana coast. Two more recent studies provide ecological overviews of the entire Texas Gulf Coast, and of specific geopressured prospect areas in Texas (100).

The unpublished Phase 3 subsidence research report from EDAW-Earth Sciences Associates proposes a number of areas for subsidence study (101). One EDAW-ESA proposal is to evaluate "the relationships between subsidence and the rate of ongoing geomorphic, hydraulic, and biological processes." Natural systems adjust gradually to the natural subsidence of the low-lying portions of the Gulf Coast. The report mentions a number of processes, such as littoral drift, river scour, peat accumulation, and fish habitat adjustment, that may mitigate the full impact of natural subsidence. Study of these processes may lead to an estimate of

---

(99) Ibid, p. II-5.

(100) See Gustavson, McGraw, and Tandy, Ecological Implications of Geopressured-Geothermal Development: Texas Louisiana Gulf Coast Region, 1977; Newchurch, Bryan, Harrison, Muller, Wilcox, Bachman, Newman, Cunningham, Hilding, and Rehage, A Plan for the Long Term Environmental Assessment of Geopressured Resource Development in the Louisiana Gulf Coast Region, 1978; Gustavson, and Kreitler, An Environmental Overview of Geopressured-Geothermal Development: Texas Gulf Coast, 1979, and; Gustavson, Reeder, and Badger, Environmental Analysis of Geopressured-Geothermal Prospect Areas, DeWitt and Colorado Counties, Texas, 1980.

(101) See EDAW-ESA Phase 3 pre-draft, recommendation number 3.

environmentally acceptable magnitudes and rates of subsidence (if any) resulting from the addition of geopressured subsidence to the existing background rates.

In addition, EDAW-ESA suggest that much might be learned by studying the impacts of ground movement on various civil engineering projects such as diking and dredging--both of which are found extensively on the Gulf Coast.

Economic Effects

Several types of land surface movement related to subsidence are more likely to disrupt man-made than natural systems. Tilt (or the similarly defined term differential settlement) measured as an angular distortion, may provide the basis for future standards of allowable subsidence. With Tables 6 and 7, Viets, Vaughan, and Harding first provide tilt data for a number of subsided areas, and then compare the severity of structural damage to a scale of tilt values. Baldwin Hills, California and the Wairakei geothermal fields are the only two with tilt values high enough to occasion appreciable damage to buildings. This type of damage is largely a result of horizontal ground movement as soils creep towards the deepest point in the bowl.

Fissuring is also likely to have its greatest impact on man-made rather than natural systems. In the Houston-Galveston area, fissuring resulted in slippage along existing faults with reported damages of about $17,000,000 dollars to 220 structures located along faults (102). Subsurface deformation can cause contamination of groundwater sources, and rupturing or buckling of wells. Dollar figures for such damage at Houston-Galveston are not available.

However, vertical movements resulting in coastal inundation caused an estimated $250,000,000 worth of damage in the Houston-Galveston area. If fissuring damages are included, the reported costs in this area (probably only a fraction of the total), are about $270,000,000 dollars. Although the types and magnitude of damage may be substantially different should subsidence result from geopressured development, the

---

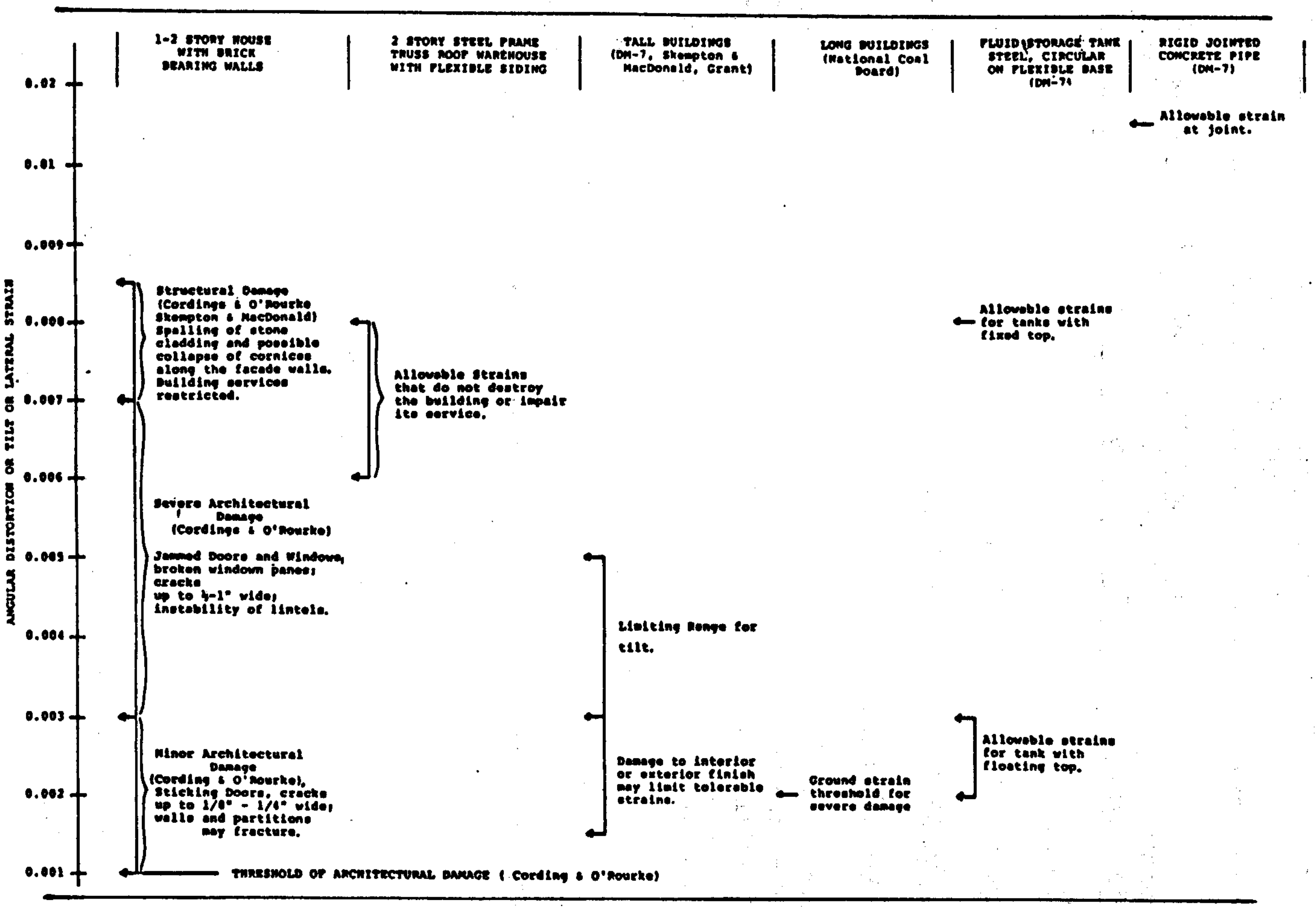
(102) Viets, Vaughan, and Harding, p. II-17.

Table 6 Tilt and Differential Settlement Values For Case Study Areas

Case Study Subsidence Area	Maximum Tilt and Differential Settlement	
	Point of Inflection	Average For 1/2 Bowl
Baldwin Hills	0.01	0.007
Houston-Galveston	0.001	0.0003
Las Vegas Valley	0.0007	0.0003
San Joaquin Valley:		
a. West of Mendota	-	0.0007
b. Tulare - Wasco	0.0007	-
c. Arvin - Maricopa	0.0003	-
Santa Clara Valley	0.001	0.0006
Wairakei	0.02	0.01
Wilmington	0.006	0.004

Source: Viets, Vaughan, and Harding, 1979.

Table 7. The Effects of Subsidence-Related Ground Surface Strains on Engineering Structures.



Source: Viets, Vaughan, and Harding, 1979.

damage at Houston-Galveston is valuable for comparison (103). Even damages equal to only a small fraction of total resource proceeds may endanger the precarious economics of onshore geopressured development. A major question that must be addressed concerns the relation between the incidence of subsidence costs and gas sales benefits.

EDAW-ESA's pre-draft Phase 3 report identifies the need to develop order-of-magnitude cost estimates and a data base for the impact of geopressured subsidence on regional resources such as agriculture, fisheries, urban development, subsurface and surface oil and gas facilities, navigational facilities, urbanized areas, etc. (104). It is not possible to site-specifically assess, for instance, the loss of farmland that may be attributed to subsidence.

Mitigation Techniques

Ideally, mitigation can either:

1. take place prior to the occurrence of substantial subsidence as a preventive measure
    - a) by altering or slowing the rate of fluid production, or by
    - b) reinjecting either into a deeper formation, or into the producing formation so that reservoir pore pressure is maintained; or

---

(103) If one assumes a discount rate of 12%, a daily production of 40,000 bbls/day of brine with 25 scf/bbl of dissolved methane, a productive well life of 20 years, and a gas price of $10/mcf, the net present value of the methane alone equals $6.6 billion dollars. The total reported Houston-Galveston economic costs represent about 4% of these hypothetical discounted geopressured methane proceeds.

(104) EDAW-ESA Phase 3 pre-draft, recommendation number 5.

2. can be aimed at halting or slowing subsidence that has already occurred
    a) by injecting fluids into shallower formations in an effort to slow the propagation of reservoir compaction through the overburden; or
    b) by following stricter design criteria for the building of tubular goods for downhole use, as well as buildings at the site.

Decreasing the rate of fluid withdrawal, and thus slowing the decrease in pore fluid pressure, is one method of either forestalling or mitigating the onset of subsidence. A potential need to decrease the production rate of a geopressured well or set of wells after an unknown period of reservoir exploitation may severely restrict the economic attractiveness of development.

Injection strategies are the other method for preventing or forestalling appreciable reservoir compaction (if injection is directly into the geopressured reservoir), or of preventing the translation of compaction into subsidence (with injection into the overburden) (105).

Injection of a fluid, usually water, can also be a strategy for decreasing the rate at which compaction is expressed as surface subsidence. This method of subsidence "control" has been used with some success at areas of severe vertical settling such as the Wilmington oilfield of California.

Beyond designing tubular goods to withstand shear faulting and to resist buckling due to vertical and horizontal ground shifts, little can be done structurally to mitigate the effects of subsidence. On-site structures could be built to stringent specifications, but this procedure may be economically unattractive.

---

(105) See the brine disposal chapter of this report for a discussion of the various injection strategies that are available for geopressured exploitation. As noted there, due to the economic and energy costs associated with deep reinjection into the producing formation, shallower reinjection (although less helpful in subsidence control) will be the favored method of disposal.

Subsidence Research

Overview

Subsidence research involves:

- developing new and improved methods for obtaining in situ fluid and rock samples with interstitial fluids intact,
- improvement and modification of laboratory techniques for duplicating the dynamic changes in in situ stress that result from decreased pore pressures,
- the refinement of simulation techniques for input of empirical compaction behavior data in an effort to predict maximum magnitudes, and perhaps eventually rates, of compaction and subsidence to be expected at a particular site.
- standardizing nomenclature as well as techniques for sampling and testing.

The next step in geopressured subsidence research is to obtain and test reliable samples of in situ materials in order to develop a data base for simulation work, as well as for verifying and developing theory. Figure 15 illustrates the order of research necessary for developing an ability to predict magnitudes and possibly rates of subsidence.

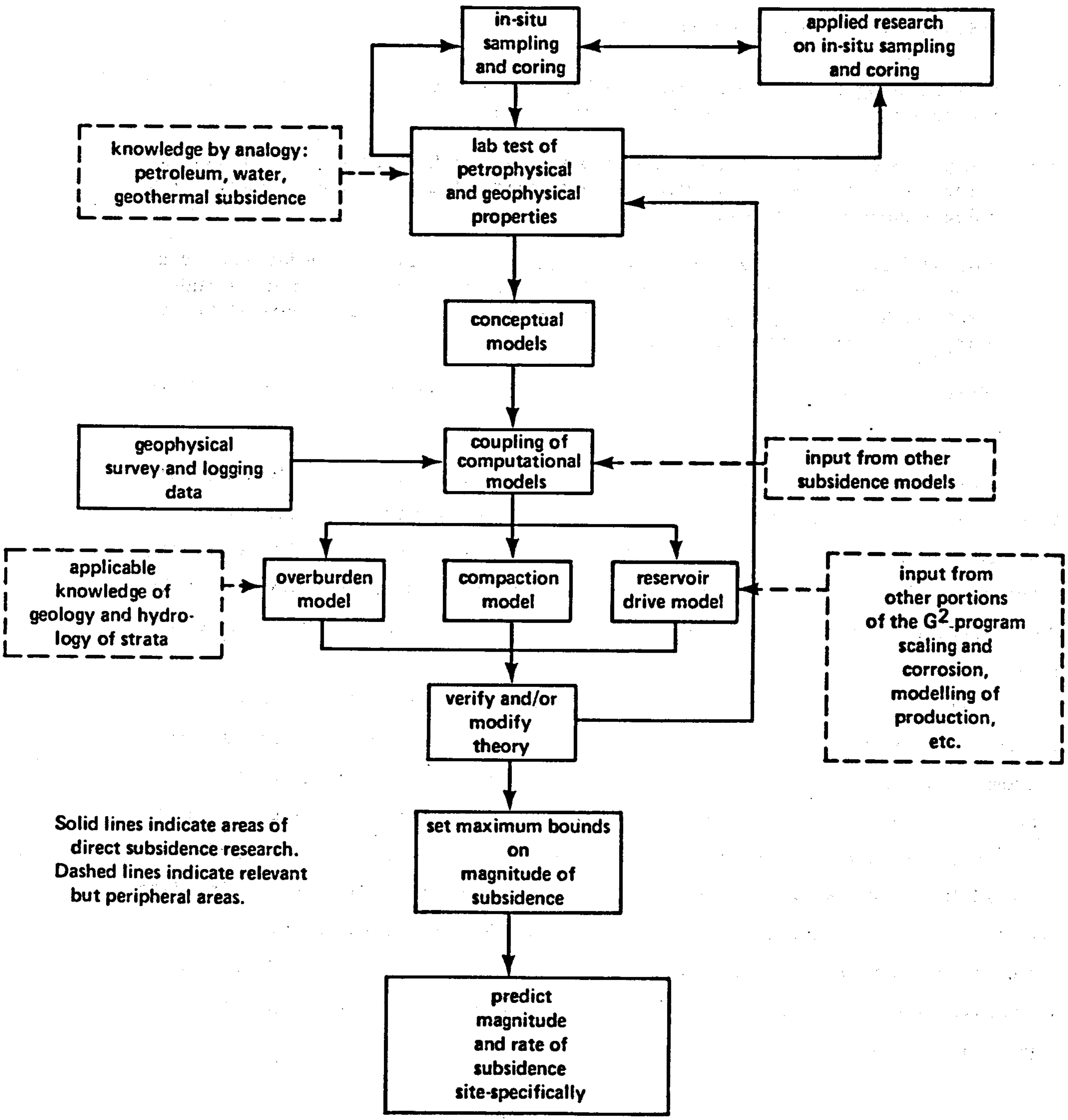
Phil Randolph of the Institute for Gas Research (IGT) believes that simulation ability is advancing more rapidly than answers can be derived from laboratory testing (106). Walt Rose, also of IGT, points to the need for increased funding of laboratory studies in order that the sophistication of simulation techniques can be balanced by laboratory data (107). As Randolph points out, the current situation is akin to having the cart ahead of the horse. Present IGT activities in the laboratory testing of subsidence factors are funded by the Geothermal Division of DOE at the rate of about $300,000 per year, enough to support a staff of six.

---

(106) Telephone conversation with Phil Randolph, March 26, 1980.
(107) Telephone Conversation with Walt Rose, July 7, 1980.

Figure 15

GEOPRESSURED SUBSIDENCE RESEARCH



Solid lines indicate areas of direct subsidence research. Dashed lines indicate relevant but peripheral areas.

XBL 808 1830

Nevertheless, research goals remain optimistic. The Lawrence Berkeley Laboratory, for instance, is funded to (108):

> a) develop techniques for distinguishing naturally occuring subsidence from that which may be caused by fluid withdrawal from geothermal wells and,
>
> b) develop techniques for operating geothermal fields in a manner that will prevent or minimize adverse effects due to subsidence.
>
> Five areas of work are included: characterization of subsidence, physical theory of subsidence, properties of materials, simulation of subsidence, and subsidence control.

The results of this DOE contract are a group of reports done for LBL by Woodward-Clyde Associates, Golder Associates, Systems Control, Inc., Earth Sciences Associates, and EDAW, Inc. As a series, these reports provide the best overview of subsidence since the work of Atherton, et al in 1976. In addition, several of the specialized volumes cover areas, such as detailed accounts of known subsidence areas, in far greater depth than attempted previously (109).

Improvement in Surface and Subsurface Techniques

On-site information relevant to the monitoring and prediction of subsidence may be gathered at three scale levels (110). Geophysical surveys yield generalized information about a relatively large volume of rock, but may miss local anomalies such as fractures that can profoundly affect the probability and form of subsidence at a particular site. Secondly, depending on the technique used, logging methods can yield information on a volume of rock that varies from a few times to perhaps

---

(108) Wise, Semi-Annual Report , p. 354.

(109) For this series of reports, see: Grimsrud, Turner, and Frame, 1978; Miller, Dershowitz, Jones, Myer, Roman, and Schauer, 1980 (3 volumes); O'Rourke and Ranson, 1979; Pinder, 1979; Van Til, 1979, and; Viets, Vaughen, and Harding, 1979.

(110) See Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, The Analysis of Subsidence Assoiciated with Geothermal Development, pp. 6-30 to 6-32 for a good discussion of the scale issue.

10^5 to 10^6 times the volume of a sample. Logging provides a variety of information over a wide range of rock volumes. Finally, sampling techniques allow for the gathering of information that may be pertinent to a specific point at a certain formation depth in a particular well. The ideal, of course, would be an infinite number of in situ samples representing all portions of the reservoir, not just the annular area at depth, as well as samples from each of the strata overlying the reservoir. In reality, the three techniques must be balanced to provide as accurate a picture as possible of compaction potential.

Of the three levels of data gathering, sampling requires the most refinement and ultimately will be of greatest help in laboratory verification and modification of existing theory.

Increased accuracy of information gathering on subsidence has benefited from indirect active research by petroleum firms (111).

O'Rourke and Ranson note that much of the necessary subsurface monitoring instrument development will not take place in the private sector because of insufficient demand. And, unfortunately, the subsidence research that is done in the private sector is frequently proprietary (112).

O'Rourke and Ranson recommend governmental funding to develop four extensometer systems. Funding of inclinometers was deemed premature. The four extensometers are: a) triple sensor induction sensor probe, b) triple sensor gamma ray detector probe, c) triple sensor reed switch probe, and d) triple sensor oscillator-type magnet detector probe. If funded, this research will probably be done for geothermal but non-geopressured applications. If geopressured becomes commercially attractive, the effort will benefit from geothermal research done on these four systems. Geopressured geothermal researchers should be aware of this project and its results.

Laboratory Testing

---

(111) See Atherton et al, p. 6-23.

(112) O'Rourke, and Ranson, Instruments for Subsurface Monitoring of Geothermal Subsidence, p. 72.

The Petroleum Engineering Department of the University of Texas does laboratory testing of geopressured cores under the direction of Ken Gray. In addition, Walt Rose of the Institute of Gas Research (IGT) and John Schatz of TerraTek (Salt Lake City), hope to begin testing in situ materials in the near future (113). Several other laboratories have the necessary equipment for duplication of in situ geopressured temperatures and pressures. Included among these are two national laboratories: Battelle Northwest, and Lawrence Livermore.

Laboratory research can be separated into two components, petrophysical and geophysical. IGT is equipped to work on the former with the study of relative permeabilities of brine and exsolved gas under reduced pore pressures. A laboratory at the University of Texas (UT) is working in the latter area, investigating the relation of bulk to matrix compressibility and other geologic parameters in an effort to move beyond the oversimplifications of elasticity theory (114).

A major priority is "creep testing", now in progress. Creep testing measures long-term time-dependent, as opposed to static, changes in reservoir parameters such as porosity and permeability due to effective stresses (and externally applied stresses) that are maintained over long periods of time. Creep tests, often conducted for about one month, approximate the loading characteristics anticipated for pressure reductions in geopressured aquifers.

No need for major advances in laboratory equipment is anticipated. What is needed are cores for study and adequate funding. In addition, the need for verification of current theory is acutely felt in geopressured subsidence research.

Computer Simulation

Miller, Dershowitz, Jones, Meyer, Roman, and Schauer make a number of detailed recommendations regarding the goals of a subsidence simulation research program (115). Figure 16 illustrates the large

---

(113) Telephone Conversations with Walt Rose, July 7, 1980, and Daniel Ennis, July 7, 1980, respectively.

(114) See coverage of compaction and subsidence theory above for a discussion of elasticity behavior as applied to compaction processes.

(115) <u>Simulation of Geothermal Subsidence</u>, 1980.

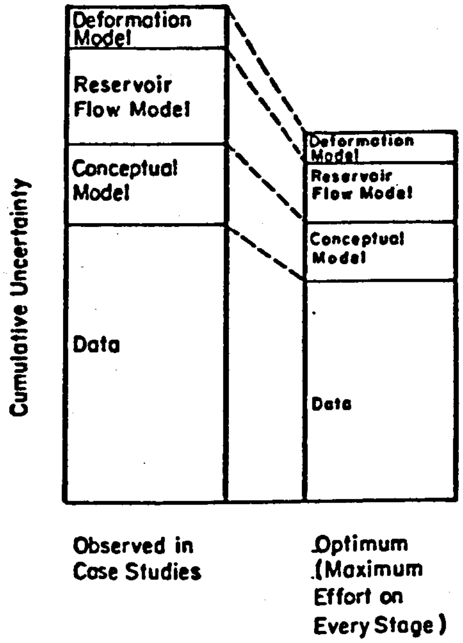


Figure 16. Contributions to Uncertainty of Geothermal Subsidence Prediction.

Source: Miller, Dershowitz, Jones, Myer, Roman, and Schauer, 1980.

uncertainty associated with the raw subsidence data now available for conceptual and computational modeling (116). The authors note that the uncertainty of modeling results is due far more to data insufficiencies than to defects in deformation models:

> "[i]t is our opinion that, due to the physical impossibility of fully characterizing a subsidence system, subsidence models will never be able to predict subsidence with great precision. It is reasonable to expect to predict the general nature and magnitude of the deformations, but... there will often be 'anomalies'...As a result, the sophistication of current deformation models appeared to be adequate, as they do not do not significantly increase prediction error" (117).

Overall recommendations include (118):

- Development of complex coupled models of reservoir flow and deformation is not desirable now. Data is insufficient and the coupling of flow and deformation increases cost more than accuracy.
- Conceptual models should be developed to the degree warranted by the data. Computational models should be developed that are appropriate to the sophistication of the conceptual models.
- The type of model should match the reservoir. One-dimensional models, for instance, are inappropriate for irregular reservoirs.

The authors make a number of recommendations specific to reservoir flow and deformation models, including the need to develop a data base of models in the public domain and the need for development of state-of-the-art simulations for the use of theorists as well as simplified simulations for nonspecialists (119).

Assuming the collection of reservoir and overburden data, the authors expect a rapid development in reservoir flow theory in the next few years that will lead to an appropriate use for more complex models.

---

(116) Ibid, p. 146.
(117) Ibid, p. 147.
(118) Ibid, adapted from pp. 147-148.
(119) Ibid, pp. 148-150.

General Studies of Geopressured Subsidence

EDAW, Inc., and Earth Sciences Associates (ESA) are working jointly on a Lawrence Berkeley Laboratory contract to develop detailed research plans on subsidence from Gulf Coast geopressured development (120). EDAW and ESA both completed earlier work on geothermal subsidence for LBL under contract to the Geothermal Division of DOE (121). The work includes input from Gruy Federal, a Houston contractor for the DOE Wells of Opportunity program, in the form of supplying information on reservoir properties and production schemes that may be utilized in producing geopressured reservoirs. In addition, a University/Industry Advisory Group has been set up to advise EDAW-ESA of research progress. The goals of the program as discussed in the proposal call for: a) preliminary evaluation and characterization of geopressured prospect areas, b) the picking of four "representative" areas for estimating the range of subsidence that might occur under various production schemes along with analysis of environmental and economic impacts resulting from subsidence at the site, and c) design of a research project to deal with unresolved subsidence concerns.

Criteria for the choice of prospect areas includes:

- availability of existing data for analyses in appropriate detail,
- general geologic setting,
- reservoir characteristics,
- recoverable resources,
- environmental setting (coastal vs. inland, or developed vs. agricultural, etc.)
- DOE/Industry development priorities (122).

The four prospects chosen for subsidence analysis are (123):

---

(120) EDAW-ESA, 1980.

(121) For earlier subsidence reports from EDAW and ESA, see: Grimsrud, Turner, and Frame, 1978, and; Viets, Vaughen, and Harding, 1979.

(122) Viets and Harding, 1979, p. I-7.

1. Austin Bayou Prospect (Brazoria Fairway), Texas
2. Gladys McCall Prospect, Louisiana
3. Southeast Pecan Island Prospect, Louisiana
4. Cuero Prospect (Dewitt Fairway), Texas (123).

Standardization of Methods

The DOE Houston office and the University of Texas at Austin are sponsoring a working group intended to provide recommendations on the standardization of sampling procedures, laboratory testing procedures, and compaction and subsidence terminology (124). Fertl notes, for instance, the number of different formulas now available for calculating formation compressibility (125). Terms are often inadequately defined, leading to unnecessary confusion. The goal of the working group is the publication of a guidebook for analytical geopressured subsidence evaluation.

Corollary Areas of Research

Geopressured research continues in a number of areas related to compaction and subsidence, a few of which are:

- study of one-phase and two-phase flow in both porous and fractured media;
- shale dewatering and possible effects on reservoir drive and compressibility;
- the lithology and depositional history of geopressured formations;
- degree of formation cementation;
- faulting mechanisms as related to the character and extent of overburden compaction and surface subsidence;

---

(123) EDAW-ESA, 1980, p.1.
(124) U. S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Overview Group", Houston, Texas, May 28, 1980; EDAW-ESA Phase 3 pre-draft, 1980, Recommendation #7.
(125) Fertl, <u>Abnormal Formation Pressures</u>, p. 90.

- the relation of subsidence to fault activity and the reverse, and;
- research on well design techniques for maintaining casing integrity despite compaction.

Conclusions

The range of uncertainty surrounding the question of geopressured subsidence has not narrowed in the past few years. The few available estimates are either based on overly simplistic assumptions, or are derived from theory with has questionable applicability to geopressured subsidence.

At this time, it is inappropriate to outline detailed research timetables. The available data for assessing geopressured subsidence has been studied and reworked as much as possible. The potential for severe impact resulting from geopressured subsidence in the low-lying areas of the Gulf Coast requires that answers not be rushed, that the necessary research be completed in a deliberate and unhurried manner. This is particularly true if reinjection of spent brines into the overburden strata will be the dominant mode of brine disposal.

The development of criteria or mandatory standards for allowable surface subsidence is premature at this time, but must be addressed if commercial geopressured development is to become feasible.

The present need is for new data: new cores to test in the lab; new numbers derived from testing for input in simulation exercises; and an ability to detachedly modify or discard inapplicable parts of the existing body of subsidence theory. Most of all, the need is for well drilling to proceed so that cores can be taken, fluid samples made, in situ logging performed, etc. Following data evaluation for the upcoming family of design and WOO wells, it may be appropriate to reassess research plans and to tentatively schedule research answers.

SUBSIDENCE BIBLIOGRAPHY

Atherton, R.W, E.J. Finnemore, M.L. Gillam, A.E. DeGance, G.P. Grimsrud, R.B. Schainker, *The Analysis of Subsidence Associated with Geothermal Development - 3 Volumes*, Systems Control, Inc., prepared for the National Science Foundation, Research Applied to National Needs, Grant No.AER75-17298, Palo Alto, California, 1976.

Bachman, Ann L., and C.G. Smith, "Subsurface Disposal of Geopressured Fluids: Potential Geological and Operational Problems with Recommendations for Disposal System Testing," Presented at the *Fourth U.S. Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Carver, Dale, Rock Mechanics with Louisiana State University at Baton Rouge, Meeting with Tony Usibelli, May 1, 1980.

Carver, Dale, Louisiana State University at Baton Rouge, Telephone Conversation with Peter Deibler, July 2, 1980.

Compaction of Argillaceous Sediments, Herman Rieke and George Chilingarian, Eds., Volume 16 in Developments in Sedimentology, Elsevier Scientific Publishing Company, New York, 1974.

Doscher, T.M., R.H. Osborne, T. Wilson, S. Rhee, D. Cox, V. Kuuskraa, "The Technology and Economics of Methane Production from Geopressured Aquifers," *Journal of Petroleum Engineering* ,December 1979, pp. 1502-1514.

Durham, Clay, William Rogers, of Magma Gulf, Houston, Texas, Meeting with Peter Deibler and Tony Usibelli, April 29, 1980.

EDAW-ESA, *Geopressured-Geothermal Study Phase 1 Report*, prepared for Lawrence Berkeley Laboratory, Subcontract #4501810, Palo Alto, California, March 6, 1980.

EDAW-ESA, "Problem Definition Study of Subsidence Caused by Geopressured Geothermal Resources Development - Phase 3 Report," (predraft), July 1980.

Ennis, Daniel, Terra Tech, Salt Lake City, Telephone Conversation with Peter Deibler, July 7, 1980.

Fertl, W.H., *Developments in Petroleum Science, Volume 2 - Abnormal Formation Pressures: Implications to Exploration, Drilling, and Production of Oil and Gas Resources*, Elsevier, New York, New York, 1976.

Garg, S.K., T.D. Riney, D.H. Brownell, Jr., "Preliminary Reservoir and Subsidence Simulations for the Austin Bayou Geopressured Geothermal Prospect," in Paul Kruger and Henry J. Ramey, Jr. Eds., *Proceedings - Fourth Workshop on Geothermal Reservoir Engineering*, Geothermal Program, Stanford University, Stanford, California, December 13-15, 1978.

Garg, S.K., T.D. Riney, and, J.W. Pritchett, "Pressure Transient Analysis for Geopressured Geothermal Wells," in *Proceedings: Second Invitational Well-Testing Symposium*, Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 25-27, 1978, pp. 60-70.

Geer, Ernest, Transco Gas Company, Inc., Houston, Texas, Meeting with Peter Deibler and Tony Usibelli, April 29, 1980.

Geertsma, J. "Land Subsidence Above Compacting Oil and Gas Reservoirs," in *Journal of Petroleum Geology* , June 1973, pp. 734-744.

Gray, Ken, Rock Mechanist with the Petroleum Engineering Department of the University of Texas at Austin, Telephone Conversation with Peter Deibler, July 9, 1980.

Grimsrud, G. Paul; Barbara Turner, and Philip A. Frame, *Areas of Ground Subsidence Due to Geofluid Withdrawal*, prepared by Systems Control, Inc. and Earth Sciences Associates for Earth Sciences Division-Lawrence Berkeley Laboratory, Berkeley, California, August 1978, LBL 8618.

Gustavson, Thomas C., Bureau of Economic Geology at the University of Texas at Austin, Meeting with Peter Deibler and Tony Usibelli, April 28, 1980.

Gustavson, Thomas C., James Dorman, G.G. Sorrells, and Lee Wilson, "Environmental Baseline Monitoring in the Area of General Crude Oil/Department of Energy Pleasant Bayou Number 1--A Geopressured- Geothermal Test Well, 1978," Presented at the *Fourth U.S. Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Gustavson, Thomas C., Charles W. Kreitler, *An Environmental Overview of Geopressured-Geothermal Development: Texas Gulf Coast*, prepared by the Bureau of Economic Geology of the University of Texas at Austin for the Lawrence Livermore Laboratory, Environmental Sciences Division, and the U.S. Department of Energy, Assistant Secretary for the Environment, Report UCRL-15094, 1979.

Gustavson, Thomas C., Florette S. Reeder, Elizabeth A. Badger, *Environmental Analysis of Geopressured-Geothermal Prospect Areas, De Witt and Colorado Counties, Texas*, prepared by the Bureau of Economic Geology at the University of Texas at Austin for the U.S. Department of Energy-Division of Geothermal Energy, Report DOE/ET/27127-1, February 1980.

Gustavson, Thomas C., Maryann McGraw, Mills Tandy, Faust Parker, and Donald E. Wohlschlag, *Ecological Implications of Geopressured-Geothermal Development:Texas Louisiana Gulf Coast Region*, U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-78/60, August 1977.

Kreitler, C.W., T.C. Gustavson, "Geothermal Resources of the Texas Gulf Coast-Environmental Concerns Arising From the Production and Disposal of Geothermal Waters," in Part 3 Environmental of *Volume 5 Legal, Institutional, Environmental* of the Second Geopressured Geothermal Energy Conference Proceedings, University of Texas at Austin, February 23-25, 1976, pp. 1-55.

Lee, Linda, Earth Sciences Associates - Palo Alto, California, Telephone Conversation with Peter Deibler, July 17, 1980.

Lofgren, Ben E., "Analysis of Stresses Causing Land Subsidence," U.S. Geological Survey Professional Paper 6000-B, in *Geological Survey Research 1968* , pp. B219-225.

Lofgren, Ben E., "Measurement of Compaction of Aquifer Systems in Areas of Land Subsidence," U.S. Geological Survey Professional Paper 24-B in *Geological Survey Research 1961*, pp. B-49 to B-52.

Loucks, Robert G., Debra L. Richmann, and Kitty L. Milliken, "Factors Controlling Porosity and Permeability in Geopressured Frio Sandstone Reservoirs, General Crude Oil/Departmant of Energy Pleadant Bayou Test Wells, Brazoria County, Texas," presented at the *Fourth U.S. Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Louisiana State University - Louisiana Department of Natural Resources, "Environmental Monitoring Plan: Parcperdue Test Well No. 1," 1980 (unpublished).

Miller, I., W. Dershowitz, K. Jones, L. Myer, K. Roman, and M. Schauer, Simulation of Geothermal Subsidence (three volumes), Golder Associates for Earth Sciences Division of the Lawrence Berkeley Laboratory, Report LBL-10794 GSRMP-6 UC-66e, March 1980.

Newchurch, Edwin J., Virginia R. Van Sickle, Ann L. Bachman, Charles F. Bryan, Douglas P. Harrison, Robert A. Muller, Charles G. Smith, Jr., "A Comparison of Six Geopressured-Geothermal Prospect Areas in the Louisiana Gulf Coast Region on the Basis of Potential Environmental Factors," presented at the Fourth U.S. Gulf Coast Geopressured/Geothermal Energy Conference Austin, Texas, October 29-31, 1979.

Newchurch, E.J., C.F. Bryan, D.P. Harrison, R.A. Muller, R.E. Wilcox, A.L. Bachman, J.P. Newman, K.J. Cunningham, R.K. Hilding, and J.A. Rehage, A Plan for the Long Term Environmental Assessment of Geopressured Resource Development in the Louisiana Gulf Coast Region, Institute for Environmental Studies:Louisiana State University, July 15, 1978, UCRL-13913.

Newchurch, E. J., A.L. Bachman, C.F. Bryan, D.P. Harrison, R.A. Muller, J.P. Newman, C.G. Smith, J.I. Bailey, G.G. Kelley, and K.C. Reibert, A Preliminary Environmental Assessment of Selected Geopressured-Geothermal Prospect Areas:Louisiana Gulf Coast Region, Volume 1 Comparison of Prospect Areas on the Basis of Potential Environmental Impacts, Volume 2 Environmental Baseline Data, Institute for Environmental Studies-Louisiana State University, October 15, 1978.

Newchurch, Edwin J., Ann L. Bachman, Charles F. Bryan, Douglas P. Harrison, Robert A. Muller, Ronald E. Wilcox, "Environmental Issues of Geopressured Resource Development in Louisiana: Integrating Different Goals and Viewpoints," Presented at the Fourth U.S. Gulf Coast Geopressured/Geothermal Energy Conference Austin, Texas, October 29-31, 1979.

O'Rourke, J.E. and B.B. Ranson, Instruments for Subsurface Monitoring of Geothermal Subsidence (prepared by Woodward-Clyde Consultants for the Earth Sciences Division-Lawrence Berkeley Laboratory, Berkeley, California) July 1979 LBL-8616.

Papadopulos, S.S., R.H. Wallace, J.B. Wesselman, and R.E. Taylor, "Assessment of Onshore Geothermal-Geothermal Resources in the Northern Gulf of Mexico Basin," in Assessment of the Geopressured-Geothermal Resources of the U.S.-1975, U.S. Geological Survey-Department of the Interior, Circular 726, 1975, pp. 125-146).

Pinder, George, State-of-the-Art Review of Geothermal Reservoir Modelling (prepared by Golder Associates for Earth Sciences Division-Lawrence Berkeley Laboratory, Berkeley, California), March 1979, LBL-9093.

Randolph, Phillip, Institute of Gas Research, Chicago, Illinois, Telephone Conversation with Peter Deibler, March 26, 1980.

Rose, Walter, Institute of Gas Research, Chicago, Telephone Conversation with Peter Deibler, July 7, 1980.

RPC, Inc., An Analysis of the Ecological Effects of Geopressured Geothermal Resource Development:Technical Paper No. 4 General Land Office - State of Texas, Austin, Texas, July 1979.

Schatz, John F., Paul W. Kasameyer, James A. Cheney, "A Method of Using In Situ Porosity Measurements to Place an Upper Bound on Geothermal Reservoir Compaction," in Proceedings: Second Invitational Well-Testing Symposium , Department of Energy-Lawrence Berkeley Laboratory, Berkeley, California, October 25-27, 1978, pp. 90-94.

Scott, Ronald F., "Subsidence-A Review," in Surendra K. Saxena, Ed., Evaluation and Prediction of Subsidence , Proceedings of the International Conference on Evaluation and Prediction of Subsidence, Pensecola Beach, Florida, Published by American Society of Civil Engineers), January 1978, pp. 1-25.

Southwest Research Institute, Geopressured Energy Availability - Final Report (prepared for the Electric Power Research Institute), Report No. EPRI AP-1457, July 1980.

Strongin, Oscar, unpublished background notes from Final Report: Issue Paper on Geopressured Resource Development Commercialization Criteria and Industry Incentives , prepared by Science Applications, Inc. for the U.S. Department of Energy - Division of Geothermal Energy, McLean, Virginia, July 26, 1979.

Thompson, Thomas W., and Kenneth E. Gray, "Part 3: Rock Mechanics Aspects of Geopressured Geothermal Reservoirs: Subsurface and Surface Behavior," in Vol.III Reservoir Research and Technology , Proceedings - Second Geopressured Geothermal Energy Conference, University of Texas at Austin, February 23-25, 1976.

U.S. Department of Energy - Assistant Secretary for Resource Applications, Environmental Assessment for DOE Sweet Lake No. 1, Cameron Parish, Louisiana, Department of Energy Report DOE/EA-0065, February 1980.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the Environmental/Laboratory Research Working Subgroup," Houston, Texas, February 23, 1978. Available from CK GeoEnergy Corporation, Suite 145, 3376 S. Eastern Avenue, Las Vegas, Nevada, 89109.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Meeting of the Environmental/Laboratory Research Working Subgroup," New Orleans, Louisiana, April 26, 1978.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fifth Meeting of the Environmental/Laboratory Research Working Subgroup," Houston, Texas, July 18, 1978.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Site Selection Working Subgroup," Houston, Texas, March 21, 1979.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the DOE/Industry Geopressured Geothermal Overview Group," Houston, Texas, March 22, 1979.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Drilling and Testing Working Subgroup," Houston, Texas, August 1, 1979.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes From - DOE/Industry Legal and Institutional, Overview, and Environmental/Laboratory Research Subgroup Meetings," Houston, Texas, May 28-29, 1980.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Newsletter," Las Vegas, Nevada, June 1980.

Van Sickle, Virginia, Louisiana State Geological Survey at Louisiana State University at Baton Rouge, Meeting with Peter Deibler and Tony Usibelli, May 1, 1980.

Van Til, C.J., *Guidelines Manual for Surface Montoring of Geothermal Areas* (prepared by Woodward-Clyde Consultants for Earth Sciences Division-Lawrence Berkeley Laboratory, Berkeley, California), May 1979, LBL-8617.

Viets, Victor F., Richard C. Harding, *Proposal for a Problem Definition Study of Subsidence Caused by Geopressured Resources* EDAW-ESA, Gruy Federal to Lawrence Berkeley Laboratory), Palo Alto, California, August 10, 1979.

Viets, Victor F., C.K. Vaughan, and R.C. Harding, *Environmental and Economic Effects of Subsidence*, (prepared by EDAW, Inc., and Earth Sciences Associates for Earth Sciences Division - Lawrence Berkeley Laboratory, Berkeley, California), May 1979, LBL-8615.

Wallace, Ray, U.S. Geological Survey geologist at Bay Saint Louis, Mississippi, Telephone Conversation with Peter Deibler, March 26, 1980.

White, William A., Maryann McGraw, Thomas C. Gustavson, "Preliminary Environmental Analysis of a Geopressured-Geothermal Test Well in Brazoria County, Texas," in *Proceedings of the Third Geopressured-Geothermal Energy Conference*, University of Texas at Austin, February 23-26, 1976.

Wise, Robert L., Ed., *Semi-Annual Report for the Unconventional Gas Recovery Program-Period Ending March 31,1979*, Morgantown Technical Information Center-U.S. Department of Energy, Report METC/SP-79/8, August 1979.

ENVIRONMENTAL IMPACTS OF GEOPRESSURED BRINE DISPOSAL

Introduction

Control and proper disposal of "spent" brine from geopressured aquifers is the other first-order environmental factor associated with geopressured geothermal development (1). Unlike the oil and natural gas production industries, where quantities of fluid wastes are small compared to the amount of energy resources produced, a single geopressured geothermal well can yield from 10,000 to 50,000 barrels of liquid per day throughout its producing lifetime (2). In addition, the brine produced is hot and chemically complex. Taken together, these factors underscore the potential for serious environmental impacts The section on residual control, above, described the technologies available for disposal of geopressured geothermal brines and some of the technical operating problems (such as scaling and corrosion) that may arise (3).

---

(1) The terms "geopressured geothermal brine," "geopressured geothermal aqueous effluent," "geopressured geothermal waters," "geopressured brine," "geopressured waters," and "spent brine," are used interchangeably in this report. All refer to fluid produced from geopressured geothermal aquifers, either before or after useful energy has been extracted.

(2) Based on 1976 Louisiana Office of Conservation statistics, the average energy-to-salt-water-production ratio was 4.89 million BTU/bbl of salt water (standard deviation 2.07 million BTU/bbl). This figure is an average for the six petroleum and natural gas districts in the state. The number is the ratio of total energy embodied in crude oil, natural gas condensate, casinghead gas, and natural gas produced divided by total salt water production in the district. According to Daniel L. McGuire Jr., of the Office of Conservation, salt water production from field to field can range from zero to dozens barrels of salt water per barrel of crude (about 600,000 BTU/bbl of salt water).

In contrast, production of methane gas from a geopressured aquifer yields a much lower energy-to-brine ratio. Assuming a range of solubilities from 20 to (very optimistically) 100 scf methane/bbl brine, the energy to water ratio would be from 20,000 to 100,000 BTU/bbl brine or 2 % of the oil/gas to salt water ratio in Louisiana. The Rapid Pressure Drawdown (RPD) should yield a higher energy to water ratio and, therefore, the impact is proportionately lessened. Estimates of this ratio are not available.

(3) The type of resource utilization will have minimal significance for the environmental impacts of brine production. A system using a full range system of hydraulic turbines, methane separators, and geothermal electric facilities may have slightly greater impacts than a methane-only facility. However, the amount of brine produced does not vary significantly from process to process (excluding the rapid flow process). Nor will the chemical composition of the brine be substantially altered. Consequently, the potential for deleterious physical and chemical impacts on ecosystems remain the same.

This section concentrates on an evaluation and review of the state of knowledge about the characteristics and possible environmental impacts of these brines. The discussion of these characteristics and impacts centers around the following questions:

- What are the chemical and physical properties of the brines ?
- How do these properties vary geographically within the Gulf Coast Region and in other parts of the United States ?
- What is known about the possible effects of brine constituents ?
- What are the brine sensitivities of Gulf Coast ecosystems ?
- What measures are available to lessen the environmental impacts of brine disposal ?
- What are the state and federal environmental laws and regulations concerning geopressured geothermal brines ?
- Is the experience of the Federal Strategic Petroleum Reserve (SPR) subsurface and surface disposal of brines applicable to geopressured geothermal brine disposal systems ?

Brine Characteristics

A number of factors must be considered in any characterization of the geopressured geothermal aqueous effluent: 1) the rate and duration of brine discharge under normal and emergency operating conditions (e.g., well blowout, pipe rupture, etc.), 2) the number of producing wells reasonably expected to be sited at a single location or in a small geographic area, 3) the thermal properties of the brine at discharge, and; 4) the chemical composition of the fluid. Each of these factors has a bearing not only on the methods and technologies of brine control, but also on the potential environmental impacts.

Volume

- Brine flow rates for a typical well should average from 10,000 to 50,000 bbl/day with total lifetime production from a single well as high as one-half billion barrels.

The amount of brine generated at a typical well in the geopressured zone is expected to range from 10,000 to 50,000 barrels per day. Actual productions depends on the well casing size, reservoir size, optimal rate of reservoir drawdown, and other factors discussed in the technology characterization section (4).

In addition to estimates of flow rates under normal operating conditions, estimates of flows under abnormal or emergency conditions are also available. The maximum flow rate, which will occur when the wellhead pressure is zero, depends on the size of the casing. Podio, et al. have calculated relationships between wellhead pressure, flow rate, kh, and casing size diameter. From their plots it can be calculated that, under blowout conditions (zero wellhead pressure) and with a 7" casing, substantially more than 100,000 barrels of fluid could be produced per day (5). Thus, a blowout release of one-half million barrels of brine, within the span of a few days, is possible.

Adding to the disposal problem is the possibility that several geopressured wells might be located in a small area, working in conjunction to "fuel" a geothermal electric facility or as separate units operating independently to produce fluid from a single fairway. Many of the early designs for geopressured geothermal production systems called for a 25 MWe geothermal electric plant powered by a cluster of 10 to 12 wells each, flowing 30,000 to 50,000 barrels of brine per day (6).

More likely than a clustering of wells for a geothermal power plant is the drilling of wells in reasonably close proximity, one-half to one mile separation for example, in order to produce a reservoir. Thus within an area of a few square miles there could be a dozen or more wells producing in total one-half million barrels of brine/day. If development were extended, under extremely optimistic economic and resource conditions, to an industry producing one tcf/year of gas from Gulf Coast aquifers (assuming a 40 scf/bbl average recovery rate), the

---

(4) RPC, Inc., An Analysis of the Ecological Effects of Geopressured-Geothermal Resource Development, Geopressured-Geothermal Development Technical Paper No. 4, Austin, Texas, July 1979, notes that under the most optimistic operating conditions a well flow rate of 120,000 bbl/day is possible. Most estimates, however, range from 10,000 to 50,000 bbl/day range.

(5) Podio, Augusto L., et al., "Reservoir Research and Technology," Proceedings: Second Geopressured Geothermal Conference-Volume 3 (Austin Texas, February 23-25, 1976) p. 19 Figure 6.

(6) See the technology characterization section, especially the discussion on geothermal utilization, for more information on these designs. Most studies now consider that this clustering of wells highly unlikely.

amount of brine produced in the region is staggering. With wells operating at 40,000 bbl/day, annual water production would be 25 billion barrels from 1700+ wells (100% load factor). (7).

How long can a geopressured geothermal well be expected to operate at a given site? Most of the initial design studies (Brown and Root, Dow) for geopressured facilities based their analyses on the assumption that a well would operate for a period of thirty years. Presumably, this assumption was a corollary to the construction of a geothermal electric plant. Thirty years is the normally assumed lifetime of an electric generating facility and apparently that planning horizon was merely extended to the geopressured resource. A second factor tending toward this assumption was the estimate of very large reservoir volumes (three cubic miles was an often-cited figure). A reservoir of that size could sustain pressure and flow levels for thirty years.

Increased emphasis on the methane content of the aquifers, diminution of the role of geothermal electricity, and decreasing size estimates for aquifers, may invalidate the thirty-year lifespan assumption (8). The lifetime is, therefore, determined by a combination of economics and the physical characteristics of the aquifer. Neither of these issues is discussed in this section; however, they should be kept in mind in evaluating the potential impacts of resource development. A well with a thirty-year lifespan might have different environmental effects at a given location than a well with a ten-year span. In the case of Gulf disposal, for example, might the dilution ability of a region be taxed beyond its limit in the former case?. Could the shorter average lifetimes for geopressured wells lead to the drilling of more total wells in the regions, e.g. three different wells at different sites as opposed to one well at one site? These are issues that should be considered.

Combining the factors discussed above, a typical geopressured geothermal well could be expected to produce from 40 million to 500 million barrels of brine during its lifetime (9). In one geographic area,

---

(7) Compare this with 1.020 billion barrels of salt water produced in Louisiana oil and gas fields in all of 1976 with a total energy output of more than five quads (equivalent to five tcf).

(8) See Southwest Research Institute report, p. 6 passim for a discussion of the reservoir size estimates.

(S.E. Pecan Island), for example, the output of brine could total several billion barrels over the lifetime of the field (10).

Temperature

- Temperatures for geopressured brine vary according to site location, but should range between 250° and 300+°F.

Fluid temperatures have been discussed in the technology section above, and are not recounted in detail here. It is sufficient to note that the brine temperatures as extracted from the wellbore are far above ambient air and water temperatures. The highest recorded temperature in the geopressured zone, as reported by Jones (11), is 525°F. More typical ranges for the brines are 200 to 325°F. Clearly, brines could not be discharged into the environment at these temperatures. Wilson, however indicates that discharge temperatures as high as 180°F have been proposed (12).

In addition to the temperature consideration, the problem of the total amount of heat released into the environment should also be noted. With a geothermal plant operating at such low input temperatures, e.g., 250-275°F the thermal efficiency of the electric generating process is extremely poor, most probably less than 10% (see the technology characterization section for a discussion of Carnot efficiency). This means that nearly all of the geothermal heat is "waste" heat that would have to be dumped into an air or water thermal sink.

Chemical Composition

---

(9) The former figure is for a well with a ten-year average output of 10,000 barrels of brine per day and a 90% capacity factor. The latter figure is for a 50,000 bbl/day well (90% capacity factor) operating for thirty years.

(10) Southwest Research Institute, op cit., Appendix 2.

(11) Jones, Paul, Proceedings of the First Geopressured-Geothermal Energy Conference, University of Texas at Austin, 1975.

(12) Wilson, John S., et al. "Surface Technology and Resource Utilization," Vol. IV, Proceedings: Second Geopressured Geothermal Energy Conference, University of Texas at Austin, February 23-25, 1976.

- The chemical composition of geopressured brines is complex and ranges in total dissolved solids TDS from 10,000 to 275,000 ppm. Concentration of a variety of chemicals including boron, ammonia, and heavy metals, make these brines significantly different from Gulf Coast seawater.

Large quantities of fluid, even fluid at an elevated temperature, do not present major environmental concerns if the chemical composition is compatible with terrestrial and marine ecosystems. Geopressured brines are, however, chemically complex and potentially hazardous wastes, notwithstanding their natural geologic origin. These brines

> "are not concentrated seawater with a regular and systematic increase in all dissolved ions, but are complex solutions that are in part the result of fluid and ion migration and chemical reactions that accompany the burial of sediments and its subsequent diagenesis" (13).

A substantial effort has been expended to characterize these brines. Kharaka and his associates at the U. S. Geological Survey have published extensively in this area and their publications are listed at the end of this section. Most of the information on the chemical composition of geopressured geothermal brines comes from data supplied by oil and natural gas wells drilled into or near geopressured zones (but very seldom into geopressured aquifers) (14). One significant problem with these data, is the dilution of samples due to the production of liquid condensate from depressurized natural gas (15). This has lead to an underestimation of the concentration of dissolved solids.

More recently, increasing numbers of samples have been obtained from actual geopressured aquifers as a result of the DOE Wells of Opportunity and new well drilling programs. Table 1 lists some of the characteristics and constituents of seawater, oilfield brines, and fluid-dominated geothermal fields compared to samples from four geopressured wells. Figure 1 illustrates the range of values for geopressured brine constituents compared to normal seawater. Table 2 and Figure 2

---

(13) Gustavson, Thomas, op. cit., p.iii.
others.
(15) Kharaka, Yousif K.; E. Callender; and W. W. Carothers, "Geochemistry of Geopressured Geothermal Waters from the Texas Gulf Coast," in _Proceedings of the Third Geopressured-Geothermal Conference_, pp. 125-127.

provide similar data for heavy metal concentrations in geopressured brines.

As indicated in the graphs and tables the chemical composition of Gulf Coast seawater is a useful measure against which to compare geopressured brine composition. In addition, the Environmental Protection Agency has published recommended toxicity levels for fluids discharged into the ocean. Together these two indices can provide a baseline for determining the possible effects of geopressured brines, especially with respect to surface discharges.

The most general parameter describing brine constituents is the level of total dissolved solids (TDS). TDS concentrations in brines obtained from the geopressured zone vary over a large range. In the Lafayette area of Louisiana, they range from 20,000 mg/L to 275,000 mg/L (ppm), while the McAllen-Pharr section of southern Texas has values from 10,000 to 40,000 mg/L. In general, the salinity increases as one moves from the southern portion of Texas along the Gulf Coast and into Louisiana (16).

In addition to the simple TDS parameter characterizing geopressured fluids the concentrations of other chemicals may also be significant. Sodium (Na) and chlorine (Cl) ions are also the major constituents by a wide margin (95% to 99%) of the total concentration. However, as Figures 1 and 2 show, concentrations of Ca^{++}, HCO^{3-}, and B^{+++}, can be an order of magnitude greater than seawater and heavy metal concentrations can be several orders of magnitude greater than seawater. Of particular note from an environmental viewpoint are the elevated levels of boron and ammonia. The former has ranges as high as 140 ppm and the latter can be up to 100 ppm (17).

---

(16) Kharaka, Yousif, et al., "Potential Problems Arising from the Disposal of Spent Geopressured/Geothermal Waters from Coastal Texas and Louisiana," p. II-48.

(17) The specific effects of boron, ammonia, and other chemical constituents of brine are discussed in the brine effects section below.

Table I

Chemical Composition of Seawater, Oil Field, Geothermal, and Geopressured Geothermal Brines

Location			Cerro Prieto	Wairakei	Lafayette,LA	Brazoria,TX	Corpus Christi,TX	McAllen-Pharr,TX
	Seawater(a)	Oilfield Brine(b)	Mexico(b)	New Zealand(c)	Weeks Island(a)	Brazoria #2(d)	Portland(a)	Pharr(a)
Sample #	—	—	—	—	77-GG-19	79-GG-204	76-GG-63	77-GG-107
Depth (m)	—	—	—	—	4,275	4,462	3,514	3,018
Temp.(°C)	—	—	—	—	117	138	123	127
Pressure (psia)	—	—	—	—	6246	11406	8406	7594
Fluid Production								
Oil (m^3/day)	—	—	—	—	21.9	—	4.8	—
Water(m^3/day)	—	—	—	—	56.0	230	7.5	7.1
Gas (1000 m^3/day)	—	—	—	—	6.1	—	25.1	3.2
TDS	34,600	N.D.	25,426	4,400	235,700	132,000	17,800	36,600
pH	8.03	N.D.	7.89		6.2	6.5	6.8	6.8
Na	10,500	12,000-150,000	8,016		78,000	38,000	6,500	9,420
Cl	19,000	20,000-250,000	14 828		143,000	80,600	9,270	22,000
Li	0.17	—	22.9	—	16	39	3.6	7.5
K	380	30-4,000	1,899	—	1,065	840	68	
Rb	0.12	—	11.2		3.4	6.3	0.3	0.1
Cs	0.0005	—	39.5		11.8	50	—	2.9
Mg	1,350	500-25,000	0.5		1,140	660	15	18
Sr	8	—	15.4		920	1,020	7.0	256
Ba	0.03	—	9.4		185	760	1.4	27
Fe	0.01	—	0.51		84	62	2.3	4.1
Mn	0.01	—	0.88		N.D.	25	N.D.	N.D.
Pb	—	—	—		300	1.1	1.2	N.D.
Zn	—	—	<0.5		45 000	1.5	3.7	N.D.
B	4.6	—	17.7		44	32	62	105
NH_3	0-0.7	—	N.D.		100	78	5.8	21.5
HCO_3	0-1,200	0-1,200	59.0		450	365	1,600	114
F	1.3	—	2.0		0.8	1.4	1.5	3.9
Br	65	50-5,000	23.7		419	82	19	78
I	0.06	1-300	0.74		18	30	25	22
SO_4	2,700	0-3,600	13.0		6.4	5.4	110	7.4
SiO_2	—	—	1,318		48	120	93	90

(a) Kharaka,Y.K.; E. Chemerya, J.C. Callender,and M.S. Lico, "Potential Problems Arising from the Disposal of Spent Geopressured-Geothermal Waters from Coastal Texas and Louisiana," in Forefronts in Ocean Technology-Part II, Marine Technology Society, Washington D.C., 1979. Table 1.

(b) Phillips, Sidney L.; Mathur Ashwani K., and Raymond E. Doebler, A Study of Brine Treatment, Lawrence Berkeley Laboratory, Berkeley, CA., EPRI ER-476, LBL 6371, November 1977. Table 1-3.

(c) Axtmann, Robert C., " Environmental Impact of a Geothermal Power Plant," Science March 1975, Volume 187, Number 4179, p 795-803.

(d) Kharaka, Yousif K; Lico Michael S.; Wright, Victoria A., and Willian Carothers, "Geochemistry of Formation Waters from Pleasant Bayou No.2 well and Adjacent Areas In Coastal Texas," presented at the Fourth United States Conference on Geopressured/Geothermal Energy:Research and Development, Austin Texas, October 29-31, 1979, Table 1.

DISSOLVED ION CONCENTRATION IN GEOPRESSURED BRINES

(Parts Per Million)

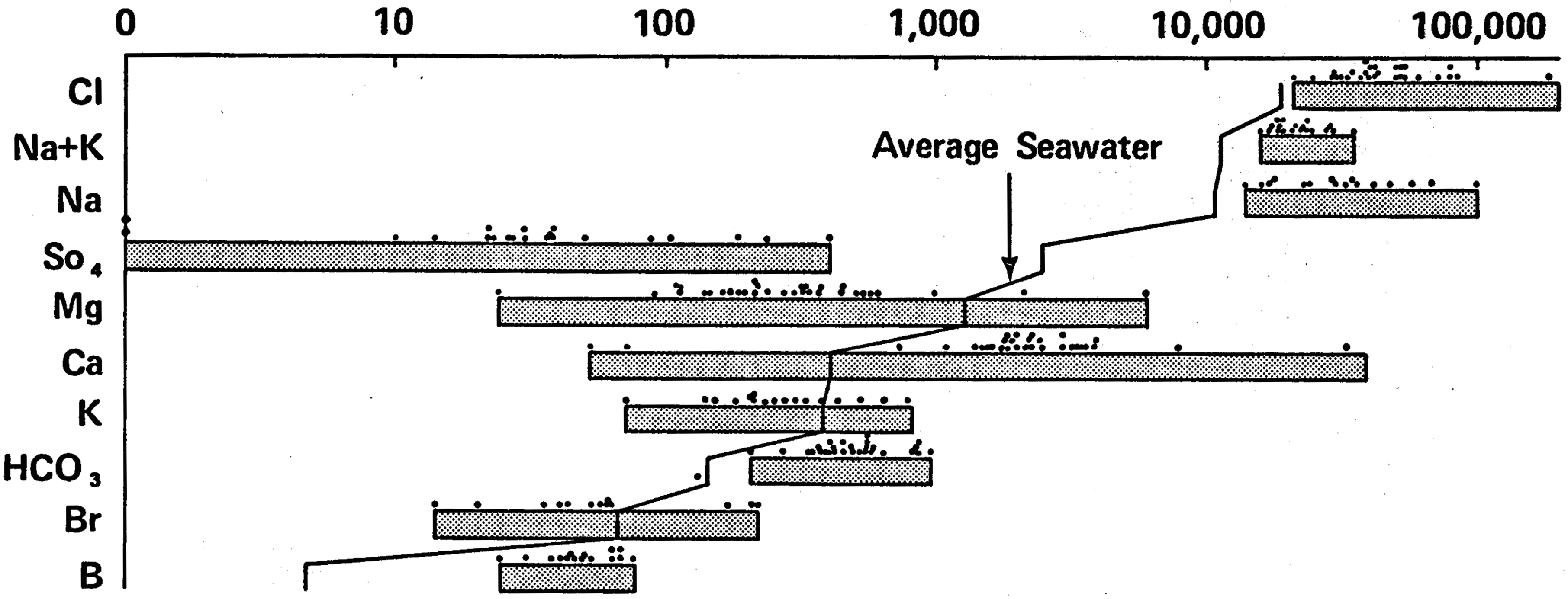


Figure 1

Source: Adapted from Gustavson, et al., 1977

Table 2

Heavy Metal Concentrations in Geopressured Geothermal Brines

Location	Houston,TX		Corpus Christi,TX		Lafayette,LA
	Cosby #1	Houston "K" #1	F.B.Jones #1	Portland A-3	St. Un. A #9
Depth(m)	3,259	3,440	3,648	3,514	4,275
Temp(°C)	117	122	136	123	117
Pressure(psia)	6,710	7,594	8,333	8,449	6,246
Fluid Production					
Oil(m^3/day)	1.0	0.2	17.0	4.8	0
Water(m^3/day)	95.4	23.1	0.3	7.5	56.0
Gas(1000^3/day)	59.5	17.7	52.3	25.1	6.1
TDS	63,700	60,700	24,600	17,900	235,700
Mn	600	1,200	670	150	ND
Fe	100	7 700	42,000	2,300	84,000
Co	1.6	1.3	1.5	1.7	ND
Ni	5.0	4.5	5.5	2.5	ND
Cu	1.3	0.2	0.2	0.2	ND
Zn	16	12	6.6	3.7	45,000
As	1.6	56	0.0	2.2	ND
Cd	76	0.1	0.1	0.0	ND
Hg	ND	ND	0.2	ND	ND
Pb	3.3	6.1	2.9	1.2	300

Source: Kharaka, Chemerya, Callender, and Lico, 1979.

HEAVY METALS CONCERTRATIONS IN GEOPRESSURED BRINES

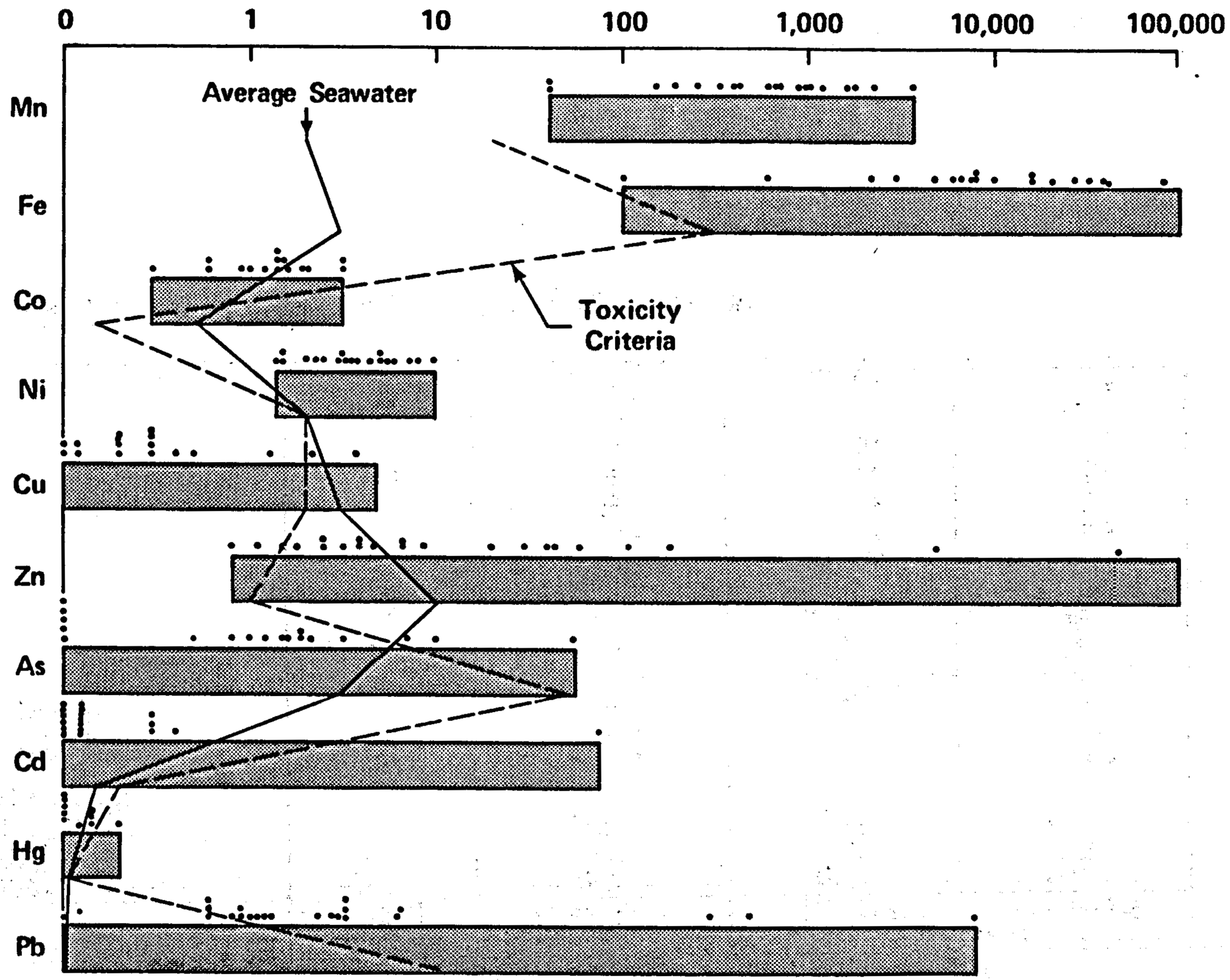


Figure 2

Source: Kharaka, Chemerya, Callender, and Lico, 1979.

Other Geopressured Regions

Detailed data for other geopressured aquifers outside of the Gulf are very limited. The one region where information on geopressured brine composition can be found is California (18). Kharaka has characterized the overall composition of California brines as follows:

> "The salinities of most geopressured waters from California are much lower than those from the Gulf Coast; the salinities are generally less than 20,000 mg/L and, in many places, less then 10,000 mg/L dissolved solids, but in a few places, the salinities reach 70,000 mg/L."

Environmental Impacts

Direct discharge into surrounding terrestrial or aquatic environments of the the geopressured geothermal aqueous effluent will generate a number of serious negative impacts. The type and severity of these impacts depends on both the characteristics of the effluent and the sensitivity of the impacted ecosystem. This section briefly sketchs out some of the impacts that have been identified in the literature (19).

The preceding described the physical and chemical composition of the brines likely to be produced in the Gulf Coast. Although the chemical and thermal characteristics of the brines vary widely throughout the Gulf Coast (e.g., TDS ranging from 10,000 to 275,000 ppm), it can safely be said that any geopressured/geothermal brine has a potential for some deleterious environmental impacts. The type and magnitude of these impacts vary according to the specific properties of a given brine and

---

(18) Kharaka, Yousif K., and Fredrick A.F. Berry, "Geochemistry of Geopressured Geothermal Waters from the Northern Gulf of Mexico And California Basins,"

(19) Although a number of works have examined the ecological impacts of geopressured geothermal brines, the most detailed and comprehensive study focusing on the Gulf Coast sections of Texas and Louisiana is that by Faust Parker, and Donald E. Wohlschlag, Ecological Implications of Geopressured-Geothermal Development:Texas-Louisiana Gulf Coast Region (U.S. Department of the Interior, Fish and Wildlife Service, FWS/OBS-78/60, August 1977). See this report especially for detailed information on the ecosystems of the Gulf Coast and for listings of

Much of this section is extracted from material presented in the above report.

the methods of disposal employed.

What information is available to help evaluate some of these potential impacts? There are several types of information that are useful:

- Laboratory and in-field experience with the effects of saline solutions on non- or low-saline environments.
- Laboratory and in-field data on the effects of specific chemicals (e.g. boron, ammonia, lead,)
- Experience gained from disposal of brine from both onshore and offshore petroleum production operations.
- Experience gained from disposal of fluids from conventional geothermal electric operations, especially liquid-dominated systems.
- Data derived from brine disposal experience as part of the Federal Strategic Petroleum Reserve Program (20).

Given the number of substances and the variations in temperature, pH, and other chemical and physical characteristics of brines a detailed summary of all ecological effects is not possible in this report. In the possible deleterious impacts of brine disposal as follows:

> "The impacts of a geothermal brine spill [or of direct surface disposal] may include an initial kill of local aquatic life because of osmotic, thermal or other toxic stress, followed by long-term possibly chronic effects of gradual dissipation of elevated levels of salinity, heavy metals and other geothermal compounds. Natural ecosystems which receive such brines are modified in a number of ways which affect water circulation systems, osmotic regulation of aquatic organisms, water stratification, specific heat, hydrogen ion balance, buffer systems, solubility of oxygen, turbidity and ion balance. Such changes result in destruction of bottom communities and soil structure and low species diversity. (21)"

---

(20) Impacts of brine disposal from the SPR program are discussed in the section on the SPR below. In brief, that section concludes that because of the relatively short duration of monitoring and the preliminary nature of test results no definitive conclusions on impacts can yet be made.

(21) Ibid. p. 142.

Elevated salinity levels are of particular concern because of the low salt tolerance, relative to typical geopressured brine concentrations, of even halophytic plant species. Maximum salt levels for these plants are only 50,000 ppm, substantially below the 275,000 ppm of some Louisiana aquifers. Additionally, even with high salt tolerance many plants (and animals) are adapted to a specific range of concentration variations. Documentation of the nature of high salt concentrations of flora and fauna is extensive. The reader is referred

Table 3 briefly list some of the toxic consituents in brine, their concentrations relative to recommended limits, and thier chief effects.

Table 3

Toxic Effects of Geopressured Brines (23)

Constituent	Max. Concentration	Effects
SiO_2	900x steam turbine limit	Algae blooms
Sr	12x drinking water standard	Limited concern
Cu	100x aquatic plant tolerance	LC_{50} from 0.0018 mg/l to 7.5 mg/l
Fe	70x freshwater limit	Destruction of benthic species
NH_3	1300x freshwater limit	Toxic 0.2 to 2.0 mg/l

Mitigation Strategies for Geopressured Brine Disposal

From the discussion in previous section it is clear that geopressured brines could serious impact the biota of the Gulf Coast. These brines if undiluted and untreated could be toxic to a wide variety of animal and plant species. The question that logically arises is; are there processes and techniques available that can limit the severity of such impacts?

In the residual control section of the technology characterization chapter, four methods of brine control were examined; 1) shallow subsurface injection, 2) deep subsurface injection, 3) surface disposal, and 4) transfer of the brine to another party for commercial use. As noted previously, shallow subsurface injection is the most promising of these

---

(22) Ibid. pp. 142-148.

options and is the most likely method to be used in the near future. In the residual control section the environmental pros and cons of each method were not explicitly considered. These pros and cons are briefly described below.

Shallow Subsurface Disposal

- Shallow injection is the most promising method currently available that is both economically feasible and environmentally acceptable.
- Under normal operating conditions shallow subsurface disposal should present no significant environmental impacts in the short term. Long-term impacts are as yet uncertain, but most probably should also be minor.

Reinjection of spent brine into a shallow (several-thousand-foot deep) formation with sufficient long-term storage capacity and favorable porosity and permeability characteristics is an environmentally sound procedure. Essentially, all that is occuring is that a natural fluid is extracted from great depth and redeposited into a formation above its original level, but sufficiently deep to preclude direct communication with water supplies or the land surface. This latter point is the key factor in lessening the environmental impacts of injected brine; namely, the brine must remain where it is put with little or no possibility of migration into other formations. (24) The major environmental concern is, therefore, determining the possibility of migration out of the recipient formation.

The Workshop on Subsurface Disposal of Geopressured Fluids, held at the University of Louisiana in 1979, remains the major source of detailed information on the impacts of subsurface disposal. (25)

---

(24) The injection of brines into shallow aquifers may cause fault activation, induced seismicity, or ground lifting under certain circumstances. These problems are discussed in the section on "second-order" environmental impacts, below. The consensus of opinion among experts is that the possibility of deleterious chemical impacts of brines on potable aquifers and ecosystems is more significant than the possible negative geological impacts. Fluid incompatibility, i.e., chemical reaction between the injected fluid and the fluid already present in the formation, is not considered in this discussion. Potential incompatibilities present technical rather than environmental problems and are examined in the residual control section.

(25) Bachman, Ann, L., Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, March 6-7, 1979, Louisiana State University, Baton Rouge, sponsored by the Louisiana Department of Natural Resources and Louisiana State University.

Workshop participants concluded that the mechanism for injected fluid migration out of the disposal zone is overpressuring of the recipient aquifer.(26) Additionally it was noted that:

> "upward migration [of geopressured fluids] to the surface or into potable aquifers is not likely because: (1) the wells are not likely to be placed near structures like salt domes which can bound the disposal aquifer; (2) abandoned, uncased wells often plug naturally with impermeable clays; (3) fractures do not extend upwards in the unconsolidated Gulf Coast sands; (4) the natural hydraulic gradients in the Gulf Coast favor the isolation of injected geopressured fluids from the near-surface; and (5) operating practices can reduce the probability of overpressuring" (27).

Texas and Louisiana state regulations, plus new rules promulgated as part of the federal Underground Injection Control Program should also lessen the likelihood of undesired fluid movement out of the recipient formation. Details of these regulations are given in the regulation section below.

The long-term integrity of the recipient formations is more environmentally uncertain than the short-term aspect. Although reinjection of brines from oil and gas operations and waste from chemical operations is a common procedure in the Gulf Coast, the total volume of fluid produced at a geopressured geothermal site over its lifetime posses substantially different problems. It has been noted that these large volumes present unique uncertainties, but that these uncertainties "are not ones of technology... but of economics--particularly the costs of treatment, maintenance, and back-up systems..." (28) Thus, although the long-term effects of reinjection remain unclear, proper operating and monitoring procedures should go far in mitigating impacts.

---

(26) Ibid., p. 163.
(27) Ibid., p.165.
(28) Ibid, p. 46. The treatment and maintenance systems mainly are for prevention of scaling, corrosion, formation damage and other technical operation problems.

Deep Subsurface Disposal

- Reinjection of spent brine into the producing formation should result in a low probability of deleterious environmental impacts.

Reinjection of spent brine into the formation from which it was originally produced is an unlikely procedure due to the extremely high energy requirements for fluid repressuring. (29) From an environmental viewpoint, however, deep reinjection is a highly desirable option. As with shallow reinjection, the major environmental concern is movement of the disposed fluid out of the recipient formation. With a program of reinjection into the production formation, however, the possibility of such communication is extremely small. First, the formation, by the very nature of its overpressured characteristics is geologically isolated from adjacent formations. Second, the high pressures normally present in the formation make it unlikely that the disposal of fluid would produce pressures above the formation fracture pressure. From a purely economic perspective the operator would want to use the lowest reinjection pressures possible. Third, the formations are extremely deep (10,000 to 20,000) feet and are, therefore, very well isolated from the ground surface or surface faulting systems.

The only major environmental concern may be the increased possibility of failure somewhere along the reinjection well lining because of a poor cement job. The likelihood of a failure is greater simply because of the need for a higher reinjection pressure than for a shallow well. Nonetheless, federal and state requirements for disposal well cementing and design should minimize this hazard.

Surface Disposal

Direct surface disposal of geopressured brines, without treatment, is environmentally less desirable than subsurface injection. Without question introduction of these brines into surface fresh water bodies

---

(29) See the residual control section for more details. Sabodh K. Garg, has published a paper, "Reinjection of Fluids into a Producing Geopressured Reservoir," that argues reinjection into the producing formation is economically feasible because of enhanced recovery factors.

such as adjacent rivers or lakes would not be permitted. Disposal into saline waters (i.e., the Gulf of Mexico) may then be the only permissible surface disposal option. (30)

The section on brine effects above discussed the problems expected in disposing of the spent fluids into saline waters such as the Gulf of Mexico. Three key factors influencing the possible impacts are the the physical and chemical characteristics of a given fluid, the amount of treatment the brine undergoes before discharge, and the dilution potential of the ocean. The characteristics of the brine stream have already been discussed above. The lower the TDS level and level of toxic components such as heavy metals and organics, the greater the possibility for dilution of the brine. Thus it is more likely that waters from a south Texas geopressured geothermal facility (where TDS levels are as low as 10,000 ppm) can be dumped into the Gulf than could 275,000 ppm waters from Louisiana, although both sources would probably require some treatment.. (31)

Treatment of the brine is also one possible way of diminishing the deleterious effects of brine on the Gulf waters. For example Kharaka, et al., note that "aeration [of the brine prior to disposal] will result in the precipitation of iron and manganese as oxyhydroxides and coprecipitation of most of the other heavy metals..." (32) This should eliminate most of the heavy metal problem, however, highly toxic organics such as ammonia would still remain. Treatment to reduce the concentration of these substances is apparently technologically feasible. The economics of such processes, however, remain to be investigated. Again, it is the massive volume of fluid produced that presents a unique disposal problem. Such volumes of fluid mean that both the amount of material requiring treatment and the absolute amount of toxins that may require

---

(30) There appears to be total agreement in the literature that surface disposal into fresh water courses is environmentally unacceptable even for the low salinity brines after treatment. See for, example, Kharaka, Y.K., K. Callender, J.C. Chemerya, and M.S. Lico, "Potential Problems Arising from the Disposal of Spent Geopressured-Geothermal Waters from Coastal Texas and Louisiana,"

(31) It is not the TDS concentration, per se, that is of most concern in determining the potential for deleterious environmental impacts, but rather the concentrations of heavy metals and other toxic chemicals.

(32) Kharaka, et al., op. cit., p. II-49.

treatment are very great, and potentially expensive to handle.

Finally, there is the problem of dilution of these large volumes of fluid to an environmentally acceptable level. On a gross level, dilution seems to be no problem. The volume of geopressured geothermal brine generated even under a very large-scale development program are minuscule compared to the volumes of the Gulf of Mexico. However, the problem is not that simple. The localized impacts of disposal could be potentially devastating under certain dispersion or concentration patterns. The nature of the mixing that could occur at a given site is a complex and incompletely understood phenomenon. Variations in seasonal salinity, current patterns, proximity to shorelines, disposal equipment design, and subsurface topography are but a few of the elements to be considered in determining the temporal and spatial variation in disposed brine. Thus, surface disposal into the Gulf would require detailed pre- and post-disposal monitoring programs with particular emphasis on fluid dispersion characteristics. Data derived from operation of the Strategic Petroleum Reserve's offshore disposal facilities should increase the information base.

Transfer to Another User

A final strategy for disposing of the spent brine is to transfer it to a facility that could make some commercial use of the brine, e.g., a chemical company that might extract useful by-products from the brine stream. Environmentally, the impact of this procedure is unclear. The problem of disposing of the large volume of brine is not necessarily eliminated. The problem is merely transferred to another entity. What the chemical and physical characteristics of the fluid would be after passing through commercial treatment depends on the processes involved. For reinjection disposal, the composition should be of little importance, assuming an acceptable recipient aquifer is available. If the spent brine were to be dumped into a surface water body, it is possible that commercial processing might decrease some of the its toxic characteristics. This merits more careful study, both for available markets for the brine and for chemical and physical composition changes in specific processes.

Regulations and Laws Affecting Geopressured Brine Disposal

Disposal of spent geopressured geothermal brines into either subsurface aquifers and surface water bodies would fall under the purview of a number of federal as well as state laws and regulations. These various laws and regulations require that a variety of monitoring, operational, and proscriptive water quality criteria be meet so as to limit the deleterious effects of disposal of waste water. This section briefly summarizes some of these requirements.

Subsurface Disposal

Subsurface disposal of brines and other aqueous effluents is a common practice throughout the U.S., and is especially prevalent in the states of Texas and Louisiana, with their extensive oil and gas production and chemical industries. As a consequence of these disposal practices, a variety of national and state regulations have been developed to minimize the possibility of spent fluid migration and contamination of groundwater supplies, oil and gas fields, and geothermal fields. In general, most of these regulations were written before the advent of geopressured geothermal development. Nonetheless, fluids produced from these deep aquifers would be controlled under many of these laws.

At the federal level, reinjection of aqueous fluids is controlled under provisions of the Safe Drinking Water Act of 1974 (P.L. 93-522, amended by P.L. 95-190). Specifically the act requires the federal Environmental Protection Agency (EPA) to "develop minimum requirements for State Programs to protect underground drinking water sources from endangerment by subsurface emplacement of fluid through well injection" (33). The recently published Consolidated Permit Regulations and Technical Criteria and Standards; State Underground Injection Control Programs, establish five classes of injection wells with reporting and operating criteria specified for each class. Although geopressured geothermal wells are not specifically mentioned, geopressured geothermal disposal wells will probably be part of Class II and production wells part of Class III (34).

---

(33) Federal Register Volume 45, No. 123, June 24, 1980, p.42472.
(34) Larry Browning, "The Federal Regulatory Framework" in Proceedings: Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, Ann L. Bachman, ed. (Baton Rouge, March 6-7, 1979), p. 12.

Requirements for Class II wells include construction, operating, monitoring, and reporting provisions that must be met before a well can receive a permit. Construction stage requirements include cementing and casing of the injection well plus the measurement of a variety of formation parameters. The chief operating requirement specified relates to injection pressure. Specifically,

> "injection pressure at the wellhead
> shall not exceed a maximum which shall
> be calculated so as to assure that the
> pressure in the injection zone during injection
> does not initiate new fractures in the injection zone.
> In no case, shall injection pressure initiate
> fractures in the confining zone or cause
> the movement of injection or formation fluids into an
> underground source of drinking water" (35).

The well monitoring program requires monitoring to take place weekly for fluid disposal operations, and sets annual reporting requirements.

The State of Louisiana regulates subsurface disposal through the agency of the Louisiana Department of Conservation (DOC), while the Texas Railroad Commission (TRC) has similar jurisdiction in that state. In both cases the subsurface injection of spent brine requires a permit from the state. As with the federal regulations, both states are concerned with protection of fresh water resources, and their regulations are similar in terms of well design and operation to those required by the federal government (36).

---

(35) Federal Register, op. cit., p. 42508.
(36) For a brief description of the TRC and DOC views toward geopressured geothermal disposal see Bachman, Ibid., pp. 3-10.

The Louisiana Department of Conservation's permits and regulations for "Underground Salt Water and Waste Disposal" are included as appendix C of the EPRI report Geopressured Energy Availability, Southwest Research Institute, July, 1980 (EPRI AP-1457).

Texas water quality laws and regulations as related to geopressured brines are detailed in K.E. Rogers and A.W. Oberbeck, "The Geopressured Geothermal Resources of Texas: Regulatory Control Over Water Pollution," The Center for Energy Studies-The University of Texas at Austin, July 1, 1977. A more summary treatment is given in RPC Inc., Legal Issues Related to Geopressured-Geothermal Resource Development, July, 1979 , pp. 21-23.

In addition, under the provisions of the Resource and Recovery Act of 1974, proposed regulations have been issued which classify any fluid as hazardous if its concentrations of arsenic, barium, radium, chromium, lead, mercury, selenium, or silver, exceeded by tenfold the drinking water standards. Consequently, geopressured brines should almost certainly fall under this classification. Although at this writing the impacts of these regulations remain unclear, the designation of the brine as hazardous should serve to increase the quality of monitoring, design, and operation of geopressured wells (37). Larry Browning of EPA also notes that "the designation, hazardous waste facility, means there will be siting limitations for geopressured activities" (38).

Surface Disposal

Presuming that disposal of brines into surface fresh water bodies or offshore within the jurisdiction of Texas and Louisiana is unlikely, control of disposal is exclusively under the control of the federal government. Chris Vais of the Environmental Protection Agency, notes that long-term discharge from a geopressured disposal unit, such as a pipeline, are regulated as under the NPDES permit system of the Clean Water Act (P.L. 92-500), specifically section 403 on Ocean Dumping Criteria. At this writing the details of the criteria had not yet been promulgated. The factors to be considered in such regulations are:

---

(37) See the EPRI AP-1457, op. cit., p. 40 for a brief discussion of possible impacts of hazardous waste designation. The report's chief conclusion was that a hazardous waste classification probably would increase disposal costs.

(38) Bachman, op. cit., p. 13.

(a) the effect of disposal of pollutants on human health or welfare, including but not limited to plankton, fish, shellfish, wildlife, shorelines, and beaches;

(b) the effect of disposal of pollutants on marine life including the transfer, concentration, and dispersal of pollutants or their by-products through biological, physical, and chemical processes; changes in marine ecosystems diversity, productivity, and stability; and species and community population changes;

(c) the effect of disposal of pollutants on esthetic, recreation, and economic values;

(d) the persistence and permanence of the effects of disposal of pollutants

(e) the effect of the disposal at varying rates, particular volumes and concentrations of pollutants;

(f) other possible locations and methods of disposal or recycling of pollutants, including land-based alternatives; and

(g) the effect on alternate uses of the oceans, such as mineral exploitation and scientific study.

The Strategic Petroleum Reserve: Baseline Experience for Geopressured Geothermal Disposal?

- The Federal Strategic Petroleum Reserve Program can provide some useful information about the possible impacts and problems of geopressured brine disposal in the Gulf of Mexico.

- SPR brines are basically saturated salt solutions at ambient temperatures and are, therefore, significantly different from geopressured geothermal brines.

- The SPR offshore monitoring programs may be useful both for data on Gulf Coast responses to hypersaline solutions and for design of a geopressured geothermal disposal monitoring program.

- Institutional problems with siting of offshore pipelines and objections from Gulf Coast fishery associations can provide important lessons for geopressured siting.

One of the technically feasible means of spent geopressured brine disposal that has been discussed above is the discharge of the aqueous effluent into surface waters, most particularly the Gulf of Mexico. However, the toxic chemicals and elevated temperatures present in nearly all brine samples plus the estimated high cost of disposal pipeline construction, have led most individuals to the conclusion that the surface disposal option is not feasible or desirable (39). Nonetheless, our information base for establishing the possible environmental impacts of surface disposal into the Gulf remains incomplete. For example, if drilling and production of the geopressured geothermal resources should occur on offshore platforms, then the feasibility of surface disposal would have to be examined (40).

One possible source of new information concerning brine disposal into the Gulf is the experience gained by the Federal Strategic Petroleum Reserve Program (SPR). The purpose of this section is to examine the brine disposal experience provided by the SPR program and to determine if any of that experience can shed light on geopressured geothermal brine control and disposal.

Under the provisions of the Energy Policy and Conservation Act of 1975 (P.L. 94-163), the U.S. Federal Energy Administration (now the Department of Energy) was mandated to establish a Strategic Petroleum Reserve program as a means to lessen the impact of oil supply interruptions. Initially, the reserve was designed to accommodate 500 million barrels of crude oil, but was subsequently expanded to one billion barrels of ultimate storage capacity. At present there are five sites, all in Texas and Louisiana, that are or will be used as storage facilities. Four of the five storage sites are deep water-leached caverns created in subsurface salt domes.

---

(39) This paper does not attempt to examine the economics of geopressured geothermal resource development or environmental control technologies. However, Fred Wrighton's and Thomas Ray's paper "Economics of Alternative Geopressured Technologies" (Louisiana State University, Baton Rouge, unpublished paper, early 1980) does make some estimates of possible disposal costs for offshore facilities.

(40) See the Offshore Geopressured Development section below for a discussion of the pro and cons of offshore development. It appears very unlikely that any development of the geopressured geothermal resource will occur offshore in the foreseeable future.

The portion of the SPR program that is germane to an examination of geopressured geothermal waste effects and control is that associated with the leaching of salt domes and disposal of the brine generated thereby. The initial step in the cavern storage process involves the drilling of a well into the upper portions of a subsurface salt dome (located at depths ranging from 305 to 1220 meters). Fresh water, taken from a nearby surface source such as a canal or river, is then pumped into the cavern to dissolve the salt from the interior of the dome. It takes roughly seven barrels of fresh water to leach a volume of one barrel in the subterranean salt domes. The hypersaline water (containing almost exclusively sodium chloride) is then pumped from the cavern and disposed of either by subsurface reinjection into adjacent formations or by surface disposal via a pipeline into the Gulf of Mexico (41).

Although subsurface injection remains the major disposal technology at the SPR sites, from an environmental viewpoint this process provides little new information (42). Therefore, only the experience with surface disposal of brines is considered in this section.

To determine whether or not the SPR surface disposal experience may be applicable to geopressured geothermal surface disposal the following questions must be addressed:

- Is the chemical and physical composition of SPR brines similar to geopressured geothermal brines?
- Are there analogous chemical and biological reactions to both types of fluids in the Gulf Coast systems?
- Does the environmental monitoring program at SPR provide potentially useful information on the impacts of disposal and can it be adapted to geopressured geothermal monitoring?

---

(41) At the present time only the Bryan Mound site near Freeport, Texas is employing surface disposal of brines. All other sites are using underground injection with plans underway for eventual surface disposal at the West Hackberry site in western Louisiana. For a general description of the Bryan Mound program see, FEA FES 76/77-6 Strategic Petroleum Reserve:Bryan Mound Salt Dome, Brazoria, County Texas, December 1977.

(42) See the residual control section of the technology characterization chapter for a discussion of the work related to formation damage and plugging of reinjection wells at SPR sites. Experiments designed and operated by the Lawrence Livermore Laboratory have provided a large amount of information on brine injection problems, however, no specific material related to environmental impacts was developed.

- What institutional and legal factors related to SPR disposal may provide information useful for geopressured geothermal development?

Physical Characteristics of SPR Brine

The chemical composition of the brines generated in the salt dome leaching process varies from site to site, but is essentially common salt (NaCl) solution at or near saturation. Total Dissolved Solids (TDS) concentrations thus range from 290,000 to 318,000 ppm at the point of exit from the well casing (43). Other constituents in the brine include Ca, SO_4, and HCO_3. Table 4 indicates some of the measured values. At the Bryan Mound disposal site there is also evidence of some discharge of heavy metals into the Gulf, however, these appear to come from the contaminants in the "fresh" water extracted from a nearby canal for use in the initial leaching process.

Table 4

SPR Brine Characteristics (ppm) (44).

Site	CL	Ca	SO_4	HCO_3	TDS
West Hackberry	170,000	603	1319	293	288,300
Bayou Choctaw	192,000	465	833	148	312,100
Bryan Mound	197,000	901	3000	110	291,800

Temperatures of the brines generated by the leaching process are those of the ambient conditions at the site where the water enters the discharge line, e.g., at the holding pond on-site. It is possible that the temperature of the brine may differ from ambient conditions prevailing at the discharge points in the Gulf and this may be a useful guide for dispersion patterns and temperature effects of "cooled" geopressured geothermal brines. Nonetheless, SPR effluent is substantially different physically and chemically from the brine effluent anticipated at geopressured facilities. The former is basically a hypersaline seawater

---

(43) The saturation concentration of sodium chloride in water varies according to temperature, and the presence of other constituents in the water, but ranges from 35.7 g/L at 0°C to 39.8 g/L at 100°C. (Lange's Handbook of Chemistry, eleventh edition, Table 10-2).

(44) "Evaluating Brine Injection for DOE's Strategic Petroleum Reserve Program" in Energy and Technology Review, Lawrence Livermore Laboratory, August 1979, Livermore, California. p. 5.

while the latter is not.

The total amount of brine generated at a site varies according to the storage capacity at the site. At the West Hackberry location, for example, total brine production from the initial leaching process (211 million barrels oil storage capacity) spanning 67 months is expected to be 2,176 million barrels, or an average of slightly more than one million barrels per day (45). This daily production compares to the total fluid output of fifty 20,000 bbl/day geopressured wells and total output equivalent to ten 20,000 bbl/day wells operating for thirty years (46).

The one site currently employing surface discharge is Bryan Mound. In May the daily discharge rate was roughly 200,000 barrels/day with a rate capacity of the discharge line of over 600,000 bbl/day (47). The discharge process is not continuous, but involves the storage of the brines in a surface pond and discharge in batches at intervals.

Physically, therefore, the comparison between the cavern leached waters of the SPR and geopressured aquifer brines is far from exact. Both of the solutions are hypersaline (with the possible exception of certain geopressured brines), but the significant difference is in the concentrations of other chemicals, for it is precisely these other chemicals such as ammonia and boron which appear to pose greatest environmental hazards. Thus one might expect similar impacts of the sodium and chloride anions and cations, but these would probably be overwhelmed by the effects of the "other" chemicals. One simply cannot expect that the SPR effluent and geopressured aquifer effluent will have the same chemical effects upon Gulf Coast waters and their flora and fauna.

---

(45) U.S. Department of Energy: Strategic Petroleum Reserve Program, Monitoring Plan for Brine-Related Activities for the West Hackberry SPR Site: Final Draft Report, January 1980 (submitted by Science Applications Inc., New Orleans, Louisiana), p. 16.

(46) The figure of 2,176 million barrels does not represent the upper limit of anticipated total lifecycle discharge. The site is designed to accommodate four fillings and drawdowns of the 211 MM barrels of oil. Since displacement of the oil from the caverns is by injection of water, total lifetime output is 3,020 million barrels. No estimate of the likelihood of four oil storage cycles is possible and thus one cannot estimate the time over which one could expect a 3 billion barrel discharge.

(47) Site visit by Tony Usibelli and Peter Deibler, April 30, 1980.

Impacts to Date

What are some of the specific environmental effects that have been noted to date at the Bryan Mound site? Unfortunately, the project has not been in operation long enough to answer that question with any certainty. The environmental coordinator for the Strategic Petroleum Reserve Program, Al Waterhouse, believes that "we [the SPR program] will be able to prove that we have done no significant damage" (48). He further notes that the area of impact of the brine disposal was confined to within three feet of the bottom and that no damage is expected to occur except at concentrations of brine above 40 parts per thousand (ppt). However, the data so far available does not give us sufficient information to determine the long-term impacts.

In the monitoring program for the West Hackberry Site, a number of possible effects of the brine on aquatic ecosystems are noted. These include: osmotic stress, ionic imbalance, decreased oxygen tension, adverse pH, temperature fluctuation, changes in trace metal toxicity, changes in hydrocarbon toxicity, and artificial density stratification (49).

Monitoring

Given that the level of knowledge about the environmental impacts of disposal of large volumes of hypersaline solutions on the Gulf Coast remains incomplete, it follows that some sort of impact monitoring program is required. In fact, at the Bryan Mound site and the proposed West Hackberry disposal site such programs have been instituted. The question then is, how is the program designed and can it provide useful information for surface disposition of geopressured geothermal brines?

Evaluation of the environmental impacts of SPR brine disposal into the Gulf is a two-fold process of both pre- and post-disposal monitoring programs (50). The pre-disposal monitoring program is designed to

---

(48) Conversation by Peter Deibler and Tony Usibelli with Al Waterhouse New Orleans, Louisiana May 1,1980.

(49) Monitoring Plan for Brine Related Activities for the West Hackberry SPR Site, op. cit., p. 2.

(50) Detailed descriptions of the West Hackberry monitoring program are given in the Final Draft Report Monitoring Plan for Brine-Related Activities for the West Hackberry SPR Site, prepared for the Department of Energy Strategic Petroleum Reserve Program by Science Applications Inc., New Orleans, Louisiana.

establish a baseline of site-specific data on the area into which the brine will be discharged. Larry de la Bretonne, a fisheries biologist at Louisiana State Univesity, notes that a one year monitoring program is a minimal requirement for understanding the ecological makeup of a disposal area. (51) Such a program involves a variety of chemical and physical sampling process including, but not limited to, detailed seawater analysis at a number of vertical and horizontal levels near to and away from the disposal line, detailed examination of all benthic and water borne flora and fauna, and an understand of time series variation in these parameters. In summary, such a monitoring program should be designed by oceanographers, marine biologists and other experts highly knowledgeable about the Gulf Coast.

Institutional and Regulatory Factors

Although the composition of SPR brines differs significantly from those expected to be generated at geopressured geothermal sites, and the data from Gulf dispersion monitoring remain incomplete, the SPR example provides some very important institutional and regulatory lessons. Problems that the the SPR program has encountered with local objections, and permits are important indicators of the possible problems that may arise in trying to dispose of geopressured geothermal brines offshore.

In discussions with those involved directly with the SPR program, as well as with concerned individuals from outside SPR, several points were often raised. First, the SPR program has been beset by managerial problems and has, consequently, been not supported or even opposed by individuals and state agencies in the Gulf Coastal region. Lack of sufficient public hearings, development of less than adequate monitoring program, frequent shifts in personnel, and failure by the federal government to communicate with state agencies and educational institutions that have special expertise have all contributed to these problems.

---

(51) Meeting with Larry de la Bretonne, Baton Rouge Louisiana, May 1, 1980.

Any development of geopressured geothermal facilities with offshore disposal will have to deal with this regional animosity, particularly if the federal government is involved in demonstration projects. Therefore, long before any such project is undertaken the government should publish detailed design plans, elicit the aid of regional biologists, oceanographers, and other experts, and contact state agencies in an effort to decrease potential conflicts farther down the line.

A second policy concern expressed was the need to recognize the incremental nature of new disposal projects. At present both the Bryan Mound SPR site and the Louisiana Offshore Oil Port (LOOP) are dumping large amounts of waste brine into the Gulf. Any large new additions, such as might occur with major development of near shore or offshore geopressured geothermal wells, must be viewed as an addition to already existing disposals. Impacts and regulation of these wells will have to take into account the possibility of multiple influences from several disposal sites. Geopressured waste disposal must be examined on both a site specific and a regional basis.

Conclusions

The hot, chemically complex aqueous effluent produced as a by-product of energy conversion from geopressured geothermal aquifers can, under certain conditions, pose serious environmental hazards to terrestrial and aquatic systems. These effects can range from minor disruptions of plant and animal species to major destruction of a wide area surrounding a large well-blowout to damage of aquatic ecosystems. However, if properly handled and disposed of into subsurface aquifers "waste" brines will have minimal impact. The key to assuring the latter is careful monitoring of operations and enforcement of existing disposal regulations.

As has been noted numerous times above, disposal of large volumes of aqueous effluents from conventional oil and natural gas operations and the chemical industry has been standard practice in the Gulf coastal region for decades. The technology is well developed for handling geopressured brines in an environmentally acceptable manner and no significant new research is necessary. Proper subsurface disposal will be chiefly an economic and not an environmental matter.

Disposal of waste waters to a surface water body is very unlikely even with major treatment. Nonetheless, research on improved treatment methods, dispersion patterns, and effects of geopressured brines on aquatic ecosystems should be encouraged, particularly if offshore development of the resource occurs.

BRINE BIBLIOGRAPHY

Bachman, Ann L.,(ed), *Workshop on Subsurface Disposal of Geopressured Fluids, Gulf Coast, Proceedings*, (sponsored by the Louisiana Department of Natural Resources and Louisiana State University) March 6-7, 1979, Louisiana State University, Baton Rouge, Louisiana.

Bachman, Ann L., and C.G. Smith, "Subsurface Disposal of Geopressured Fluids Potential Geological and Operational Problems with Recommendations for Disposal System Testing," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Center for Energy Studies-University of Texas at Austin, *GGIS-The Geopressured Geothermal Information System: Geopressured Geothermal Bibliography (Extract)* (prepared by Thomas Hill), April, 1980.

De la Bretonne, Larry, Louisiana State University Fishery Extension Service, Conversation with Peter Deibler and Tony Usibelli May 1, 1980.

Fowler. William A., "Pressures, Hydrocarbon Accumulation, and Salinities-Chocolate Bayou Field, Brazoria County, Texas, *Journal of Petroleum Technology*, April, 1970 pp. 411-422.

Garg Sabodh, "Reinjection of Fluids into a Producing Geopressured Reservoir," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Gault, Jack, James Hall, John S. Wilson Herb Micheal, Burchard P. Shepard, and Gary Underhill, "Preliminary Analysis of Electric Generation Utilizing Geopressured Geothermal Fluid," in *Proceedings: Second Geopressured Geothermal Energy Conference-Surface Technology and Utilization, Volume IV*, Austin, Texas, February 23-25 1976.

Gregory, A. Ray, and Milo M. Backus, "Geopressured Formation Parameters, Geothermal Well, Brazoria County, Texas presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Gustavson, Thomas C., James Dorman, G.G. Sorrells, and Lee Wilson, "Environmental Baseline Monitoring in the Area of General Crude Oil/Department of Energy Pleasant Bayou Number 1--A Geopressure- Geothermal Test Well, 1978," present at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin Texas, October 29-31, 1979.

Gustavson, Thomas C., M.M. McGraw, Mills Tandy, Faust Parker, and Donald E. Wohlschlag, *Ecological Implications of Geopressured-Geothermal Development: Texas Louisiana Gulf Coast Region*, U.S. Department of the Interior. Fish and Wildlife Service, FWS/OBS-78/60, August 1977.

Hankins, B.E., Raymond E. Chavanne, A. Russel, O. Carroll Karkalits, and Joseph I. Palermo "Results of Flow Tests of Edna Delcambre No. 1: I. Summary of Water Analysis presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference*, Austin, Texas, October 29-31, 1979.

Hodgson, Susan, "Cerro Prieto Geothermal Field," *Geothermal Hot Line* (California Division of Oil and Gas, Vol. 10, No.1, January 1980).

Kharaka, Yousif K., U. S. Geological Survey, Conversation with Peter Deibler and Tony Usibelli, Menlo Park, California, June 27, 1980.

Kharaka, Yousif K., Edward Callender, and Raymond H. Wallace, "Geochemistry of Geopressured Geothermal Waters from the Frio Clay in the Gulf Coast Region of Texas," *Geology*, Volume 5 April 1977, pp.241-244.

Kharaka, Yousif K., Micheal S. Lico, and William W. Carothers, "Predicted Corrosion and Scale-Formation Properties of Geopressured Geothermal Waters from the Northern Gulf Of Mexico Basin," *Journal of Petroleum Technology*, February, 1980, pp. 319-324.

Kharaka, Yousif K., Micheal S. Lico, Victoria A. Wright, and William W. Carothers, "Geochemistry of Formation Waters from Pleasant Bayou No. 2 Well and Adjacent Areas in Coastal Texas," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference* Austin, Texas, October 29-31, 1979.

Kreitler C.W., and T.C. Gustavson, "Geothermal Resources of the Texas Gulf Coast--Environmental Concerns Arising from the Production and Disposal of Geothermal Waters: Phase 0 Scope-of-Work and Management Study," in Proceedings: First Geopressured-Geothermal Energy Conference, University of Texas at Austin, 1975.

Newchurch, E.J., C.F. Bryan, D.P. Harrison, R.A. Muller, R.E. Wilcox, A.L. Bachman, J.P. Newman, K.J. Cunningham, R K. Hilding, and J.A. Rehage, A Plan for the Long Term Environmental Assessment of Geopressured Resource Development in the Louisiana Gulf Coast Region, Institute for Environmental Studies: Louisiana State University, July 15, 1978, UCRL-13913.

Newchurch, E. J., A.L. Bachman, C.F. Bryan, D.P. Harrison, R.A. Muller, J.P. Newman, C. G. Smith, J.I. Bailey, G.G. Kelley, and K.C. Reibert, A Preliminary Environmental Assessment of Selected Geopressured-Geothermal Prospect Areas: Louisiana Gulf Coast Region, Vol. 1 Comparison of Prospect Areas on the Basis of Potential Environmental Impacts, Vol. 2 Environmental Baseline Data, Institute for Environmental Studies-Louisiana State University, October 15, 1978.

RPC, Inc., An Analysis of the Ecological Effects of Geopressured-Geothermal Resource Development:Technical Paper No. 4, General Land Office, Austin, Texas, July 1979.

_________, Legal Issues Related to Geopressured-Geothermal Resource Development, General Land Office, Austin, Texas, July 1979.

Schmidt, Gene W., "Interstitial Water Composition and Geochemistry of Deep Gulf Coast Shales and Sandstones," The American Association of Petroleum Geologists Bulletin, Vol. 57 No.2, February 1973 pp. 321-337.

Southwest Research Institute, Geopressured Energy Availability, prepared for the Electric Power Research Institute, Palo Alto, California AP-1457 (Final Report July 1980).

Sullivan, Brian R., "New EPA Injection Well Rules Outlined," in Oil and Gas Journal, August 13, 1979, U.S. Department of the Army, New Orleans District-Corps of Engineers and Environmental Protection Agency-Region VI, "Public Hearing in the Matter of Installation by the U.S. Department of Energy of a 36-Inch Brine Discharge Pipeline (and Associated Work) from the West Hackberry Dome Storage Area near Hackberry, Louisiana, to a Point in the Gulf of Mexico near the Calcasieu Pass Ship Channel, and for Discharges into the Gulf of Mexico and Black Lake," Cameron, Louisiana, January 30, 1980.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second Geopressured Geothermal Environmental/Laboratory Research Working Subgroup," Houston, Texas, Nov. 3 1977 (published by GeoEnergy Corporation, Suite 145, 3376 South Eastern Avenue, Las Vegas, Nevada 89109).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Second Geopressured Geothermal Site Selection Working Subgroup," Houston, Texas, Nov. 4, 1977 (GeoEnergy Corp., address above)

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting Concerning DOE/General Crude/DOE Contractors-Plans for Brazoria Well," GeoEnergy Corp., address above).

U S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the Environmental/Laboratory Research Working Subgroup," Houston, Texas, Feb. 23, 1978 (GeoEnergy Corp., address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the Site Selection Working Subgroup," New Orleans, Louisiana, April 25, 1978 (GeoEnergy Corp., address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Meeting of the Environmental/Laboratory Research Working Subgroup," New Orleans, Louisiana, April 26, 1978 (GeoEnergy Corp., address above).

U S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fifth Meeting of the Environmental/Laboratory Research Working Subgroup," Houston, Texas, July 18, 1978 (GeoEnergy Corp., address abve).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Fourth Site Selection Working Subgroup," Houston, Texas, March 21, 1979 (GeoEnergy Corp., address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Drilling and Testing Subgroup," Houston, Texas, August 1, 1979 (GeoEnergy Corp., address above).

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Informal Meeting of the Environmental/Laboratory Research Subgroup," Houston, Texas, May 29, 1980 GeoEnergy Corp., address above).

U.S. Department of Energy, *Final Environmental Impact Statement-Strategic Petroleum Reserve, Bryan Mound Salt Dome, Brazoria County, Texas* (Final Supplement to FEA FES 76/77-6), December 1977, DOE/EIS-0001.

U.S. Department of Energy-Strategic Petroleum Reserve Program, *Monitoring Plan for Brine-Related Activities for the West Hackberry SPR Site-Final Draft Report* (Prepared by Science Applications Inc., Suite 103, 800 Commerce Road West, New Orleans, Louisiana), January 16, 1980.

Van Sickle, Virginia, Louisiana Geological Survey, Conversation with Peter Deibler and Tony Usibelli, Baton Rouge. Louisiana, May 1, 1980.

Vanston, John, et al., Vol. 5, *Legal, Institutional, and Environmental*, in *Proceedings: Second Geopressured-Geothermal Energy Conference, February 23-26, 1976*, Center for Energy Studies, University of Texas at Austin, 1976.

Wallace, R.H., T.F. Kraemerm, R.E. Taylor, J.B. Wesselman, "Assessment of the Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin, in *Assessment of the Geothermal Resources of the United States-1978* (U. S. Geological Survey-Department of the Interior, Circular 790, 1978, pp. 132-155).

Waterhouse, Al, Environmental Coordinator for the Federal Strategic Petroleum Reserve Program, Conversation with Peter Deibler and Tony Usibelli, New Orleans, Louisiana, May 1, 1980.

Wilson, John, Burchard Shepard, Sidney Kaufmann, *An Analysis of the Potential Use of Geothermal Energy for Power Generation Along the Texas Gulf Coast*, (Dow Chemical U.S.A. for the Texas Governer's Energy Advisory Council, Project N/T-1, Austin Texas, October 1975).

SECOND-ORDER ENVIRONMENTAL IMPACTS

The possibility of surface subsidence and the potential deleterious effects of hot saline brines are the most important environmental concerns associated with geopressured geothermal development. Both a review of the literature and discussions with environmental experts leaves little doubt about this conclusion (1). There are, however, second-order environmental impacts, which, on a short term basis, such as at a test well site, can assume increased importance, (see the non-unique impacts section below). On a long-term commercial basis these impacts, associated with noise, air pollutant emissions, radioactivity, etc., are of a much smaller magnitude than those arising from subsidence or brine disposal. In most instances, they can be controlled with minimal effort or expense. The ultimate environmental feasibility of geopressured geothermal development on a large scale will not be determined by these secondary environmental impacts, but by the impacts of subsidence and brine disposal.

This section contains brief summaries of these second-order impacts, highlighting some of their more prominent aspects. References are provided in footnotes and at the end of this section for more detailed information. The environmental factors examined in this section are:

---

(1) Some of the major works describing the range of environmental impacts of geopressured geothermal development include:

Gustavson, Thomas C.; M.M. McGraw; Mills Tandy; Faust Parker, and Donald E. Wolshchlag, Ecological Implications of Geopressured-Geothermal Energy Development Texas-Louisiana Gulf Coast Region, August 1977

RPC Inc., An Analysis of Ecological Effects of Geopressured-Geothermal Resource Development, July 1979.

NewChurch, Edwin, J.; Ann L. Bachman, Charles F. Bryan, Douglas P. Harrison; Robert Muller, and Ronald E. Wilcox, "Environmental Issues for Geopressured Resource Development in Louisiana: Integrating Different Goals and Viewpoints," October, 1979.

- Air pollutants
- Noise
- Occupational exposure
- Solid waste
- Radioactivity
- Induced seismicity
- Fault activation
- Thermal effects
- Non-unique impacts of site development

Air Pollutants

- Air pollutant emissions will be small during both well drilling and energy production phases. Hydrogen sulfide levels, often high at geothermal plants, should be extremely small and probably would not require control technology.

The two sources of air emissions at a geopressured geothermal site are emissions of gases associated with the brine stream and air pollutants resulting from the operation of ancillary equipment, such as diesel motors, used principally during well drilling operations. Only the former is considered here (2).

The major gaseous emissions from the brine stream will be methane (CH_4), together with other gaseous hydrocarbons. However, because these are economically valuable energy by-products, atmospheric emissions of these hydrocarbons certainly will be kept to an absolute minimum. Flaring of the gas is extremely unlikely, except for short duration wells test . Some other gases are also expected to be found in solution, but meaningful estimates as to amounts and their variation along the Gulf Coast are not yet available. Gas composition tests from the Pleasant Bayou No. 2 Well, as reported by Kharaka, et al. are given in Table 1 (3).

---

(2) Diesel engines to power the mud pumps, rotary table, etc., may have locally significant air impacts. Nevertheless, these emissions are common to all oil and gas drilling operations and are not unique to geopressured geothermal.

(3) Kharaka, Yousif K., Michael S. Lico, Victoria A. Wright, and William W. Carothers, "Geochemistry of Formation Waters From Pleasant Bayou No. 2 Well and Adjacent Areas In Coastal Texas," presented at the Fourth United States Gulf Coast Geopressured-Geothermal Energy Conference: Research and Development, October 29-31, 1979, Austin, Texas.

Table 1

Composition of Gas Produced from Pleasant Bayou No. 2 Well (Mole Percent)

	Sample Number	
	79GG201G	79GG204G
Gas ratio (scf/bbl)	27	21
Methane (CH_4)	88.93	84.51
Ethane (C_2H_6)	4.65	2.97
Carbon Dioxide (CO_2)	5.24	10.54
Nitrogen (N_2)	0.67	0.57
Hydrogen Sulfide (H_2S)	<0.01	----
Sulphur Dioxide (SO_2)	<0.05	----
Oxygen (O_2)	<0.02	----
Argon (Ar)	<0.02	----

Of the pollutants listed above, only hydrogen sulfide and sulphur dioxide present any potential air pollutant hazard, and the concentrations listed are at levels that should be of little concern (4). In their review of the literature, RPC Inc. concluded that "[s]tudies to date indicate that it is unlikely that H_2S emissions will cause significant ecological or health effects," and that odor considerations will be the only issue likely to be environmentally important (5).

Noise

- Substantially elevated noise levels will occur mostly during drilling and completions work at the site and will be the same as noise levels encountered at any deep drilling operation. Noise from operation of geothermal electric facilities or resulting from well blowouts may occur, but should be of minor overall impact.

---

(4) CO_2 emissions may be of environmental concern given massive development of the resource, as they could contribute to the thermal "greenhouse effect". With the level of development likely in the near term, however, high carbon dioxide levels are less an environmental problem and more a problem in that they mean less useful gas (methane, ethane, etc.,) per barrel of brine produced.

(5) RPC inc., op. cit., p 69.

Elevated noise levels around geothermal electric generating facilities have been an issue of some concern in development of the resource (6). Studies at the Pleasant Bayou test site, however, have shown that noise levels, associated almost exclusively with non-unique activities of well drilling and completion, had a minimal affect on ambient noise levels (7). Wells drilled in regions with little industrial, commercial, or residential development, where ambient noise levels are low, would have a more a deleterious effect However, the transitory nature of well drilling and completion mean that these effects would be short-term.

The other possible sources of increased noise are the operation of geothermal electric plants and from a well blowout. Noise from water-dominated geothermal plants can be noticeable; however, the small size of any geopressured geothermal electric plants and the availability of silencers should obviate such problems. As for well blowouts, it is possible to encounter high noise levels, but the relatively low probability of blowouts and the water-dominated nature of the production stream should make this a minor problem. In sum, noise is not expected to be a significant environmental concern.

Occupational Exposure

- Occupational hazards have not been explicitly considered in geopressured geothermal environmental literature. All indications are that these hazards should be similar, if not identical to oil/gas drilling operations and geothermal, and hydrocarbon production operations. Statistics indicate that oil and gas drilling is one of the most hazardous industrial occupations.

---

(6) See Pasqualetti, M. J., "Geothermal Energy and the Environment: The Global Experience," in Energy Volume 5, March 1980, pp. 154-157 for a discussion of the problem and mitigation measures that have been undertaken at geothermal projects such as The Geysers, in California.

(7) Gustavson "Environmental Baseline Monitoring at Pleasant Bayou , presented at the United States Gulf Coast Geopressured-Geothermal Energy Conference:Research and Development, October 29-31, 1979, Austin, Texas.

Predicted noise levels from a 2100 horsepower drilling rig were 60 dBa at approximately 1000 feet, falling to 50 dBa at 2500 to 3000 feet, assuming no background noise. Subsequent measurements made at the time of drilling determined that there was no significant noise increase in the near by town (Peterson's Landing).

Little attention has been directed to the problem of occupational dangers during the drilling, completion or operation of geopressured geothermal energy facilities. Neither RPC nor Gustavson et al., specifically address the issue of occupational exposure. Occupational hazards during the drilling operations should be the same as the hazards occurring around any deep drilling operation and are not unique to geopressured geothermal facilities. During the operation of the plant, risk of injury or death depend on the facility configuration, e.g. methane separation only, methane separation with geothermal-generated electricity, etc.

The major source of information on occupational hazards is the U.S. Bureau of Labor Statistics (8). According to their data, drilling of oil and gas wells (SIC 1381) is one of the most hazardous industrial occupations. For the drilling industry, the annual rate of lost work days per 100 full-time employees was 205 in the period 1972 through 1975. By comparison, the rate for bituminous and lignite coal mining, traditionally considered as a hazardous occupation, during the period 1973 through 1975, was 112.6. Data disaggregated for production processes is not available.

Solid Waste

- Generation of solid waste will consist largely of drilling waste and waste generated at site and should be of little overall concern.

Solid wastes is generated by drilling operations (cores) and from normal site waste disposal. These wastes are common to all large drilling operations and should present no major environmental problems if existing standard disposal practices are followed, and if existing laws and regulations are observed.

---

(8) U.S. Department of Labor, Bureau of Labor Statistics, Handbook of Labor Statistics 1978, Bulletin 2000, 1979, Table 160 "Occupational Injury and Illness Incidence Rates, by Industry, 1972-1975."

Radioactivity

- Radon-222 has been detected in natural gas samples from geopressured geothermal aquifers. The radiation levels, however, are comparable to typical natural gas industry values and should pose no noticeable health hazard.

Ham et al., report the results of radioactivity analyses for natural gas produced from the Edna Delcambre and Fairfax Foster Sutter wells (9). Table 2 gives these measured Radon-222 concentrations.

Table 2

Radon- 222 Content of Natural Gas

Site	Amount (pCi/l)
Edna Delcambre Sand #3	24-59
Edna Delcambre Sand #1	15-100
Fairfax Foster Sutter #2	70-90

From natural gas wellhead measurements made in the United States and Canada over the last 70 years, maximum concentrations of radon ranged as high as 1450 pCi/l with a U.S. mean of approximately 100 piC/l (10). Gesell's study concluded that "no serious problems are likely to exist from external inhalation of ^{222}Rn-bearing NG [Natural Gas] or NG products, or inhalation of combustion products" (11).

Induced Seismicity

- Both production and disposal of large volumes of fluid from geopressured reservoirs can lead to pressure changes that may induce seismic activity. The Pleasant Bayou No. 1 tests show that this can occur, but the small magnitude of the events are of little

---

(9) Ham, Russell A.; James N. Beck, Raymond E. Chavanne, B.E. Hankins, Joseph I. Palermo, and Stearns W. Rogers, "A Comparison of Selected Parameters from Tested Geopressured-Geothermal Wells," presented at the Fourth United States Gulf Coast Geopressured-Geothermal Energy Conference:Research and Development, October 29-31, 1979, Austin, Texas.
These tests were performed to meet EPA reporting regulations.

(10) Gesell, Thomas F., "Occupational Radiation Exposure Due to ^{222}Rn in Natural Gas Products," in Health Physics, Vol 29, (November), p. 681.

(11) Ibid p. 686.

environmental concern.

There are two potential causes of increased seismic activity associated with geopressured geothermal activities: fluid production, and injection of spent brine. Both relate to changes in the pressure regimes underground. These changes can affect the faulting systems present in an area and, in turn, can induce seismic events. Various sources cite evidence of seismic activity, including an earthquake of intensity V (Modified Mercalli) that occured in east and coastal Texas oil fields in 1931 (12). The only evidence that directly ties geopressured activities with increased local seismicity comes from the Pleasant Bayou No.1 environmental baseline tests (13). Prior to completion of the well there was no evidence for microseismic activities in excess of magnitude 0.25 within four kilometers of the well site. Following operation of the well several larger seismic events were observed. Table 3, list several of the larger events, out of a family of 70 documented seismic occurrences.

Table 3

Pleasant Bayou No. 1 Microseismic Events.

Date	Magnitude (R)
Nov. 3, 1978	1.00
Nov. 3, 1978	1.03
Nov. 7, 1978	1.33
Nov. 13,1978	0.90
Nov. 15,1978	1.31

The correlation between the geopressured well tests and increased seismic activity is clearly present. The small magnitude of the events, however, indicates that the possibility of serious damage is slight. Nonetheless, monitoring of both well flow and shut-in tests, and of brine disposal should continue.

---

(12) RPC Inc., Ibid p 85.

(13) Gustavson, et al.,"Environmental Baseline Monitoring..." op. cit.

Fault Activation

- Fault activation (i.e., fault displacement) is a possible consequence of geopressured geothermal fluid withdrawal, but probability of occurrence remains highly uncertain.

Activation of faults is an additional event that may arise because of massive fluid withdrawal or injection. The Gulf Coast region is underlain by a vast network of growth-induced faults. These faults may be displaced by overpressuring, differential compaction and subsidence, or seismically induced liquefaction (14). Only compaction and differential subsidence have been identified as feasible mechanisms in the Gulf Coast. The section on subsidence discussed the processes involved in compaction and subsidence in the Gulf Coast. In general, the probability of fault activation remains highly speculative. At a minimum, however, any potential development site should include mapping of fault traces as part of the preliminary survey.

Thermal Effects

- Increased temperature levels due to disposal of waste heat could create deleterious effects on aquatic systems. These impacts are discussed in more detail in the brine section of this chapter.

Disposal of "waste" heat from geopressured geothermal energy facilities could deleteriously affect aquatic ecosystems. Because of the low temperatures (250°F to 300°F), use of geopressured fluids for electric generation means very large amounts of heat will be generated. (See the geothermal electric section and residual control section for a discussion of plant efficiency and waste heat.)

A variety of adverse impacts of elevated temperatures on aquatic systems have been identified. These include decreases in dissolved oxygen content of the water, increased metabolic rates for organisms, and prevention or diminution of of reproductive capacities (15). For a more detailed discussion of the environmental impacts of thermal "pollution"

---

(14) RPC Inc., op. cit., pp 81-83.
See the section on residual control for a discussion of the impacts of formation overpresssurization.

(15) Ehrlich, Paul; Anne Ehrlich, and John Holdren, Ecoscience:Population, Resources, Environment, 2nd Edition, 1977. p. 680.

and its interaction with brine constituents, see the brine section above.

Non-unique Impacts

- Non-unique impacts of geopressured-geothermal development are associated with well drilling and completion, and site development. On a short-term test site basis, these impacts can be relatively severe. On a long-term commercial development basis, subsidence and brine disposal would probably overshadow these impacts.

Development of a site for a test or production facility can involve significant local impact. Development activities at a well site can include access road and bridge construction, dredging, spoil disposal and landfill, bulkhead construction, plant construction, geophysical surveys, levee construction, electrical and telephone line construction, and pipeline construction (16).

The impact of these activities vary from site to site depending on the ecological sensitivity of a given location. For example, in Newchurch et al., "Comparison of Six Geopressured-Geothermal Prospect Areas in the Louisiana Gulf Coast Region on the Basis of Potential Environmental Impacts," there were large variations of surface disruption due to site preparation and construction. Coastal marshland, where fish and shellfish propagation are particularly important, are more ecologically sensitive than more upland regions. For test wells, where the duration of operation typically is only a few months or years, surface disruption in wetland areas due to site development, raises the most serious environmental concern (17). (17)

In a more extended time frame (e.g., a commercial well operating for decades), the initial disruption caused by site development should be less important. Brine disposal and, perhaps, subsidence will assume greater importance.

---

(16) See section three, "Ecological Impacts of Non-unique Activities," in An Analysis of Ecological Effects of Geopressured-Geothermal Resource Development," RPC, Inc., July 1979, for a summary and review of the literature on impacts of well drilling and site development.

(17) NewChurch, op. cit., places non-unique site development activities highest on the priority list of environmental impacts, at a test well.

SECOND-ORDER IMPACTS BIBLIOGRAPHY

Center for Energy Studies-University of Texas at Austin, GGIS-The Geopressured Geothermal Information System:Geopressured Geothermal Bibliography (Extract), (prepared by Thomas Hill) April, 1980.

Gustavson, Thomas C.; James Dorman, G.G.Sorrells, and Lee Wilson, "Environmental Baseline Monitoring in the Area of General Crude Oil/Department of Energy Pleasant Bayou Number 1--A Geopressure- Geothermal Test Well, 1978," presented at the Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference Austin, Texas, October 29-31, 1979.

Gustavson, Thomas C.; M.M. McGraw, Mills Tandy, Faust Parker, and Donald E. Wohlschlag, Ecological Implications of Geopressured-Geothermal Development:Texas Louisiana Gulf Coast Region, U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-78/60, August 1977.

Kreitler, C.W., and T.C. Gustavson, "Geothermal Resources of the Texas Gulf Coast--Environmental Concerns Arising from the Production and Disposal of Geothermal Waters: Phase 0 Scope-of-Work and Management Study," First Geopressured-Geothermal Energy Conference, Volume 1, Austin, Texas 1975 .

Newchurch, E.J., C.F. Bryan, D.P. Harrison, R.A. Muller, R.E. Wilcox, A.L. Bachman, J.P. Newman, K.J. Cunningham, R.K. Hilding, and J.A. Rehage, A Plan for the Long Term Environmental Assessment of Geopressured Resource Development in the Louisiana Gulf Coast Region, Institute for Environmental Studies:Louisiana State University, July 15, 1978, UCRL-13913.

Newchurch, E. J., A.L. Bachman, C.F. Bryan, D.P. Harrison, R.A. Muller, J.P. Newman, C.G. Smith, J.I. Bailey, G.G. Kelley, and K.C. Reibert, A Preliminary Environmental Assessment of Selected Geopressured-Geothermal Prospect Areas:Louisiana Gulf Coast Region:

Vol. 1 Comparison of Prospect Areas on the Basis of Potential Environmental Impacts,

Vol. 2 Environmental Baseline Data, Institute for Environmental Studies-Louisiana State University, October 15, 1978.

Pasqualetti, M.J., "Geothermal Energy and the Environment: The Global Experience," *Energy*, Volume 5, No. 2, February 1980, pp. 111-165.

RPC, Inc., *An Analysis of the Ecological Effects of Geopressured-Geothermal Resource Development:Technical Paper No. 4*, General Land Office, Austin, Texas, July 1979.

Science and Public Policy Program, University of Oklahoma *Energy Alternatives: A Comparative Analysis* (Norman, Oklahoma, May 1975).

Vanston, John, et al., *Volume 5 Legal, Institutional, and Environmental*, in *Proceedings: Second Geopressured-Geothermal Energy Conference, February 23-26, 1976*, Center for Energy Studies, University of Texas at Austin, 1976.

Wilson, John, Burchard Shepard, Sidney Kaufmann, *An Analysis of the Potential Use of Geothermal Energy for Power Generation Along the Texas Gulf Coast* (Dow Chemical U.S.A. for the Texas Governer's Energy Advisory Council, Project N/T-1, Austin Texas, October 1975).

OFFSHORE GEOPRESSURED GEOTHERMAL DEVELOPMENT

Introduction

No geopressured geothermal wells have been intentionally drilled and produced in the offshore area of the Gulf Coast. In addition, there are no formal DOE plans to conduct testing of either a design well or a Well of Opportunity (WOO) offshore, much less to commence commercial development. It is almost certain that proof of the feasibility or infeasibility of geopressured development will occur onshore in Texas and Louisiana.

A number of pros and cons of any eventual offshore development policy can be identified, however. Little research has been done on offshore geopressured assessment, although the U.S. Geological Survey (USGS) is now starting to look at five offshore prospect areas (1).

At present, many researchers, government officials, and industry spokesmen state that either economic or environmental costs, or both, will preclude offshore development.

The question of offshore development is more complex than a simple yes of no; however, there are factors that act in favor of offshore as opposed to onshore development. The purpose here is to identify as many factors as possible, both advantageous and disadvantageous, in an effort to: a) determine what research is needed to answer questions about offshore development, and b) to identify the trade-offs involved should offshore development occur.

The first section looks at the current work of the USGS on the geology of potential offshore geopressured prospects. Following the USGS section is: 1) a preliminary and incomplete qualitative listing of the environmental, economic, legal, institutional, and policy pluses and minuses related to offshore geopressured development; 2) a discussion of these issues; and 3) an identification of research needs.

---

(1) Wallace, Ray, "Distribution of Geopressured-Geothermal Energy in Reservoir Fluids of the Northern Gulf of Mexico Basin," in The Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference, Austin, Texas, October 29-31, 1979.

Current USGS Work

Wallace discusses the latest activities of the USGS in a paper presented at the Fourth Geopressured Geothermal Conference in October of 1979. Wallace's work extends the more generalized geopressured efforts detailed in USGS Circular 790 (2).

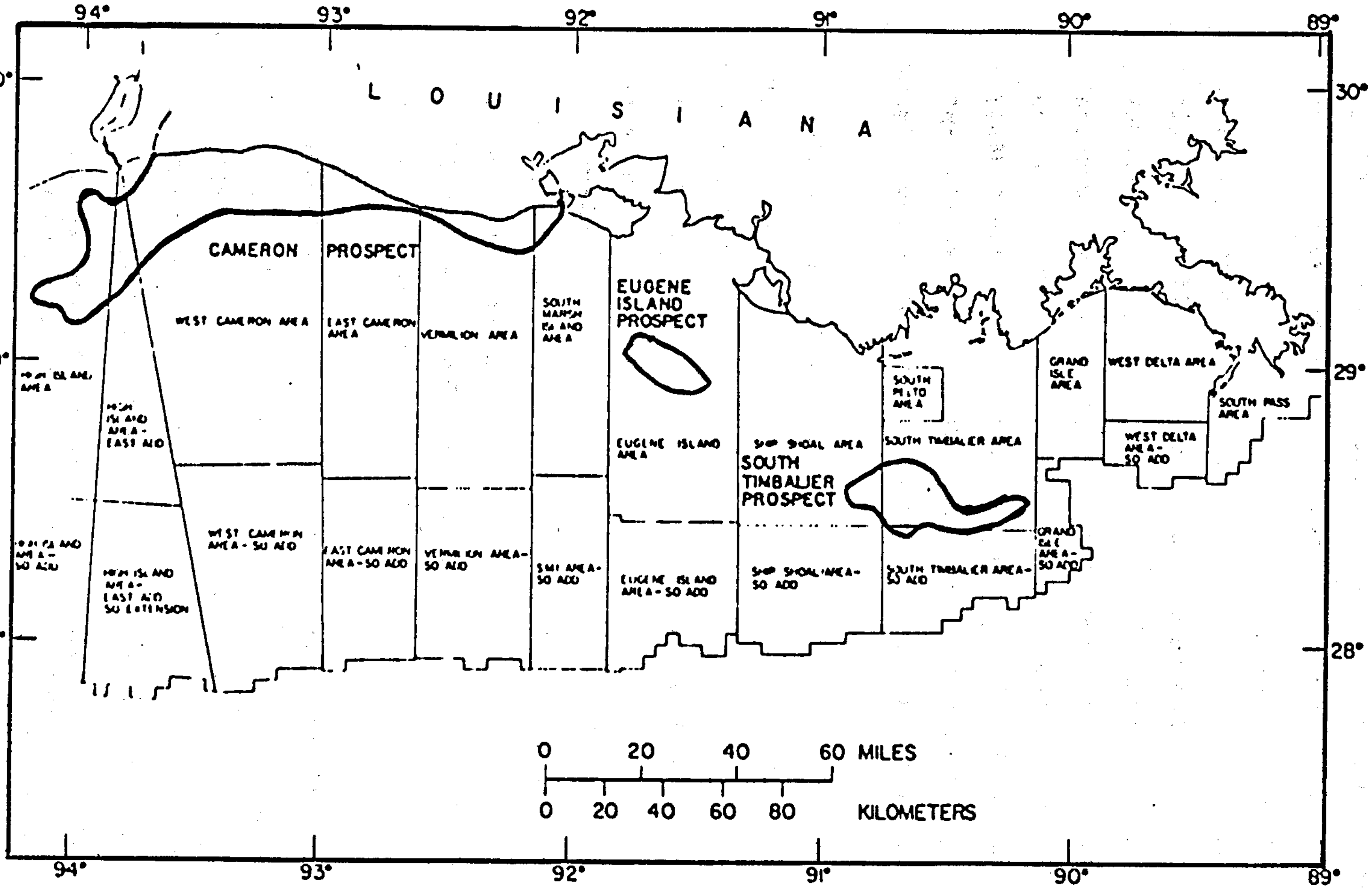
Wallace notes that about 50% of the total in-place (not necessarily producible) thermal and methane resource base exists offshore. Wallace identifies five prospect areas for offshore development as having "excellent sandstone thickness," and "favorable pressure and temperature conditions" (3). The five prospect areas are picked according to an evaluation of the accessible fluid resource base, which Wallace defines as the "energy in the geopressured water in sandstones and shales reachable by production drilling without regard to the amount recoverable or cost of recovery" (4).

Wallace's assessment is based on well logs and geophysical information from petroleum industry records. The data are considered to be excellent except for offshore Texas, where drilling has been relatively sparse (5). The five prospects are shown in Maps 1 and 2 which are reproduced from Wallace's paper (6). The Cameron Prospect of western Louisiana covers a large area both onshore and offshore. The other prospects, Eugene Island and South Timbalier offshore of Louisiana, and the Brazos and Brazos South-Mustang Island East in the Texas coastal waters, occur entirely offshore. Wallace is also examining Johnson's Bayou, a prospect that covers an area both onshore and offshore in western Louisiana (7).

The USGS is modeling the recoverable resource base of the Johnson's Bayou prospect, mapping sediments, and looking at promising compartments for trapped geopressures. This work is only in a preliminary stage. One difficulty noted by Wallace is an inability to get short-term brine disposal permits from the Environmental Protection Agency (EPA) for

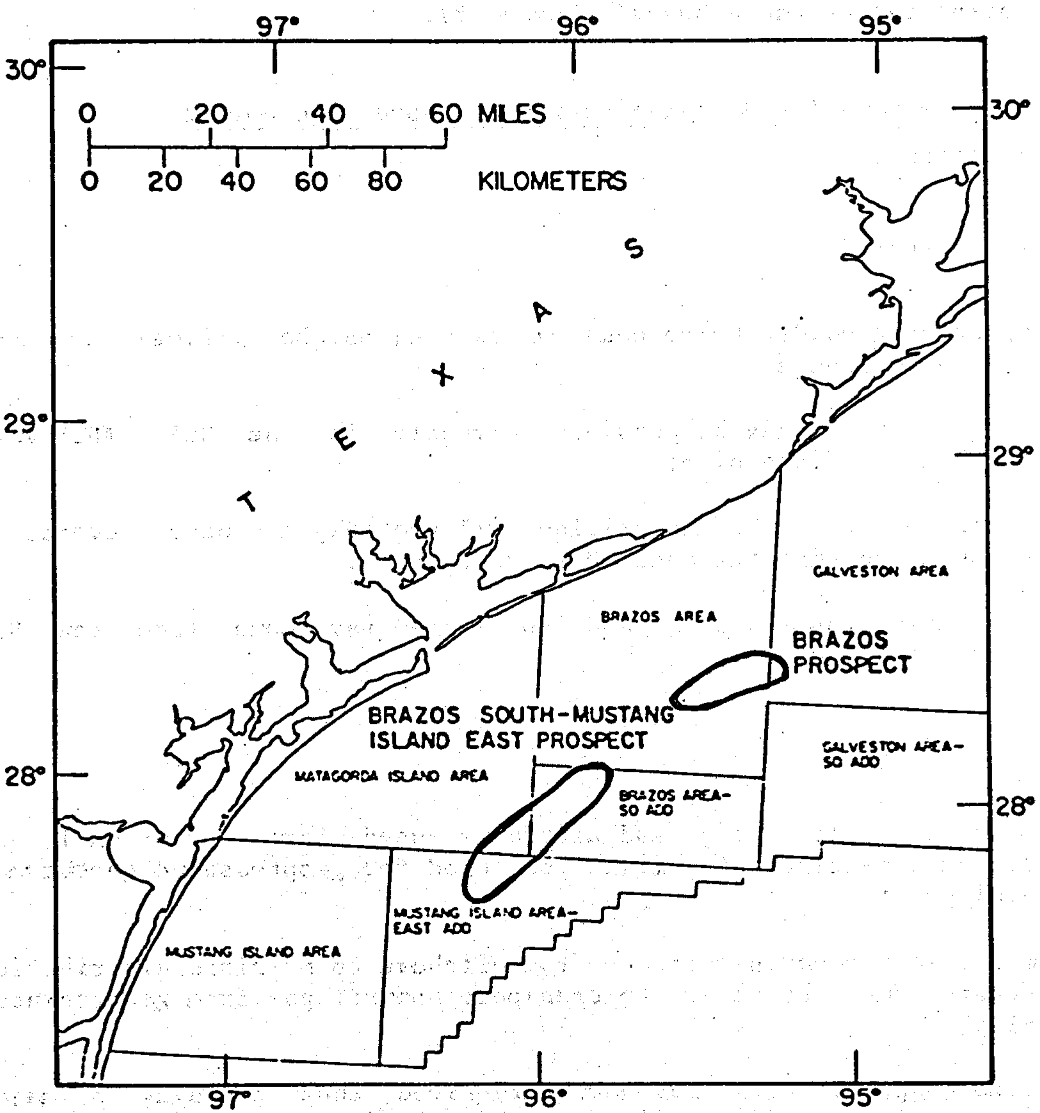
---

(2) See particularly Map 3, "Geopressured Geothermal Energy in Reservoir Fluids of the Northern Gulf of Mexico Basin," in Circular 790 (Available in a separate packet).
(3) Wallace, Ray, op. cit., p.1088.
Ibid, p.1090.
(5) Ibid, p.1095.
(6) Ibid, pp.1115, 1116.
(7) Telephone conversation with Ray Wallace, June 18, 1980.



MAP 1
LOCATION OF GEOPRESSURED-GEOTHERMAL PROSPECT AREAS
OCCURRING OFFSHORE LOUISIANA

Source: Wallace, 1980.



MAP 2
LOCATION OF GEOPRESSURED-GEOTHERMAL PROSPECT AREAS
OCCURRING OFFSHORE TEXAS

Source: Wallace, 1980.

barge operations at the Johnson's Bayou (8).

Factors to be Considered in Evaluating Offshore Development

First the pros:

environmental:

- Impact of subsidence--an unknown onshore, may be minimal or nonexistent offshore;
- brine disposal--may be possible directly in the Gulf following treatment or dispersion;
- impacts of accidents and spills--will probably not be as severe in the outer continental shelf area as onshore;
- brine diffusion research and knowledge--may come from the SPR experience;

economic:

- Amortized drilling rigs and platforms--used for conventional oil and gas development, might be used for geopressured geothermal development;
- amortized product pipelines--from offshore to mainland distribution centers, may be used to transport natural gas from geopressured wells;
- brine disposal wells--may not be required, thus avoiding a major first-year expenditure with a beneficial impact on the net present value of the project.

legal:

- Uncertainty regarding onshore liability for brine accidents and subsidence may be obviated;
- Only one governmental layer of legal requirements because of drilling in federal waters.

---

(8) Ibid.

institutional:

- SPR offshore brine dumping-- may provide a partial analogy to the policy and environmental questions offshore geopressured development will raise.

policy:

- The existing federal offshore leasing mechanisms can be used with minor modifications.

Prior to discussing the issues raised above it is useful to consider the factors that will militate against offshore development. The cons include:

environmental:

- Well blowouts are about five times more frequent offshore than onshore;
- adequate treatment to alter the chemical composition or dispersion/diffusion of brines may not be feasible;
- temperatures of disposed brines may be too high to allow for adequate diffusion in the Gulf seawater;
- total volumes of brine disposal required per platform for an economic operation may be too high to physically allow for adequate chemical and temperature pre-treatment or dispersion/diffusion;
- differential subsidence beneath the drilling platform might require stopping the operation.

economic:

- Existing and in-place rigs, although amortized, may be of an inadequate size for deep drilling;
- due to different characteristics of geopressured as compared to conventional petroleum reservoirs, directional drilling of several wells from one platform may be infeasible;
- existing platforms and pipelines may not coincide in location with geopressured prospects;
- brine disposal too near to shore may adversely affect shellfish harvesting, a major Gulf Coast industry;

- if activity at each platform involves multiple wells or multiple completions per well, partial or total subsurface injection may be required.

institutional:

- In the wake of the Strategic Petroleum Reserve experience, one not fondly viewed by many in the Gulf Coast, federal activities will be closely scrutinized by regional interests.

Discussion of the Issues

Environmental

Brine disposal, one of the two major environmental problems for onshore development is the environmental issue associated with offshore development. Offshore development may hinge on the ability of industry and regulators to develop adequate treatment and diffusion capability.

Offshore development has the advantage of reducing the already considerable strains on the onshore coastal hydrological systems imposed by the petroleum and petrochemical industries. The ecological systems of southern Louisiana and Texas are governed by salinity gradients, and many plant and animal species can tolerate only slight variations in water salinity (9). Wetlands habitat, particularly when governed by salinity gradients, is extremely fragile.

Any analogy of geopressured brines to production fluids requiring disposal from conventional offshore wells is slight. Conventional wells produce a relatively minute fraction of effluent and the reduced scale proportionately reduces the scope of the problem. Figure 1 schematically compares seawater and geopressured brine constituents chemical concentration (10).

The EPA's final regulations covering continuous discharge into the Gulf have not yet been promulgated (11). The regulations will be issued under authority of section 403 of the Federal Water Pollution Control Act. The process will involve applying for a National Pollution

---

(9) Gustavson, et al. especially pp. 138-175.
(10) Adapted from Gustavson, et al. p.27.
Conversation with Chris Vais, EPA San Francisco office, July 10, 1980.

DISSOLVED ION CONCENTRATION IN GEOPRESSURED BRINES

(Parts Per Million)

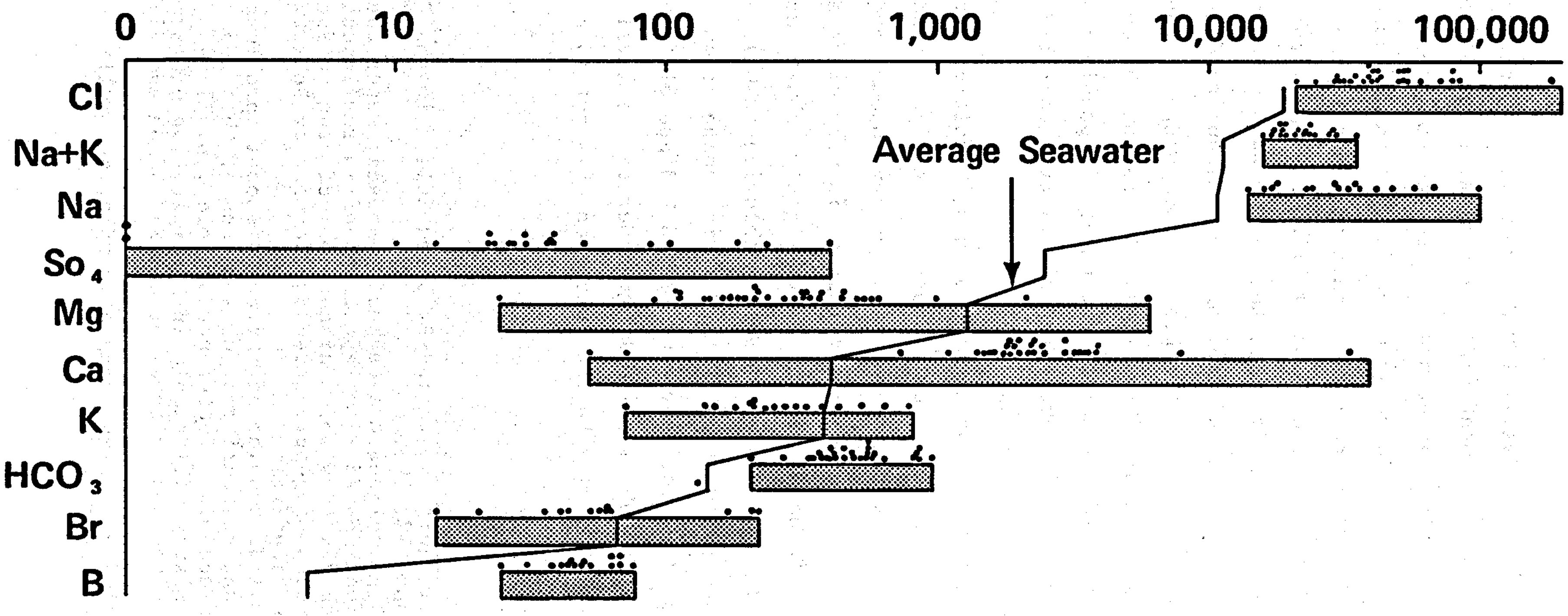


Figure 1

Source: Adapted from Gustavson, et al., 1977

Discharge Elimination System (NPDES) permit. A draft rule has been released for public comment (12). The final rule will be effects-based rather than technology-based and is expected to involve bioassays of any proposed effluent for ocean dumping (13). A major concern will be the avoidance of bioconcentration of toxic elements in the food chain.

In most instances treatment of brine to remove toxic heavy metals is not technically difficult, but the necessary aeration of the brine may result in corrosion and scaling problems during disposal operations. The most environmentally troublesome components of the brine appear to be boron (B) and ammonia (NH_4) (14). At present, boron cannot be easily treated or removed. Ammonia treatment is possible but expensive. As Kharaka et al. note, "geopressured waters are generally not compatible chemically with ocean waters" (15).

The SPR experience of dumping brines, resulting from salt cavern leaching, into the Texas Gulf Coast at the Bryan Mound site provides a partial analogy to offshore geopressured development and brine disposal. The SPR effluent, it must be stressed, is very different from geopressured fluids. Temperatures are only slightly above ambient, and the brine is near-saturation with sodium chloride (NaCl), but does not have the complex and potentially toxic ionic composition of geopressured brine. Plans now call for a maximum SPR disposal from the Bryan Mound site of about 600,000 barrels of brine per day, a level that would probably only be reached with the operation of about 15 geopressured wells (16).

---

(12) "Ocean Discharge Criteria--Proposed Rule," in the <u>Federal Register</u>, February 12, 1980.

(13) Effluent guidelines are technology-based; water quality criteria are effects-based. See Department of Energy/Industry Meeting Minutes, March 22, 1979 for a discussion of the offshore brine disposal aspects of geopressured development by Robert Hartely of EPA's Cincinnati office.

(14) For a full discussion of brine disposal problems see the brine effect and residual control sections of this report.

(15) Marine Technology Conference article , p. II-49. They go on to say that "mixing will result in precipitation of large quantities of carbonates and sulfates of Ca, Sr and Ba and ozyhydroxides of iron."

(16) This estimate assumes single completion wells flowing at 40,000 barrels per day.

It is perhaps too early in the history of SPR brine disposal to determine the ability of the diffusers to adequately disperse the brine into Gulf waters (17). Nevertheless, SPR modeling and monitoring of Gulf currents and brine dispersion may prove helpful for future research into offshore geopressured development.

Until more is known about the chemical constituency of offshore geopressured brines, their ability to diffuse under various conditions, and the toxicity tolerance levels for Gulf biota, it is difficult to compare a geopressured brine spill or well blowout with an offshore petroleum well accident. Newchurch et al. note that: "Although there are major fisheries in the offshore portions [of the Atchafalaya Bay, Louisiana geopressured prospect], impacts on fish from accidental spills would be local and temporary because of the excellent dispersion and dilution properties of the Gulf of Mexico" (18). In contrast to petroleum, brine will mix with the Gulf Waters rather than form a spreading layer on the surface. Still, it should be noted that the incidence of conventional well blowouts offshore is about five times the incidence of onshore (19). At present there is not enough drilling experience with geopressured geothermal onshore, much less offshore, to assess the blowout rate for these highly-pressured wells.

Offshore subsidence may occur with little of no adverse effect on human or natural Gulf ecosystems. Newchurch et al, state that: "Surface subsidence would go unnoticed unless the bowl of subsidence intersected the coast" (20). Subsidence could present difficulties for drilling operators should production tubing buckle, the platform sink, or differential subsidence create an imbalance in the platform with possible

---

(17) There is some disagreement over the adequacy of the diffusers. The officials in charge of on-site monitoring are less optimistic than the environmental officer at SPR's New Orleans headquarters. Meetings with Al Waterhouse, New Orleans, May 1, 1980; Jim Scott and Brian Luchianow, Bryan Mound, April 30, 1980.

(18) Newchurch, Edwin J., et al. discussion under the heading of "Test Program Activities in the Gulf of Mexico." Note that this discussion is in the context of test-scale levels of activity. Although brine production will likely be at rates below commercial, the effects of a test well and of a production well blowout should be roughly equivalent.

(19) RPC report, statistics of the Texas Railroad Commission, p.29.

(20) See footnote 18 for the relevant section of Newchurch's paper.

tubular bucking and unsafe operating conditions.

Economic

Conventional drilling platforms and rigs must be dismantled following cessation of use in a no longer productive area (21). Disposal and product pipelines are allowed to settle into the Gulf silt as long as there is no hazard to shipping. Platform removal is strictly enforced near to the shore. The increased costs due to an inability to drill more than several wells (possibly with multiple completions) from one platform in order to achieve economic production of geopressured reservoirs, may be offset by the presence of an amortized platform and pipelines. The capital requirements on these installations normally have been charged against earlier petroleum and natural gas production (22). In addition, treatment and disposal of brines in the Gulf, if feasible, may be far less expensive than drilling disposal wells.

Wrighton and Ray use a techno-economic simulation model to compare the costs of various configurations for resource production and brine disposal. In discussing offshore development, they note the very positive impact on the present net value of the project resulting from the absence of disposal wells. Drilling costs are a major first year expenditure, the avoidance of which allows for a more favorable schedule for tax payments (23). Conversely, if disposal wells are required, the effect on the economics of the project may be major.

If existing rigs are used to drill into shallower and non-overpressured formations, the rig size may be inadequate to handle deep geopressures. In addition, there is a need to compare the coincidence of conventional drilling areas with the preliminary offshore geopressured prospect areas identified by Wallace. Wallace states that, "conventional oil and gas production installations and natural gas pipelines for transmission to shore are in place in most of these areas [five

---

(21) "Outer Continental Shelf Mineral and Right-of-Way Management," 43 CFR 3300. The regulations [in §3340.1(a)(6)] require platform removal following termination of a lease. The regulations are promulgated by the Bureau of Land Management.
(22) Telephone conversation with Ray Wallace, March 26, 1980.
(23) Wrighton and Ray, p.7.

identified prospect areas partially or completely offshore]" (24).

Finally, high salinities and the presence of various dissolved ions in brines can be lethal to many commercial species. Thus disposal will have to be carried out in such a manner as to avoid deleterious interference with the Gulf Coast shellfish industry.

Legal

Onshore development of geopressured geothermal resources involves legal constraints on three levels: federal, state, and local. To add to the potential confusion, the Napoleonic code in use in Louisiana is found nowhere else in the country. Offshore drilling of geopressured zones will involve only the federal layer of legal involvement. All parties involved will be more aware of their individual responsibilities. The issue of onshore subsidence, for instance in Louisiana, in which the state owns the flooded inland waterways, would be obviated through offshore development. There are no readily apparent legal disadvantages to offshore development of the resource.

Institutional

On the optimistic side of the issue, the SPR experience can be useful for anticipating the difficulties that may be encountered in offshore geopressured development. Technically, SPR development may not yet have progressed far enough to ascertain the success or lack of success of its brine disposal operation. Politically, however, the attitude of past SPR administrators toward the regional and local interests of Louisiana and Texas may have created an unfortunate situation for geopressured development. Federal efforts must be made to include state officials and representatives of interest groups early in the planning process, not only to promote understanding and cooperation, but also to take advantage of the expertise of regional scientific experts (25).

---

(24) Wallace's Fourth Conference paper, p.1131, and the above discussion of Wallace's work.

(25) Meeting with Larry de la Bretonne, Baton Rouge, May 1, 1980.

Policy

Existing mechanisms for offshore leasing are well developed and all of the involved parties have had substantial practice in their use. Offshore leasing in federal waters is controlled by the Department of the Interior (26).

Areas of Research

A few areas of research pertinent to offshore development of the resource can be identified from the above discussion. A preliminary list includes:

- what types of treatment of fluids are required and economically and technically feasible on an offshore drilling platform?
- what financial considerations must be balanced by a petroleum firm considering offshore geopressured drilling?
- to what extent are existing platforms and rigs in the Gulf coast useable for geopressured drilling?
- what modifications in existing federal statutes will be necessary to allow for offshore geopressured development?
- how far do shellfish harvesting grounds extend into the Gulf?
- will SPR diffuser technology be wholly applicable for geopressured or is the the development of new technology required?
- if disposal wells are necessary offshore, how will the added cost balance with amortized platforms and pipelines?
- what would be the severity of impact of a worst case geopressured brine spill or blowout?

---

(26) See "Outer Continental Shelf Mineral and Right-of-Way Management," 43 CFR 3300 (Subpart 3310 in particular); and "Bidding System for Outer Continental Shelf Oil and Gas Leasing-Final Rule," 10 CFR 376.

OFFSHORE DEVELOPMENT BIBLIOGRAPHY

"Bidding Systems for Outer Continental Shelf Oil and Gas Leasing-Final Rule," 10 CFR 376, in the *Federal Register*, Vol.45 No.30, February 12, 1980, pp.9536-9540.

de la Bretonne, Larry, Louisiana State University--Fisheries Cooperative Extension Service, Baton Rouge, Louisiana, Meeting with Peter Deibler and Tony Usibelli, May 1, 1980.

Gustavson, Thomas C., M.M. McGraw, Mills Tandy, Faust Parker, and Donald E. Wohlschlag, *Ecological Implications of Geopressured-Geothermal Development: Texas Louisiana Gulf Coast Region*, U.S. Department of the Interior Fish and Wildlife Service, FWS/OBS-78/60, August 1977.

Kharaka, Yousif, K. Callender, J.C. Chemerys and M.S. Lico, "Potential Problems Arising from the Disposal of Spent Geopressured-Geothermal Waters from Coastal Texas and Louisiana," *Proceedings: Marine Technology Society Annual Meeting*, New Orleans, Louisiana, October 1979, pp. II-47 to II-54.

Kharaka, Yousif K., Micheal S. Lico, and William W. Carothers, "Predicted Corrosion and Scale-Formation Properties of Geopressured Geothermal Waters from the Northern Gulf Of Mexico Basin," *Journal of Petroleum Technology* February, 1980 pp. 319-324.

Newchurch, Edwin J., Virginia van Sickle, Ann L. Bachman, Charles F. Bryan, Douglas P. Harrison, Robert A. Muller, Charles G. Smith Jr., "A Comparison of Six Geopressured-Geothermal Prospect Areas in the Louisiana gulf Coast Region of the Basis of Potential Environmental Impacts," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference*, Austin, Texas, October 29-31, 1979.

"Ocean Discharge Criteria--Proposed Rule," 40 CFR 125, Environmental Protection Agency, in the *Federal Register*, Vol.45 No.30, February 12, 1980, p.9548.

"Outer Continental Shelf Minerals and Right-of-Way Management," Bureau of Land Management, 43 CFR 3300, p.477.

RPC, Inc , *An Analysis of the Ecological Effects of Geopressured-Geothermal Resource Development:Technical Paper No. 4* General Land Office, Austin, Texas, July 1979.

Scott, Jim and Brian Luchianow, Assistant Director and Environmental Officer, respectively, Bryan Mound Strategic Petroleum Reserve Site, Texas, Meeting with Peter Deibler and Tony Usibelli, April 30, 1980.

U.S. Department of Energy/Industry Geopressured Geothermal Resource Development Program, "Minutes of the Third Meeting of the DOE/Industry Geopressured Geothermal Overview Group," Houston, Texas, March 22, 1979 (Available from CK GeoEnergy Corporation, Las Vegas. Nevada).

U.S. Environmental Protection Agency, *Quality Criteria for Water*, Washington, D.C., 1976.

Vais, Chris Water Quality Division of the Environmental Protection Agency Region 10, San Francisco, Telephone conversation with Tony Usibelli, July, 10, 1980.

Wallace, R.H., T.F. Kraemerm, R.E. Taylor, J.B. Wesselman, "Assessment of the Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin, in *Assessment of the Geothermal Resources of the United States-1978*, (U. S. Geological Survey-Department of the Interior. Circular 790, 1978, pp. 132-155).

Wallace, Ray H., "Distribution of Geopressured-Geothermal Energy in Reservoir Fluids of the Northern Gulf of Mexico Basin," presented at the *Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference*, Austin, Texas, October 29-31, 1979.

Wallace, Ray H , U S. Geological Survey geologist at Bay Saint Louis, Mississippi, Telephone conversation with Peter Deibler, March 26, 1980.

Wallace, Ray H., U.S. Geological Survey geologist at Bay Saint Louis, Mississippi, Telephone conversation with Tony Usibelli, June 18, 1980.

Waterhouse, Al, Environmental Coordinator for the Federal Strategic Petroleum Reserve Program, Meeting with Peter Deibler and Tony Usibelli, New Orleans, Louisiana, May 1, 1980.

Wrighton, Fred, and Thomas Ray, Louisiana State University, Baton Rouge, "Economics of Alternative Geopressured Technologies," unpublished paper, early 1980.

APPENDIX A: NON-UNIQUE DRILLING AND COMPLETION TECHNOLOGY

Introduction

The following is a brief discussion of the major aspects of any petroleum drilling and completion program. Certain steps may be omitted for particular wells (either conventional or geopressured) and the sequence of events may be altered. Diagrams are used to illustrate technology and techniques in common use.

Several important geological parameters that differentiate a conventional from a geopressured well plan are worthy of note. Figure 1 illustrates the geopressured region, the area between hydrostatic and lithostatic gradients. Figure 2 demonstrates the relationship of formation pore pressure and fracture pressure to an idealized mudweight program for a geopressured well. Cementing and casing program design is also based on the relationship of the formation pressure to the pore pressure. Note the small overbalance of mud weight relative to pore pressure for an idealized drilling program. This relationship applies for both geopressured and normally pressured wells.

Surface Equipment

Figures 3,4,5,6,and 7 illustrate the layout of on-site drilling equipment for any type of oil and gas well. Rotary drills, as shown in Figure 3, are used almost exclusively in today's drilling. Turbo drills, as shown in Figure 4, are used occasionally with a rotary rig because the need for a rotary drilling string is eliminated. Turbodrills may be used in future geopressured wells in order to reduce casing wear.

Figures 5 and 6 illustrate the power requirements on-site for the drilling rig, the mud pump, and the drawworks.

Figure 7 shows a generalized blowout preventer stack. A stack for a highly pressured well may have additional rams for back-up protection in case of a well kick. Note both manual and hydraulic controls. In addition, many preventer stacks have remote electronic controls in case of a blowout.

Finally, Figure 8 illustrates the technique for "tripping in" the well. Drill string (or casing) is stored vertically in racks, rested

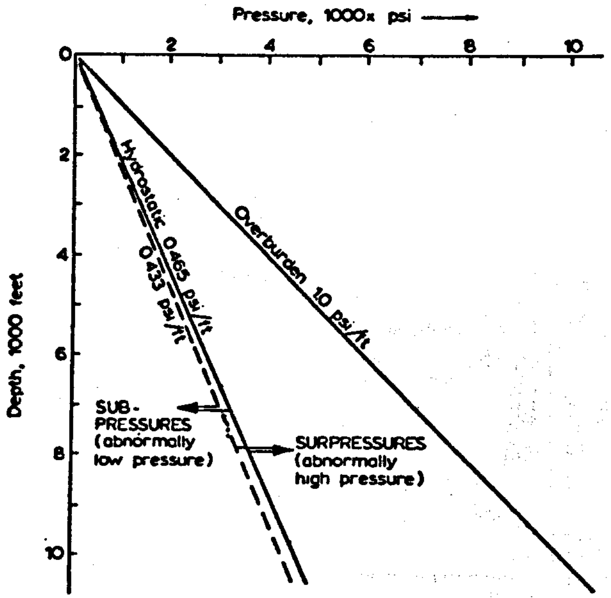


Figure 1 Subsurface Pressure Concepts

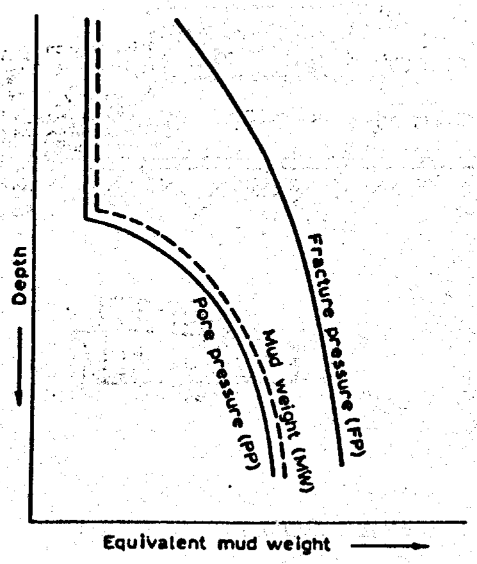
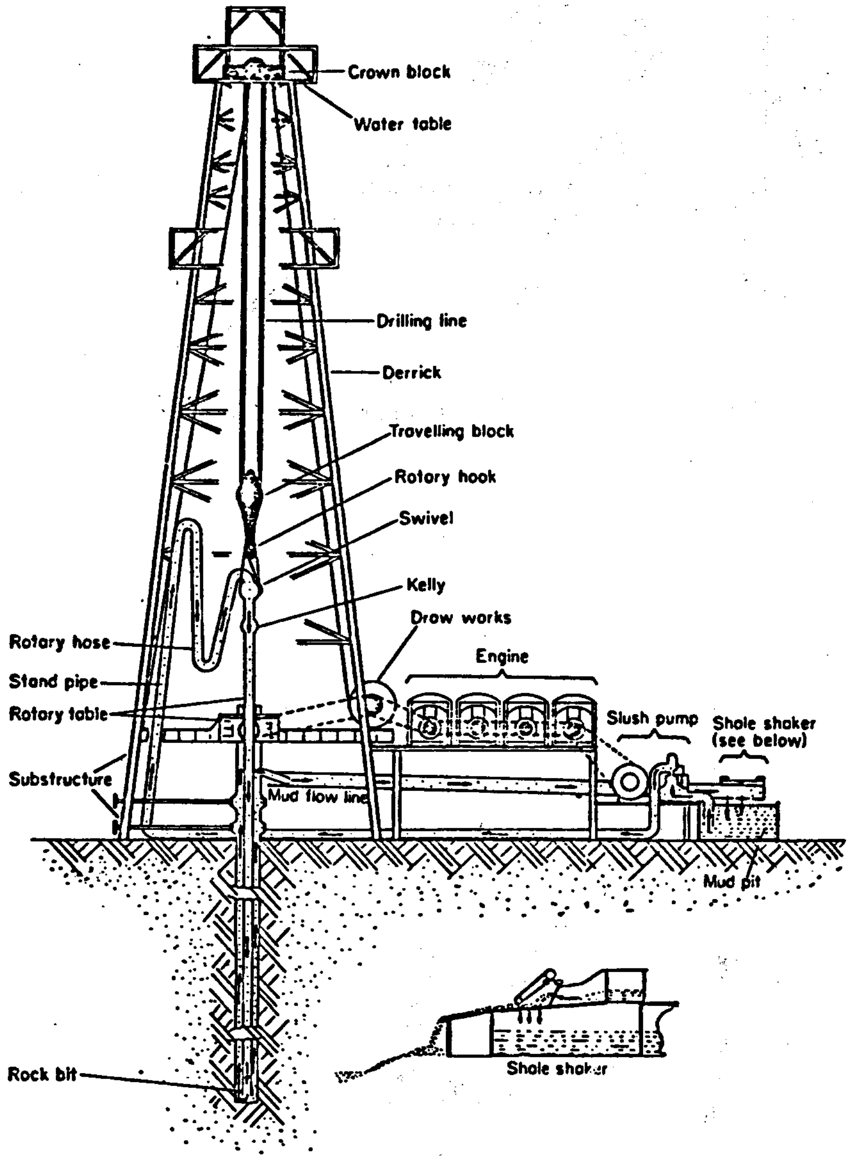


Figure 2 Generalized Trends of the Three Key Parameters: Formation Pore Pressure, Ideal Mudweight Requirements, and Fracture Pressure in a High-Pressure Well

Source: Fertl, 1976.



Rotary Drilling

Figure 3

Source; Crook, 1976.

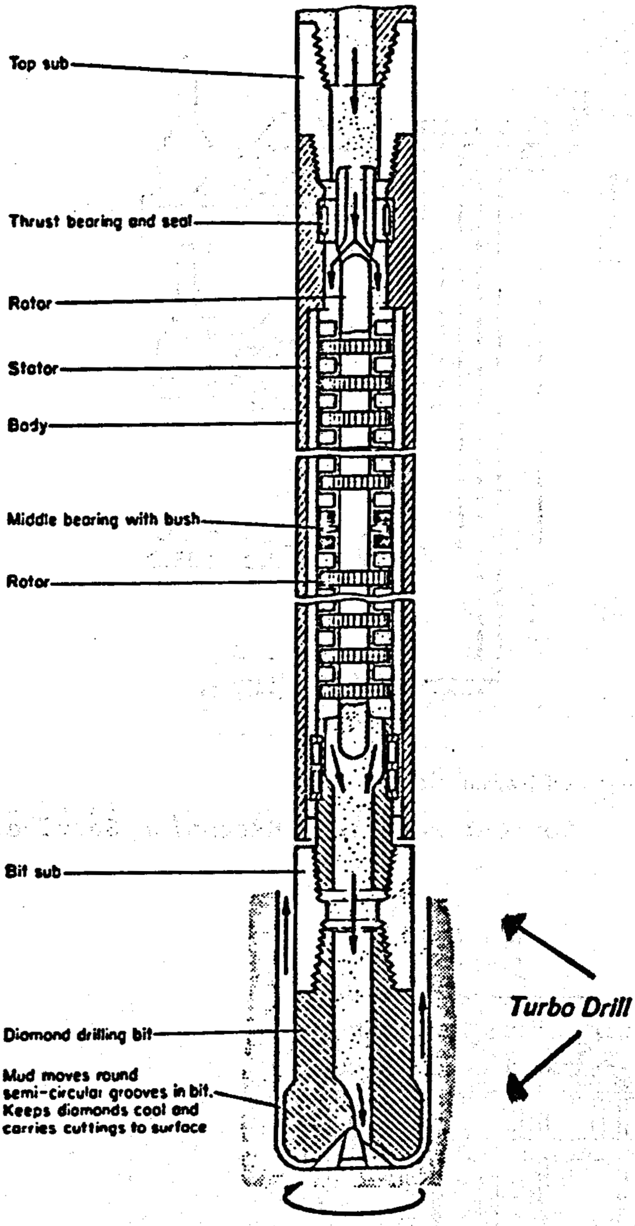
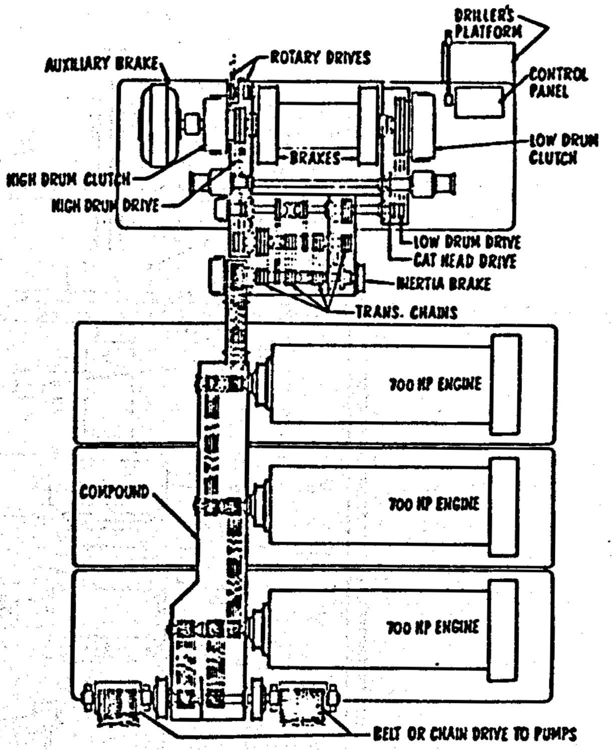


Figure 4
Source: Crook, 1979

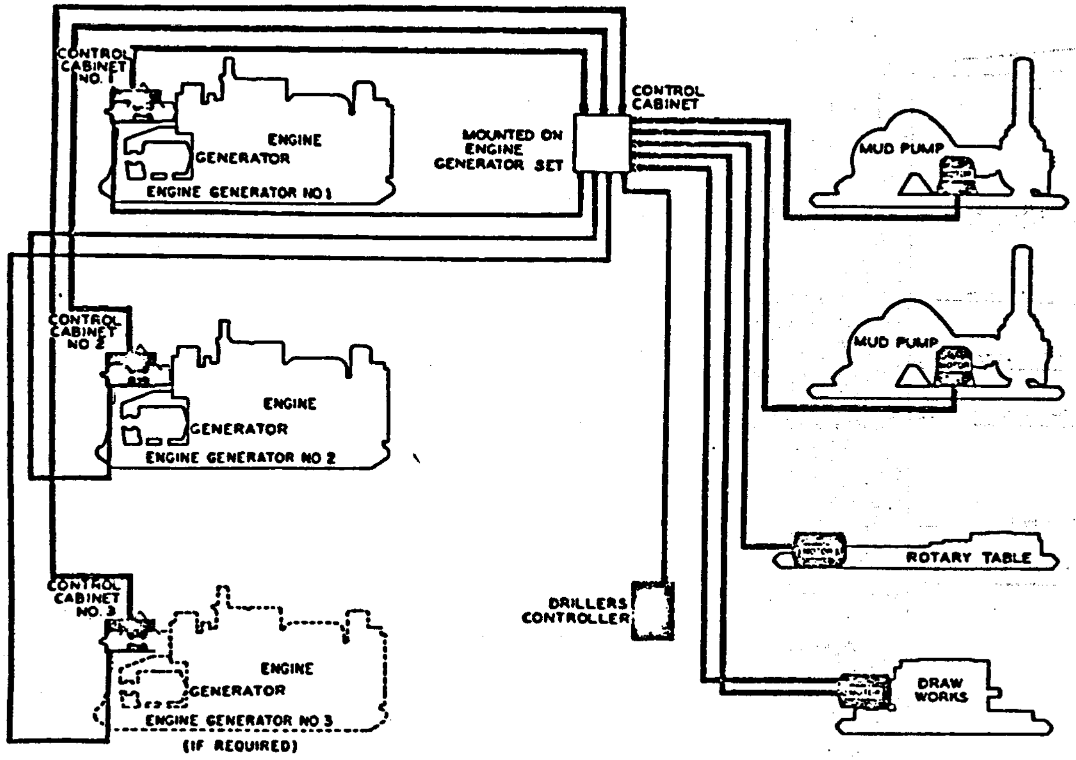


Multi-engine and chain drive transmission arrangement for a mechanical drilling rig.

Figure 5

Source: Petroleum Extension Service, 1979.

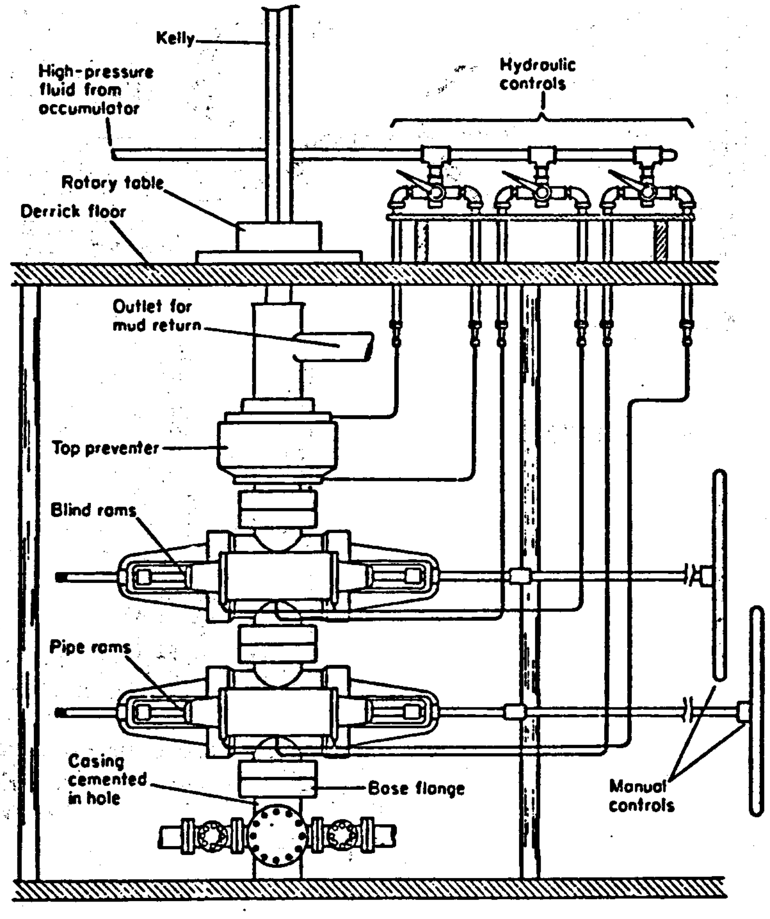
Figure 6



Diesel-electric system for power and transmission.

Source: Petroleum Extension Service, 1979.

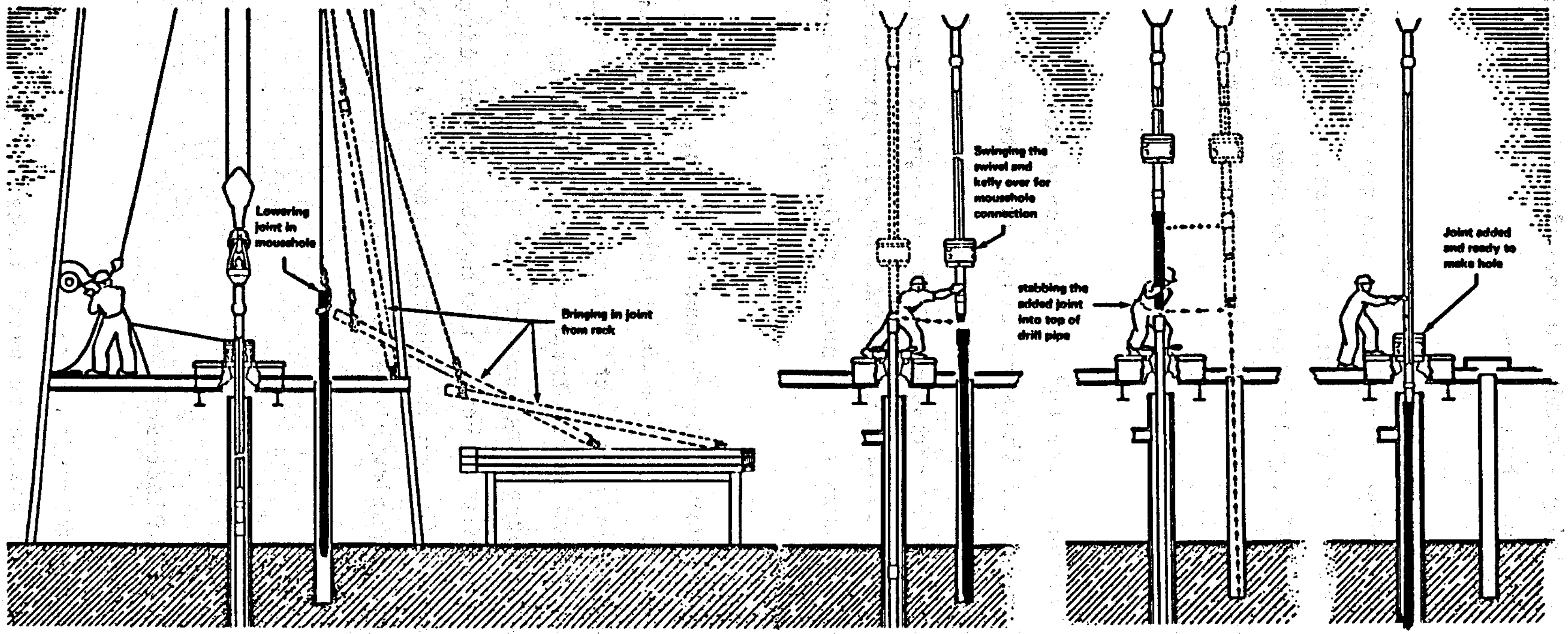
Figure 7



Blow out Preventer Stack

Source: Crook, 1976.

Figure 8



Source: Petroleum Extension Service, 1979.

individually in the mousehole prior to connection to the kelly, and then added to the drill string already in the pipe. "Tripping out", or pipe removal, is a reversal of the process.

Drilling Control

A number of techniques are used to control drill stem deviations. One of these, a standard drift survey instrument, is illustrated in Figure 9. Directional drilling is often intentional, but may be avoided with geopressured wells because of the complexities already involved in geopressured drilling.

Mud Engineering

Figure 10 illustrates the mud circulation system for a rotary drilling operation. Samples of shale cuttings and returned drilling mud are analyzed in the mud house, and modifications in the mud mix are made through additions to the hopper. Mud is pumped into the wellbore through the drill stem, flows out around the bit (providing cooling and waste removal), and returns to the surface through the annulus.

Logging and Testing

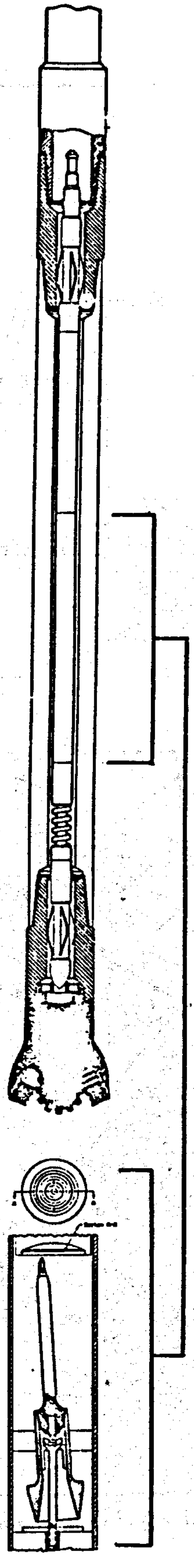
There are a variety of techniques used for logging and sampling wells. These techniques are generally used in conjunction with others to facilitate maximum data collection and accurate interpretation. In Figure 11, electric logging requires lowering a sensing device into the wellbore. Methods of attaching sensors to the drill stem frequently allow for electric logging without interruption of drilling. Drill stem testing, as in Figure 12, requires physical sampling of well bore fluid and formation material during a cessation in drilling.

Completion

Casing Selection and Placement

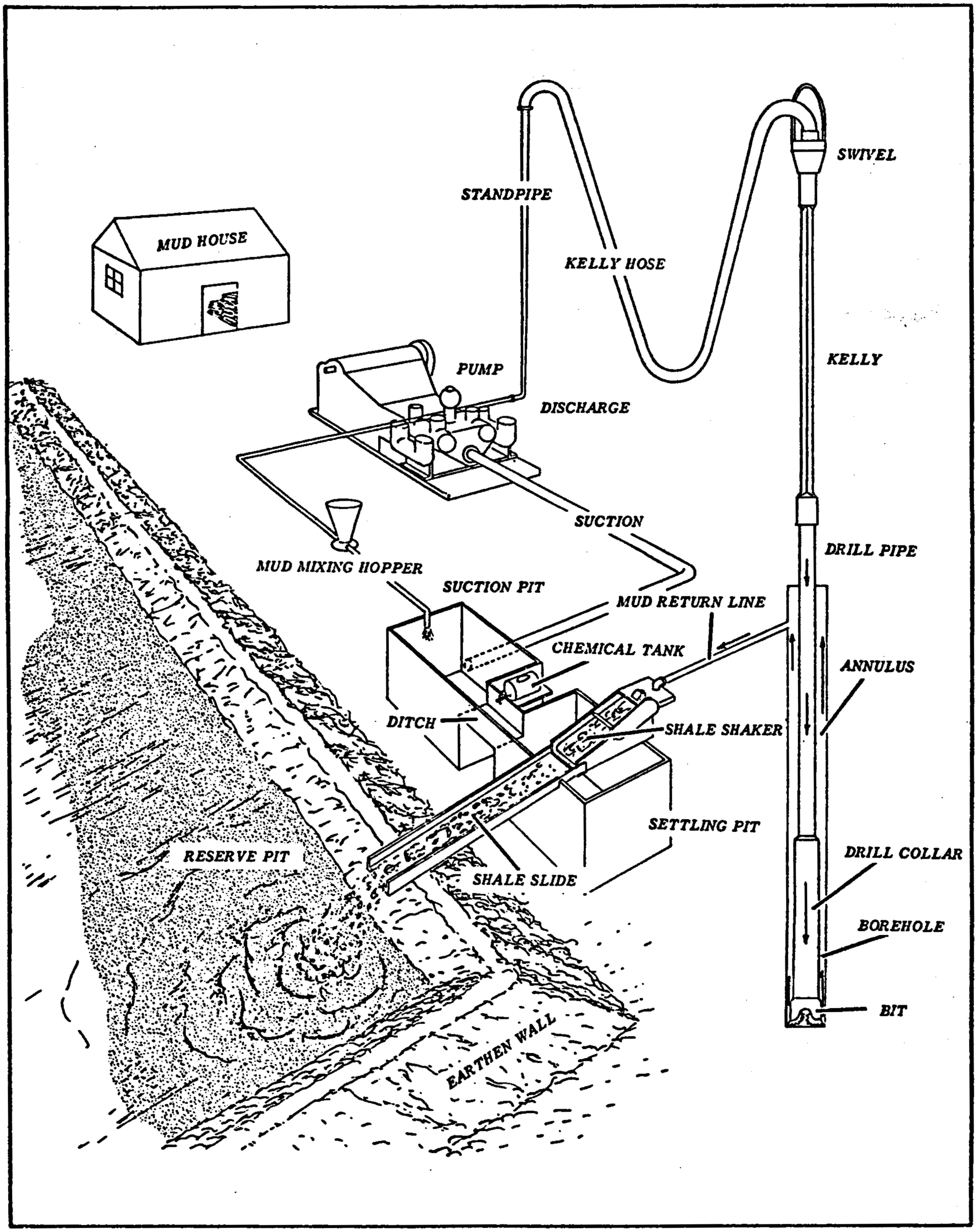
Figure 13 relates formation pore pressure and fracture pressure to the selection of casing points to avoid kicks. Figure 14 schematically

Figure 9



The drift survey instrument is positioned above the bit to make a record of drift angle. The record is made when a paper disk is punched by a pendulum-balanced stylus inside the instrument.

Source: Petroleum Extension Service, 1979.

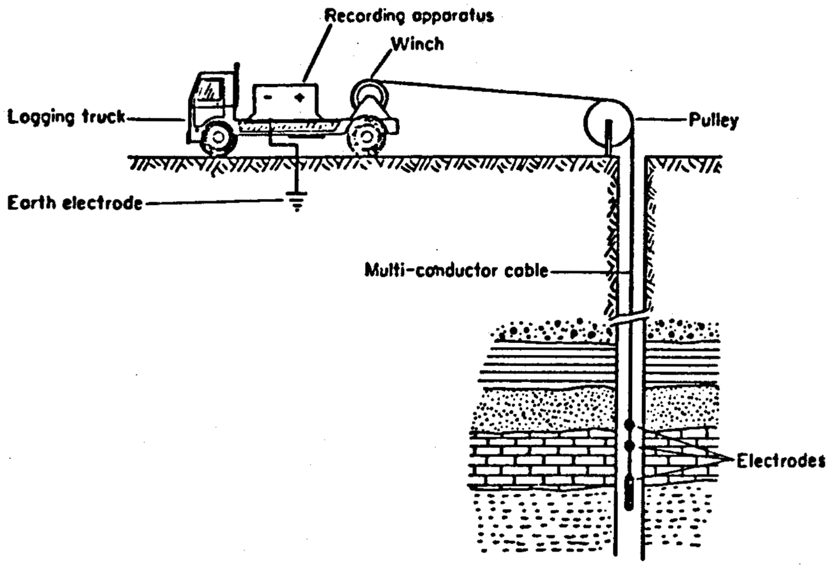


Rotary rig fluid circulation and mud treating system.

Figure 10

Source: Petroleum Extension Service, 1979.

Figure 11



Electric Logging

Source: Crook, 1979.

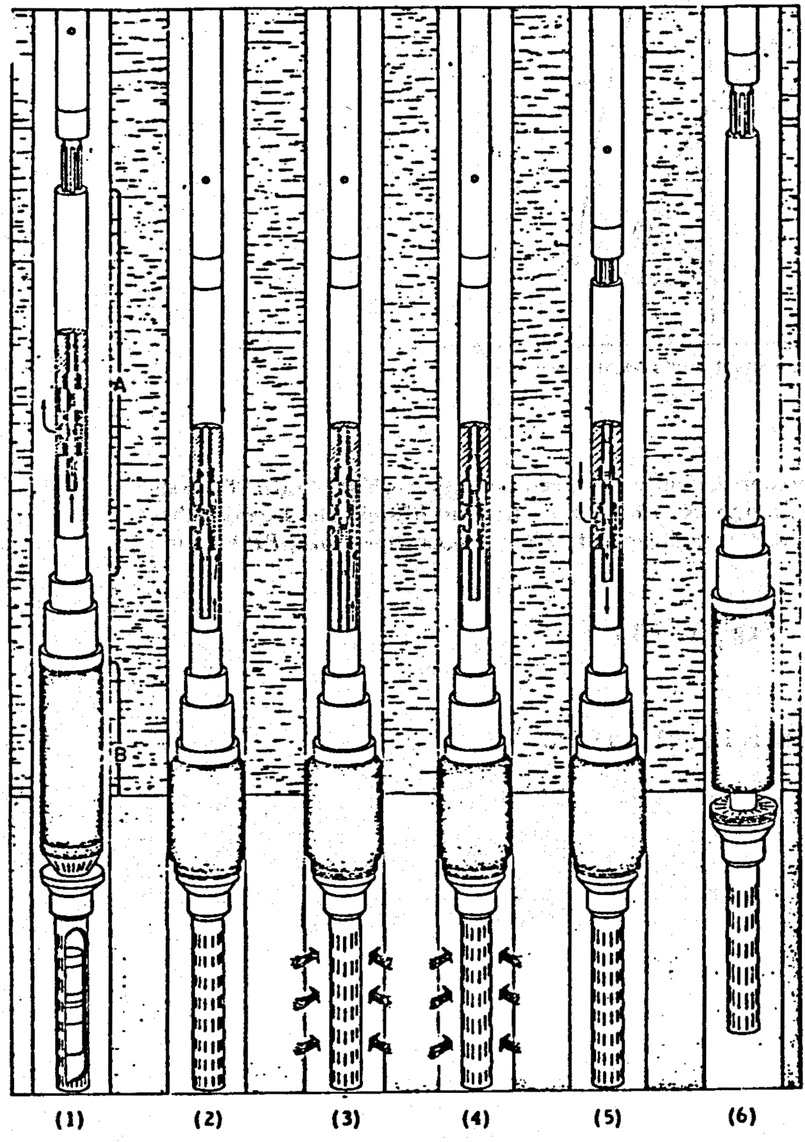
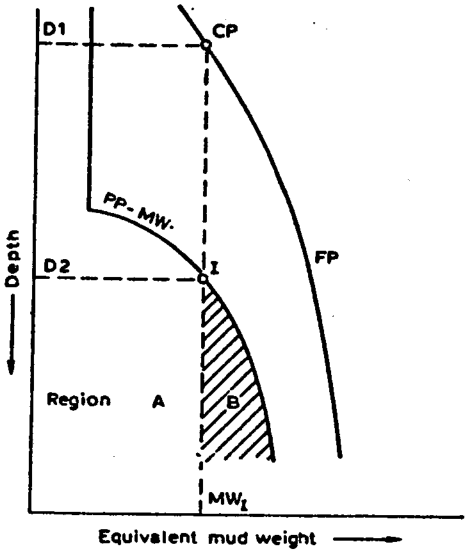


Figure 12

Principles of drill stem testing. The section A contains the tester valve. The packer is indicated at B. Pressure recorders are shown at C. (1)Running in tool on empty drill pipe. Bypass valve open. (2) Packer set on bottom to isolate test zone. (3) Production valve opens. Formation fluids enter drill pipe. (4) Test ends. Production valve closes. (5) Bypass valve opens. (6) Packer recedes. Tool pulled from hole.

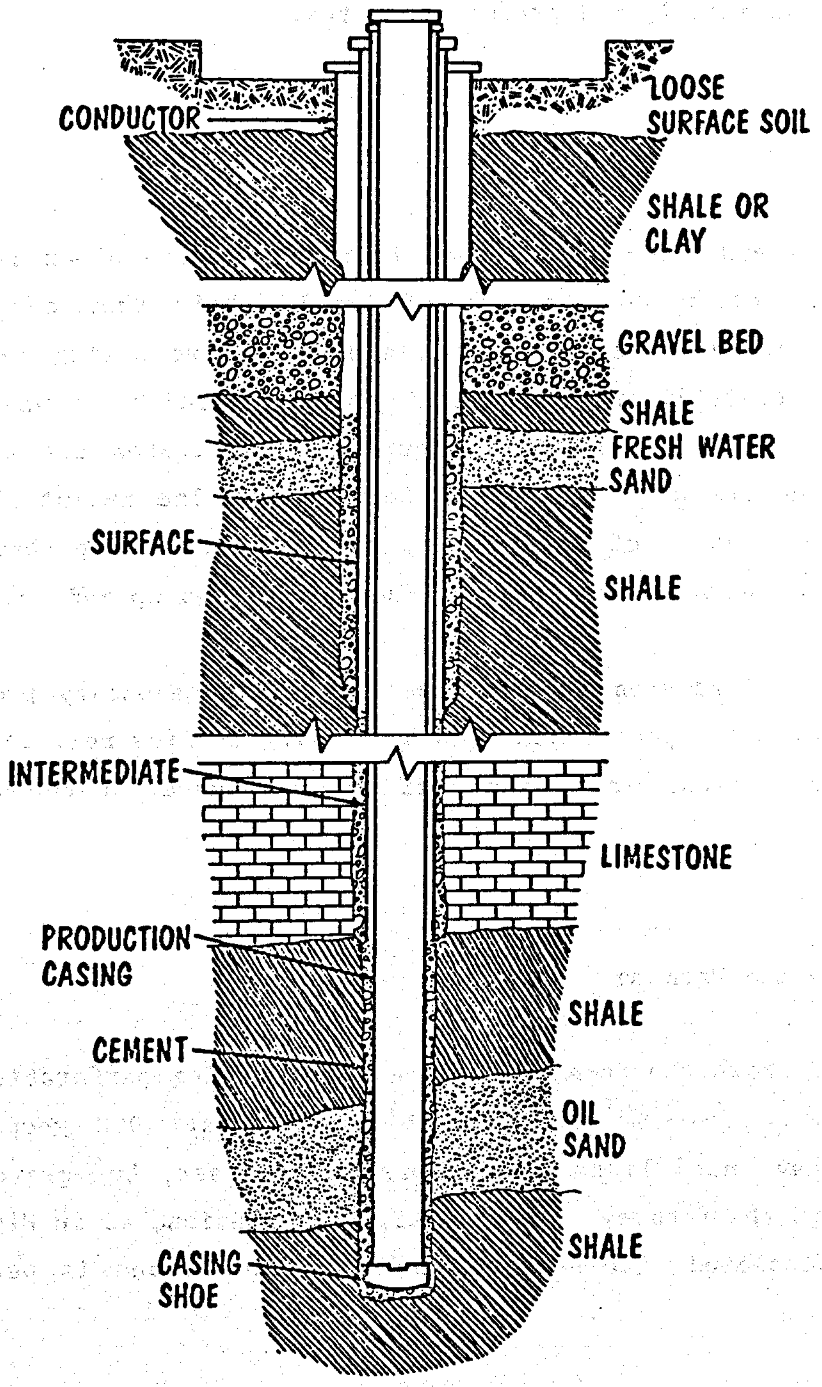
Source: Petroleum Extension Service, 1979



Casing point selection under perfectly balanced conditions. Note "safe" drilling and well killing conditions in Region A, whereas in Region B well kicks cannot be handled and circulation is lost. *CP* = casing point; *FP* = fracture pressure; *PP* = pore pressure; *MW* = mud weight.

Figure 13

Source: Fertl, 1976.



Casing strings and pipe used in an oil well.

Figure 14

Source: Petroleum Extension Service, 1979.

shows the shallow conductor casing, the surface, the intermediate, and the production casing. Diameters go from wide to narrow with depth and are dependent on anticipated production rates.

Cementing

Scratchers and centralizers used in cementing are shown in Figure 15. Scratchers clean the annulus of small debris that can inhibit cementing; centralizers maintain the casing placement during cementing. Scratchers and centralizers are generally used regardless of whether the entire annulus is to be cemented. Figure 16 illustrates the cementing process. Plugs are used to isolate formations. The cement slurry is pumped into the center of the casing, exiting the casing through the casing shoe at bottom hole depth, and then circulates up and sets in the annulus.

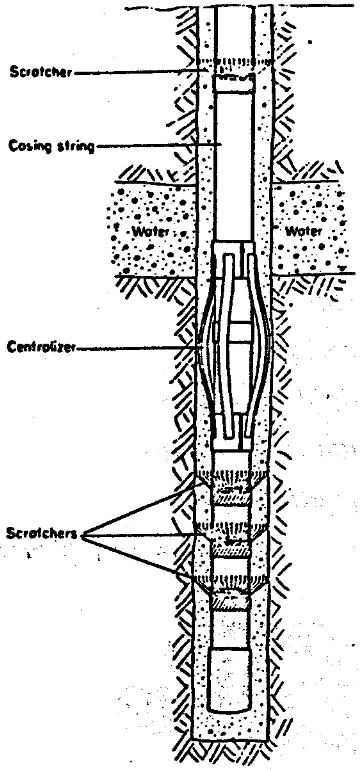
Figure 17 illustrates squeeze cementing. This secondary process is used to: a) correct a poor cement job by filling in fissures, b) isolate a producing formation, or c) seal off water leakage in the cemented annulus.

Perforating and Packing

Figure 18 shows the on-site equipment for casing perforation. Figure 19 includes four major types of completions. DOE geopressured design wells have used liner completions in the past, but gravel packs may be tried in the future. For a multiple completion, as in Figure 20, each zone is isolated with packers, and the lowest zone is perforated first.

Acidizing

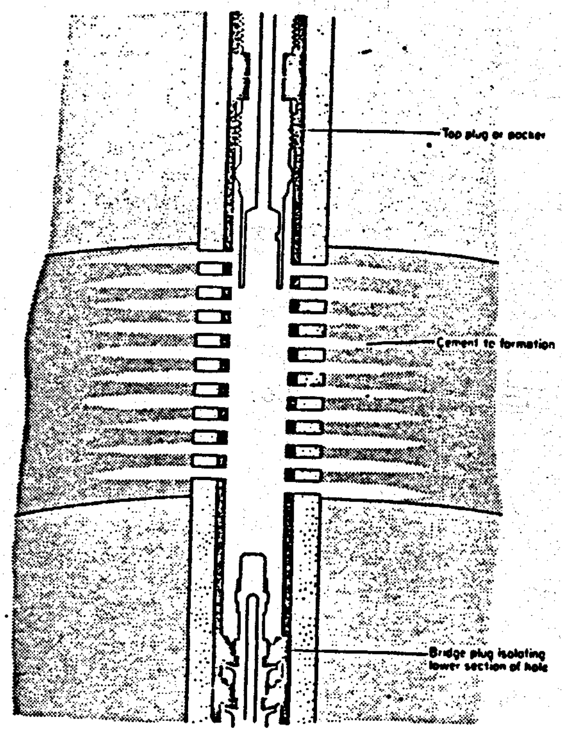
Acidizing is one method of increasing formation permeability. Figure 21 illustrates the acidizing treatment of a well with a cased well.



Array of Scratchers and Centraliser installed on the bottom joints of casing

Figure 15

Source: Crook, 1976.



Squeeze Cementing

Figure 17

Source: Crook, 1976.

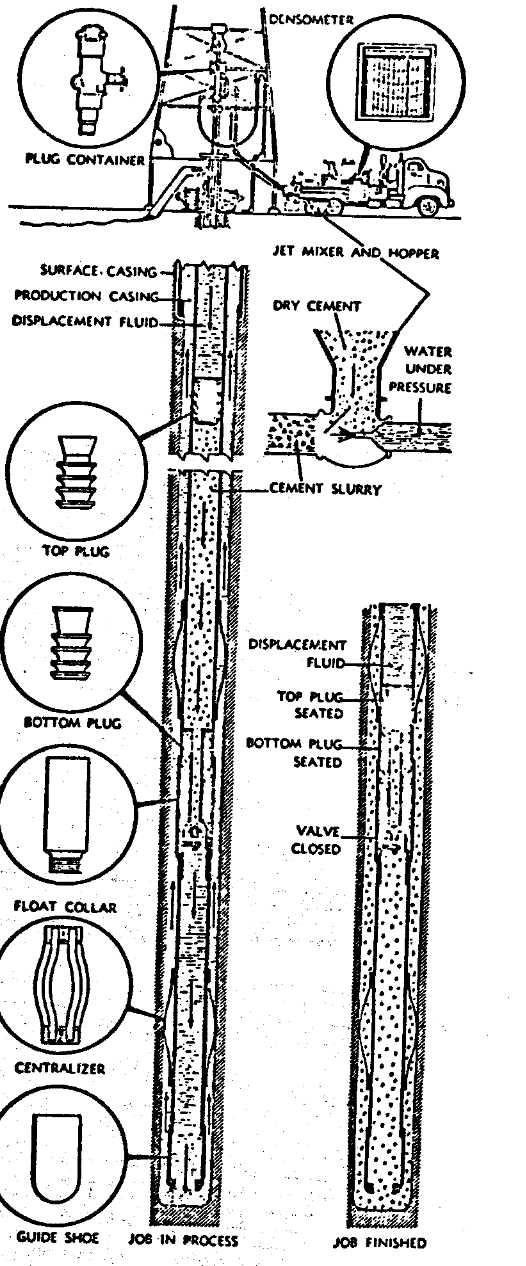
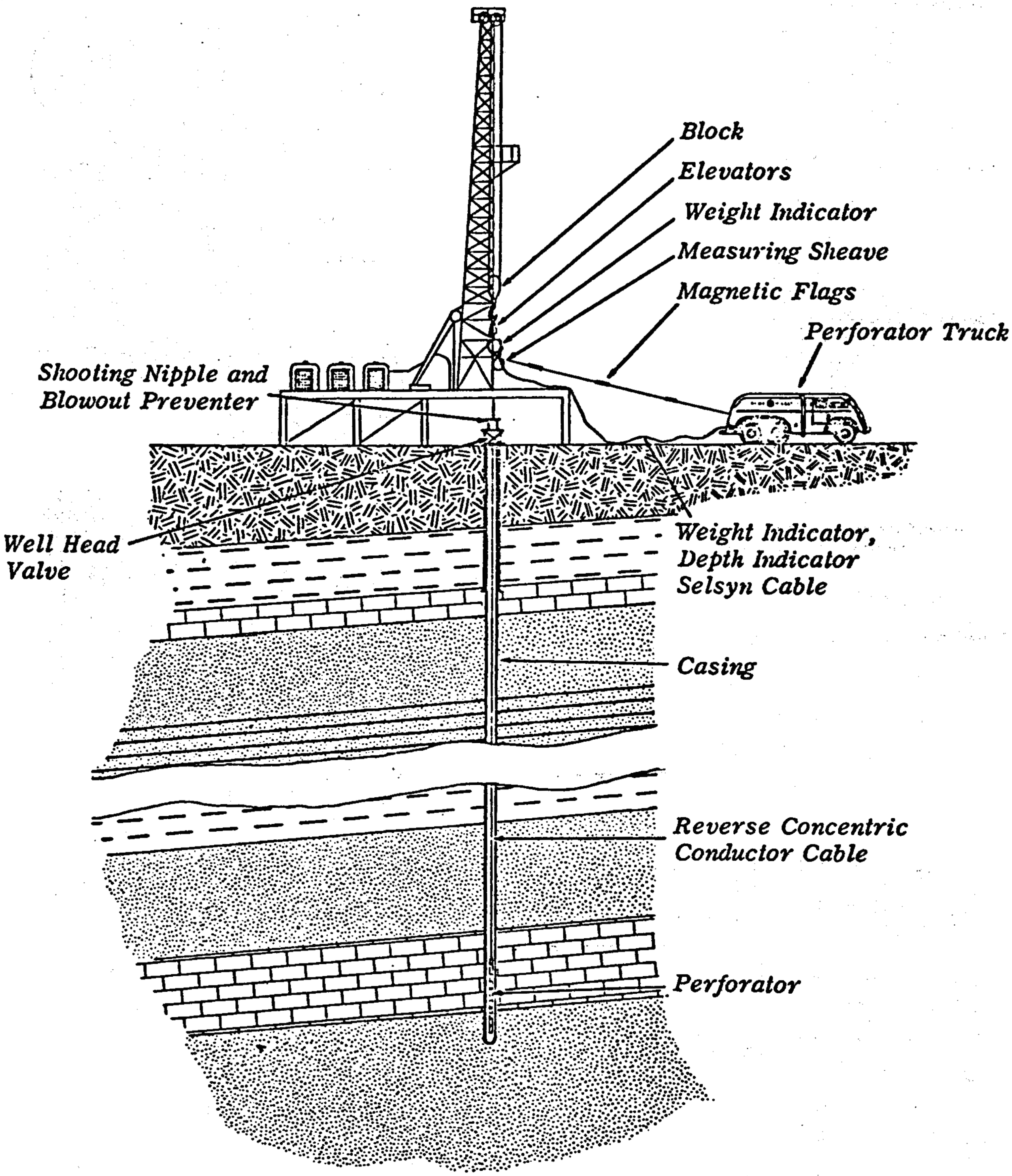


Diagram of a casing cementing job.

Figure 17 Figure 16

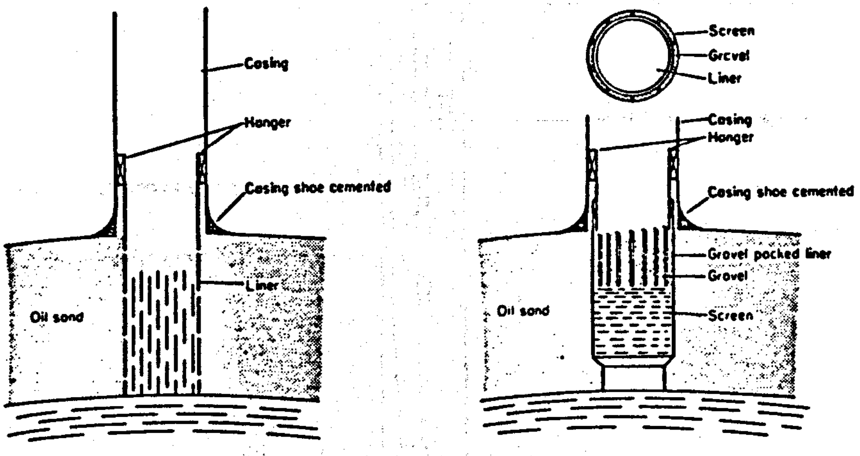
Source: Petroleum Extension Service, 1979



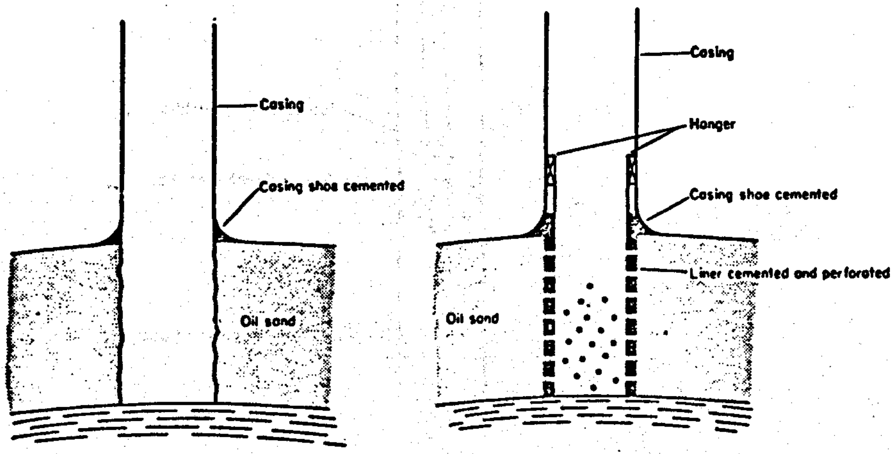
Layout of equipment to perforate a well.

Figure 18
Source: Petroleum Extension Service, 1979.

COMPLETION



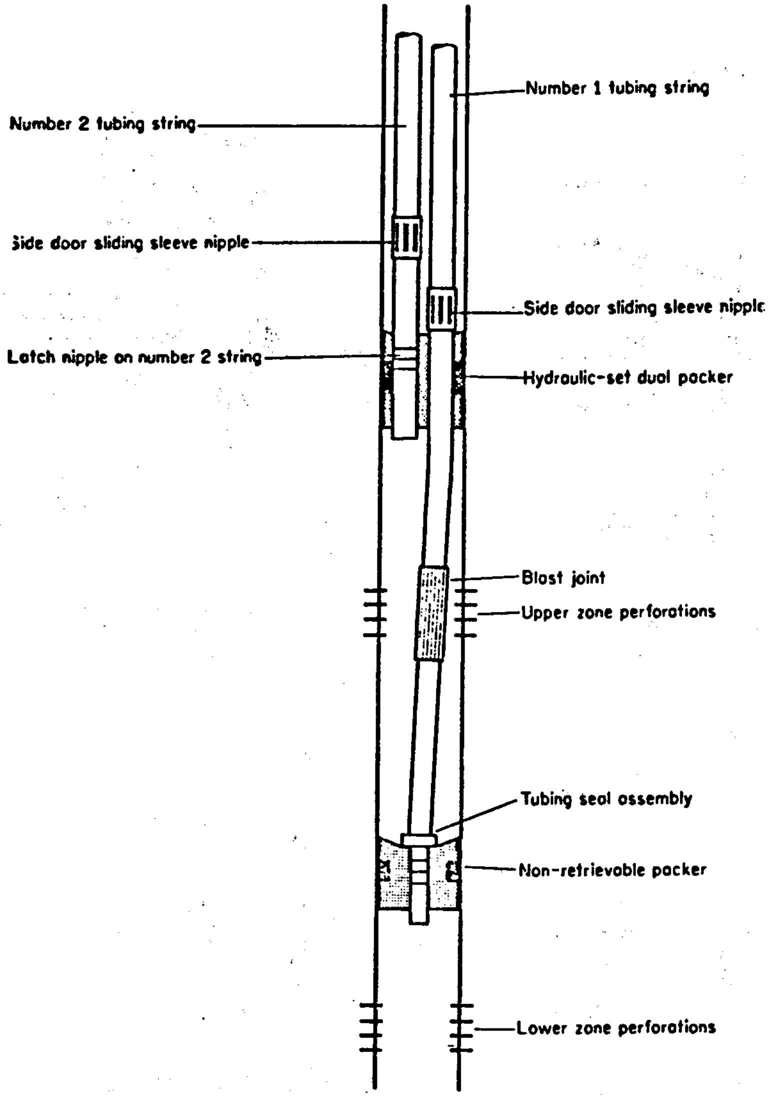
Slotted Liner Completion *Gravel Packed Completion*



Bare Foot Completion *Liner Completion*

Figure 19

Source: Crook, 1976.



Dual Completion

Figure 20

Source: Crook, 1976.

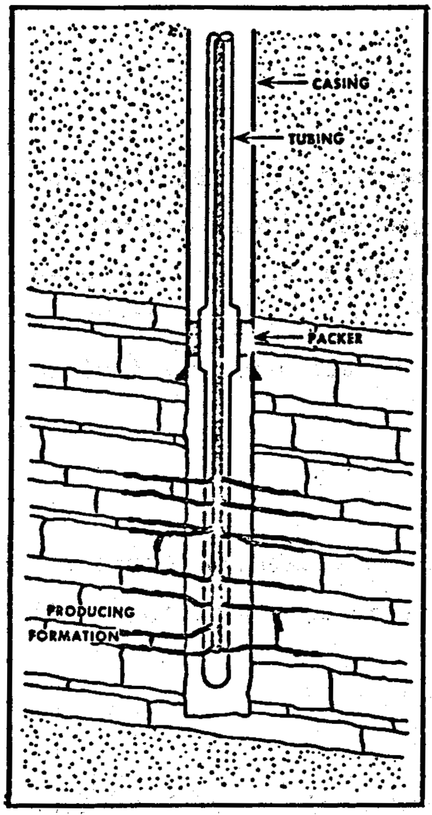


Diagram of an acidizing treatment.

Figure 21

Source: Petroleum Extension Service 1979.

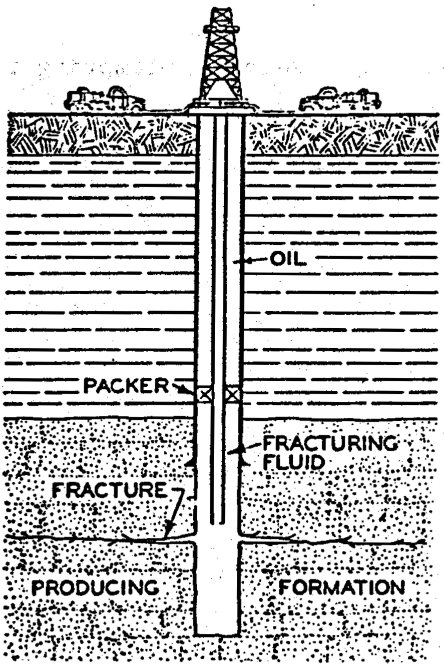


Diagram of a fracturing treatment. A packer is set to separate the producing formation from that above it.

Figure 22

Source; Petroleum Extension Service, 1979.

Acidizing is used primarily for carbonate formations.

Fracturing

Fracturing is an alternative method of increasing permeability, and hence production, from the target zone. A sand and fluid mixture is forced into the formation and the resulting fissures are propped open with gravel, nut shells, or other small hard objects. Figure 22 shows the fracturing process. As in cementing, packers are used to isolate formations.

Wellhead Assembly (Christmas Tree)

Following the setting and cementing of the casing, the Christmas Tree (Figure 23) is installed. This is the surface equipment that will control production flows from the well.

Fishing

Fishing involves attempting retrieval of lost tools or broken pipe. Specialized contractors have developed a number of tools for fishing, several of which are illustrated in Figures 24, 25, 26, and 27.

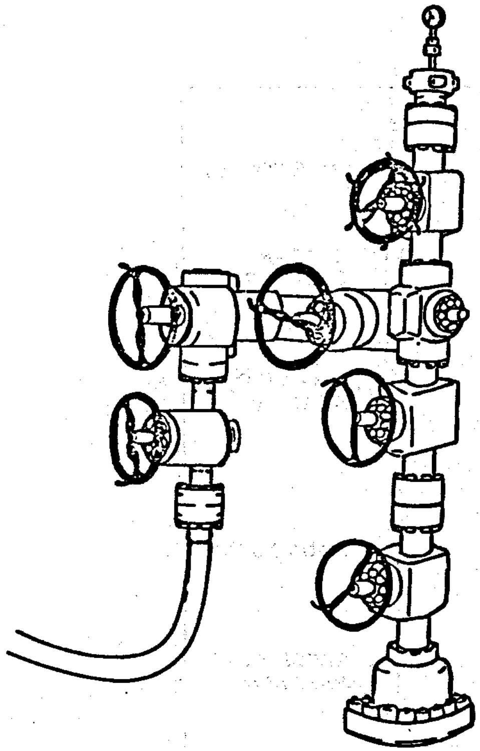


Figure 23

Source: University of Oklahoma, 1975.

Mills are used to smooth the top of sides of a fish.

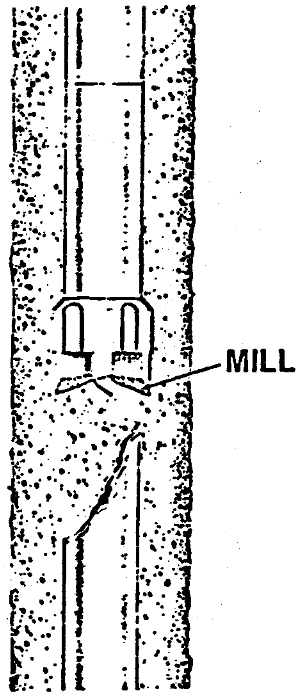
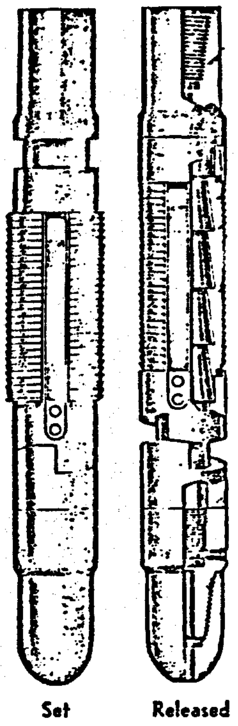


Figure 25

1. Mill. Cuts away irregularities and permits useful contact.
2. Spear. Goes inside and holds a fish by friction.
3. Overshot. Goes over and grabs the outside of a fish.
4. Washover Pipe. Goes over a fish to permit circulation in the annulus between the fish and wall of the hole.
5. String Shot. Permits back off of the drill string above a fish.
6. Accessory devices such as jars, to loosen and retrive a fish, and safety joint to permit release of the fishing string.

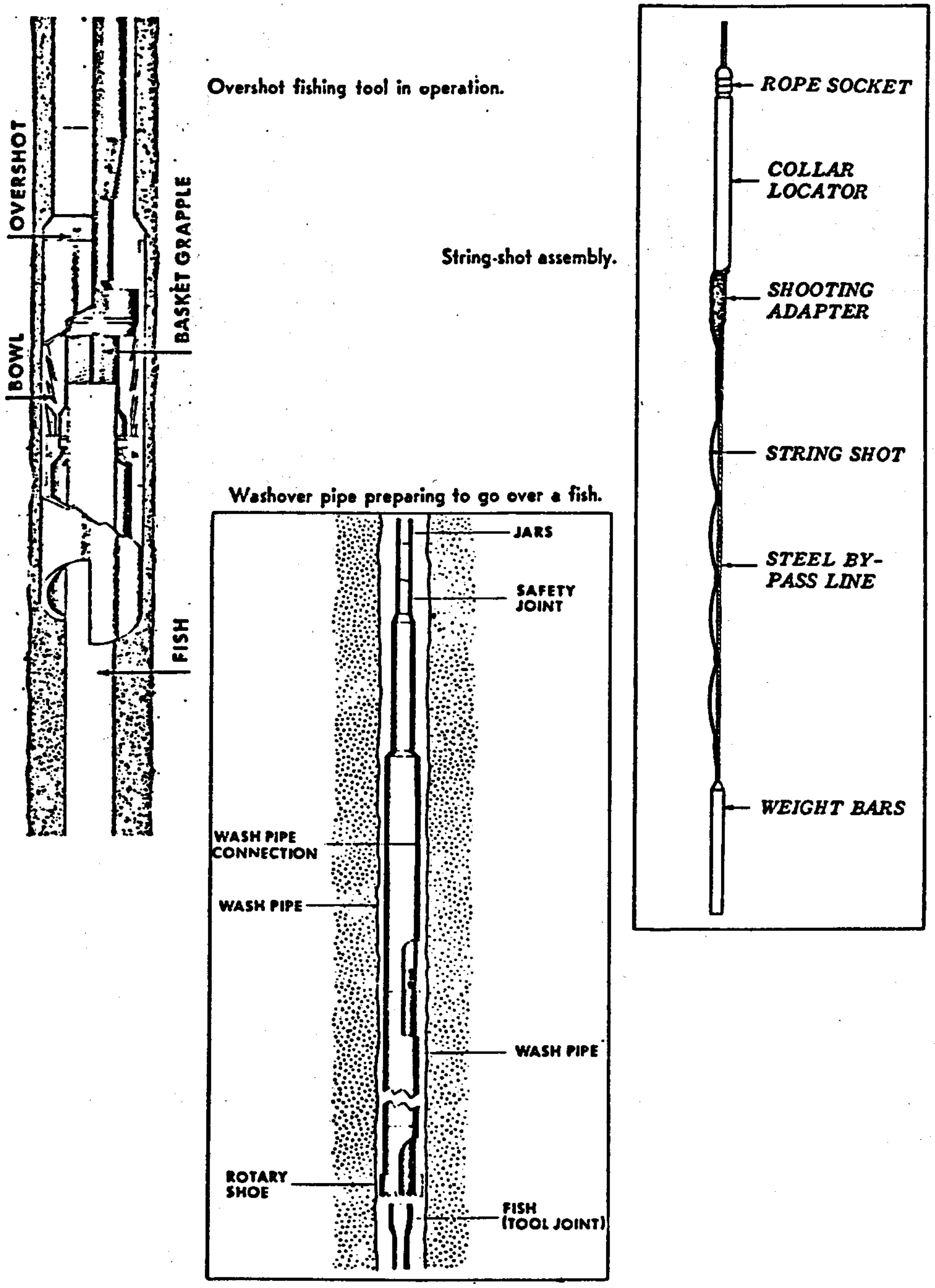
Figure 24

Spear fishing tool.



Figures 24, 25, and 26 Source: Petroleum Extension Service, 1979.

Figure 26



Overshot fishing tool in operation.

String-shot assembly.

Washover pipe preparing to go over a fish.

Figure 27

Source: Petroleum Extension Service, 1979.

APPENDIX B: METHANE SOLUBILITY IN AQUEOUS SOLUTIONS

The dissolved methane content of geopressured geothermal brines is of paramount importance for the eventual commercial development of the resource. Prices of natural gas have risen to a point where production of gas rather than electricity will be the deciding economic factor. A high methane/brine production ratio clearly will increase the potential for development of the resource (1).

Since 1901 a number of studies have sought to establish the aqueous solubility of methane under a variety of pressure, temperature, and dissolved solids conditions (2). Despite all this laboratory work, the saturation levels of methane in aqueous solutions over a wide range of physical parameters (temperature, pressure, etc.) remains controversial. The solubility of methane is directly related to the temperature and pressure of the aqueous solution and inversely related to the salinity (amount of dissolved solids) and presence of other gases in the solution. However, because the temperatures and, more important, the pressures, are so high (up to 400+^{o}F and 22,500 psia) laboratory experiments require a relatively high degree of skill to perfect. Price notes three potential problems with methane solubility experiments in the laboratory: a) leakage of methane around the seals and fittings on the containers, b) lack of equilibrium in the solution, and c) pressure changes in the flask before and after testing (3).

Additionally, in-field data from actual geopressured geothermal aquifers is limited because of the small number of wells that have been drilled and because of problems encountered with bottom hole sampling equipment (4).

---

(1) The RPD process may greatly increase the ratio of methane to brine production. However, assuming the there is no interstitial gas in the reservoir, the amount of brine in place depends only on its saturation concentration.
(2) See Leigh Price, "Aqueous Solubility of Methane at Elevated Pressures and Temperatures," in <u>Bulletin of the American Society of Petroleum Geologists</u>, Volume 63, 1979, pp. 1527-33, for a bibliography of these studies up to 1979.
(3) Price, op. cit., p. 1531.
(4) See the section on drilling and completion, above, for a discussion problems with bottom hole samplers under high pressure and temperature conditions.

The most widely cited experimental data for methane solubility are the works of Culbertson and McKetta (1951) and Haas (1978). The most recent published work is that of Blount, Price, Wenger, and Tarullo (5). Figure 1 is a plot comparing some of Blount's experimental results with those of Haas. There are significant differences between the two sets of data. Resolution of the issue of solubility ultimately rests on examination of in-situ samples, and this, in turn, will require refinement of sampling equipment and the drilling of a number of additional wells.

In addition to the issue of solubility of methane in aqueous solutions, several other factors related to methane concentrations are:

- Methane saturation values may not correspond directly to levels found in geopressured aquifers, as the methane may be at sub or supersaturated levels;
- Presence of other gases, especially carbon dioxide, may decrease the amount of methane present, (6) and;
- Concentrations of dissolved solids, other than sodium and chlorine (NaCl), may be related to salt concentrations and methane solubility (7).

---

(5) Culbertson, O.L., and J.J. McKetta Jr., "The Solubility of Methane in Waters at Pressured to 10,000 psia," Petroleum Transactions, Vol. 192, 1951, pp. 223-226.
Haas, John L., "Empirical Equation with Tables of Smoothed Solubilities of Methane in Water and Aqueous Sodium Chloride Solutions up to 25 Weight Percent, 360°C, and 138 MPa," (U.S. Geological Survey, Preliminary Open File Report No. 78-1004, 1978).
Blount, Charles, Leigh Price, Lloyd Wenger, and Micheal Tarullo, "Methane Solubility in Aqueous NaCl Solutions at Elevated Temperatures and Pressures," presented at the Fourth United States Gulf Coast Geopressured/Geothermal Energy Conference Austin, Texas, October 29-31, 1979.

(6) Data from recent geopressured aquifers indicates that concentrations of carbon dioxide may be as high as 10% of the total dissolved gases present. Personal communication with Bob Morton, Bureau of Economic Geology, Austin, Texas, May 1, 1980. See also the results of gas composition tests conducted at Pleasant Bayou No 2 in the "Second-Order Impacts" section.

(7) Solubility studies have only been conducted in distilled water or distilled water with NaCl added. No experiments have included trace metals, or other constituents such as ammonia or boron.Yousif Kharaka (personal communication) U.S.G.S. Menlo Park, June 24, 1980 , has noted that investigation of other constituents may yield different solubility results.

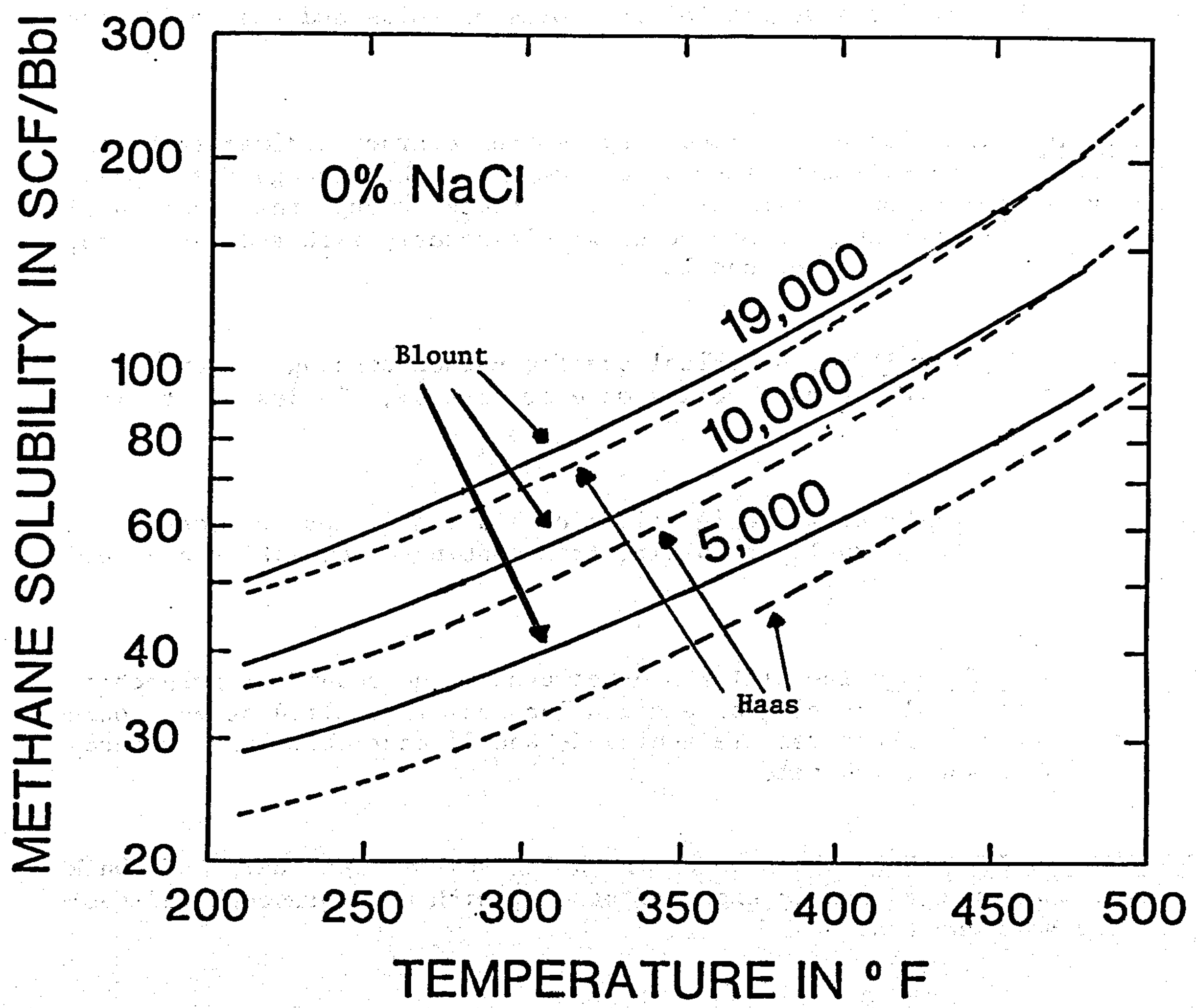


Figure 1

SOLUBILITY OF METHANE IN STANDARD CUBIC FEET PER BARREL (SCF/Bbl) ON A LOG SCALE VERSUS TEMPERATURE IN ° FAHRENHEIT AT 5,000; 10,000; AND 19,000 psi IN DISTILLED WATER.

Source: Blount, Price, Wegner, and Tarullo, 1979.

APPENDIX C: SUBSIDENCE GLOSSARY*

BULK MODULUS- A modulus of elasticity that relates a change in volume to the hydrostatic state of stress. It is the reciprocal of compressibility.

BULK VOLUME- Sum of the volumes of the pores or voids and the solid rock matrix.

CEMENTATION- The diagenetic process by which coarse sediments become lithified or consolidated into hard, compact rocks through the deposition or precipitation of minerals in the spaces among the individual grains of the sediment. It may occur simultaneously with sedimentation, or the cement may be introduced later.

COMPACTION COEFFICIENT- A numerical coefficient expressing the change in length per unit stress of a rock sample or stratum, divided by its initial length.

COMPACTION, NATURAL- Decrease in volume of sediments, as a result of compressive stress, usually resulting from continued deposition and settling of overburden rock.

COMPACTION, RESIDUAL- The difference between 1) the amount of compaction that will occur ultimately for a given increase in applied stress, once steady-state pore pressures are achieved, and 2) that which has already occurred at a specified time.

COMPRESSIBILITY, BULK- The change in bulk volume per unit of bulk volume, per unit change in external stress, with pore pressure and temperature held constant.

COMPRESSIBILITY, PORE- The change in the pore volume per unit of pore volume, per unit of external stress, with pore pressure and temperature held constant.

ELASTICITY, MODULUS OF- The ratio of stress (or change in stress) to

---

* Sources for this glossary include: Atherton, Finnemore, Gillam, DeGance, Grimsrud, and Schainker, The Analysis of Subsidence Associated with Geothermal Development, Vol. 3, 1976; Compaction of Argillaceous Sediments, Herman Rieke, and George Chilingarian, Eds., 1974; Fertl, W.H., Abnormal Formation Pressures, 1976; and Proceedings: Invitational Well-Testing Symposium, Lawrence Berkeley Laboratory, October 19-21, 1977, Report No. LBL-7027.

strain (or change in strain) for a material under given loading conditions; numerically equal to the slope of of the secant (or tangent) of a stress-strain curve.

ISOTROPY- Refers to the directional characteristics of the elastic properties; i.e., isotropy implies independence of direction, while orthotropy implies principal moduli directions are orthogonal

MOBILITY- The ratio of absolute permeability to viscosity.

P WAVES- Longitudinal or compression waves in which the motion of the particles of the medium is in the same direction as the wave propagation.

PERMEABILITY- A measure of the ability of a medium to transmit fluids that is related to the effective porosity. Measured in darcys or millidarcys.

PERMEABILITY, RELATIVE- The differential ability of a medium to transmit one substance in relation to another in a two-phase flow. Used to refer to the relative abilities of evolved gas and brine to flow to the annulus.

POISSON'S RATIO- The ratio of the lateral unit strain to the longitudinal unit strain in a body that has been stressed longitudinally within its elastic limit. It is one of the elastic constants.

POROSITY- Ratio of the void space to the bulk volume - usually expressed in percent. Analogous to void ratio but preferred by petroleum engineers and geologists.

POROSITY, EFFECTIVE- Refers to the interconnected pores through which fluids are able to move.

POROSITY, TOTAL- Refers to the total pore space of a rock volume without regard to ability to transmit fluids (permeability).

S WAVE- Transverse waves characterized by movement of the particles of the medium at right angles to the direction of wave propagation.

SPECIFIC STORAGE- Hydrological term for the volume of water that a unit volume of the formation releases from storage under a unit decline in head.

SPECIFIC WEIGHT- Weight per unit of volume.

STRESS, APPLIED- Total external stress applied to the reservoir system. Not the same as the effective stress.

STRESS, EFFECTIVE- That part of the load (force per unit area) that is not counteracted by other forces and is available to cause compaction. Equal to total stress of the system minus pore pressure. The term is confusing because of different meanings in common usage. Effective stress is sometimes used to refer to total stress including pore pressure.

More technically, it is the stress or pressure that is borne by and transmitted through the grain-to-grain contacts of a formation, and thus affects its porosity or void ratio and other physical properties. In one-dimensional compression, effective stress is the weight (per unit area) of sediments and moisture above the water table (or hydrostatic head of the aquifer), plus the submerged weight (per unit area) of sediments between the water table and the specified depth, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the saturated sediments above the specified depth. Thus effective stress may be defined as the algebraic sum of the two body stresses, gravitational stress and seepage stress. Effective stress may also be defined as the difference between geostatic and neutral stress.

STRESS, PRECONSOLIDATION- The magnitude of the previous or historical overburden load. Of great importance to compaction studies as an indication of the maximum stress encountered by the strata. Usually determined empirically by breaks in the slope of the void ratio vs. log pressure curve for the strata. Portion of the compression curve above this break is the 'virgin region' and indicates load magnitudes greater then those to which the specimen has previously been subjected.

STRESS, SEEPAGE- Stress created by the seepage force, which is transferred from the water to the porous medium by viscous friction. Seepage force is exerted in direction of flow.

SURVEY NET- A series of surveying or leveling stations that have been interconnected in such a manner that closed loops or circuits have formed, or that are so arranged as to provide a check on the consistency of the measured values.

TRANSMISSIVITY- The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

VOID RATIO- Ratio of voids volume to solids volume. Analogous to porosity but preferred by soil scientists and rock mechanists. Important for compaction studies.