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**AN ANALYSIS OF ECOLOGICAL EFFECTS OF
GEOPRESSURED—GEOTHERMAL RESOURCE
DEVELOPMENT**

Geopressured—Geothermal Technical Paper No. 4

July 1979

Work Performed Under Contract No. ET-78-G-05-5958

**RPC, Inc.
Austin, Texas**

**U. S. DEPARTMENT OF ENERGY
Geothermal Energy**

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Geopressured-Geothermal Technical Paper No. 4

AN ANALYSIS OF ECOLOGICAL
EFFECTS OF GEOPRESSURED-GEOTHERMAL
RESOURCE DEVELOPMENT

The General Land Office of Texas
Bob Armstrong, Commissioner

RPC, Inc.
Austin, Texas

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July 1979

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ABSTRACT

This report identifies the activities involved in geopressured-geothermal resource production and discusses their ecological impacts. The analysis separates those activities that are unique to geopressured-geothermal development from those that also occur in oil and gas and other resource developments. Of the unique activities, those with the greatest potential for serious ecological effect are: (1) accidental brine discharge as a result of a blowout during well drilling; (2) subsidence; (3) fault activation and enhanced seismicity; and (4) subsurface contamination of water, hydrocarbon, and mineral reservoirs. Available methods to predict and control these effects are discussed.

In virtually every aspect of the study, however, information specific to Texas geothermal resource development was found to be inadequate. The analyses provided here should be refined as more Texas-specific geothermal resource data and experience become available. In addition, each geothermal resource production site will contain features that must be considered in a case-by-case assessment.

CONTENTS

	<u>Page</u>
1. Introduction	1
2. Summary of Findings	3
3. Ecological Impacts of Nonunique Activities	7
Road Construction	7
Description	8
Environmental Effects	8
Bridge Construction.....	8
Description	8
Environmental Effects	9
Dredging.....	9
Description	9
Environmental Effects	9
Spoil Disposal and Landfilling	10
Description	10
Environmental Effects	10
Bulkhead Construction	11
Description	11
Environmental Effects	11
Plant Construction	11
Description	12
Environmental Effects	12
Plant Operation and Maintenance	12
Description	12
Environmental Effects	13
Geophysical Surveys	13
Description	13
Environmental Effects	13
Levee Construction	13
Description	14
Environmental Effects	14
Wellsite Construction	14
Description	14
Environmental Effects	14
Drilling	15
Description	15
Environmental Effects	15
Production	15
Description	16
Environmental Effects	16

(Contents, continued)

	<u>Page</u>
Emergency Brine Storage	16
Description	16
Environmental Effects	16
Deep Reinjection Brine Disposal	17
Description	17
Environmental Effects	17
Electrical and Telephone Line Construction	18
Description	18
Environmental Effects	18
Pipeline Construction	18
Description	19
Environmental Effects	19
4. Ecological Impacts of Unique Activities	21
Brine Discharges	22
Summary of Effects	22
Detailed Discussion of Effects	22
Characterization of Accidental Brine Discharges	22
Environmental Variables Which Influence Impact Magnitude..	25
Selection of Reasonable Worst Case	31
Analysis of Impacts of Brine Spills.....	31
Geologic Alterations	44
Summary of Analysis	44
Detailed Discussion	45
Subsidence	45
Fault Activation and Induced Seismic Activity	52
Subsurface Contamination	56
Hydraulic Lifting	58
Prediction of Subsidence and Fault Activation	59
Management of Subsidence, Fault Activation, and Inter- formation Fluid Movement	62
Monitoring the Effects of Geothermal Resource Development	66
Water Consumption, Air Emissions, and Noise	68
Summary of Analysis	69
Detailed Discussion	69
Water Consumption	69
Hydrogen Sulfide Emissions	72
Noise	74
Summary of Impacts, Prediction and Control of Unique Geothermal Resource Development Activities	79
Subsidence	79
Causes	79
Effects	79
Indicators	80

(Contents, continued)

	<u>Page</u>
Prediction	80
Control	81
Remarks	81
Fault Activation	81
Causes	81
Effects	82
Indicators	82
Prediction	83
Control	83
Remarks	83
Hydraulic Lifting	83
Causes	83
Effects	84
Indicators	84
Prediction	84
Control	84
Remarks	85
Induced Seismic Activity	85
Causes	85
Effects	85
Indicators	86
Prediction	86
Control	86
Remarks	86
Accidental Brine Discharge	87
Causes	87
Effects	87
Indicators	87
Prediction	87
Control	88
Remarks	88
Appendix A: Review of Geothermal Resource Development Activities and Their Ecological Effects	89
Appendix B: Methods for Assessment of Environmental Impacts of Geothermal Resource Development	99
References	119

LIST OF TABLES

	<u>Page</u>
1 Estimates of Geothermal Well Flow Rates Under Blowout Conditions	25
2 Properties of Soils Representative of Those in Geothermal Prospect Areas	28
3 Chemical Composition of Selected Formation Waters From the Texas Gulf Coast.....	30
4 Aggregation of Coastal Ecosystems for Analysis of Accidental Spills with the Major Unifying Aspects Leading to the Aggregation .	32
5 Primary Ecological Alterations in the Aggregated Ecosystems	33
6 Approximate Concentrations of Various Brine Constituents Resulting From Even Distribution of One Inch of Brine in Various Depths of Soil Having a Moisture Content of 0.1 Inch of Water Per Inch of Soil	36
7 Dilution of a Geothermal Brine With Typical Freshwater Stream Flow	38
8 Dilution Ratio Required When Mixing Typical Estuarine Water with a Geothermal Brine to Reach Specified Water Quality Criteria	41
9 Some Upper Salinity Limits for Brackish Marsh (BM), Salt Marsh (SM), and Grassflat (GF) Plants	43
10 Estimated Water Requirements for Alternative Cooling Techniques for 50 MW(e) (Net) Electric Generation (Geothermal)	71
11 Predicted Project-Related Noise at 50 Feet	76
12 Noise Attenuation by Distance Alone (No Effects of Wind, Relative Humidity, Topography, etc.)	77
13 Comparison of Noise Produced During Geothermal Resource Development With Other Familiar Sound Levels	78

(List of Tables, continued)

	<u>Page</u>
A1 Activities Associated with Development of a Geothermal Energy Project	92
A2 Aggregations of Coastal Ecosystems on State-Owned Lands and Waters Within Geothermal Fairways	93
A3 Activities Associated With Geothermal Development and Ecosystems in Which They May Occur	94

LIST OF FIGURES

	<u>Page</u>
1 Distribution of Dissolved Ions From 37 Geopressured Fluid Samples From Louisiana and Texas	29
2 Typical Geopressured-Geothermal Reservoir Configurations	47
3 Physiological Effects of Hydrogen Sulfide	73
B1 Procedure for Determining Ecological Impacts of Subsidence	113

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This technical paper is one of a series of four papers in which the legal, financial, socioeconomic, and ecological aspects of geopressured-geothermal resource development on Public Free School Lands are discussed.

Many individuals contributed to the production of this paper. The project manager for the entire study was Ann Orzech; the team leader for the ecological analysis was Andrew Reed. Principal investigators were William Brogden, Chris Caran, Denise Girard, and Bruce Snyder. The technical editor was Nancy Grona; production assistance was provided by Kyle Pierce and Lori Snyder. The cover was designed by Kyle Pierce.

Ronald T. Luke
President
RPC, Inc.

1. INTRODUCTION

The objective for this study is to produce information relevant to rule-making for geopressed-geothermal development on state-owned land. This paper identifies and discusses ecological impacts that could result from geopressed-geothermal energy production. The analysis involved the identification of resource development activities, determination of the ecological systems in which these activities would likely take place, and identification of the types of impacts associated with the activities in the various ecosystems.

During the analysis, it became obvious that many of the anticipated geopressed-geothermal resource development activities are identical or very similar to typical oil and gas development activities. Furthermore, many of these activities have been previously studied, under the auspices of both oil and gas and geothermal production. (The term "geothermal," as used in this report, means "geopressed-geothermal.")

This paper distinguishes those activities that are unique to geopressed-geothermal resource development from those that are similar to other types of development in order to focus analysis on factors not previously studied extensively. Appendix A discusses in detail the derivation of activities, ecological systems in which they might occur, and criteria applied in identifying unique activities. Appendix B describes the methods used to assess environmental impacts of geothermal resource development.

Chapter 2 summarizes the findings of the ecological analysis. Chapter 3 describes the geothermal development activities that are similar to other energy development activities already occurring along the Texas coast and summarizes the ecological effects of the activities. This chapter is drawn exclusively from secondary sources. Chapter 4 discusses the ecological impacts of those activities which are not similar to other energy development activities and which have not been extensively investigated in previous studies. In particular, the impacts of brine discharges and brine storage; subsidence, fault activation and subsurface contamination of water, hydrocarbons, and other mineral reservoirs; and noise, air emissions, and water consumption are analyzed.

This report will be examined by individuals with widely varying experience in geothermal and other energy resource development activities and their effects. Readers with extensive background in certain subject areas may wish to focus on the Summary of Findings (Chapter 2) and to skim or skip entirely portions of the detailed analysis (Chapters 3 and 4). For example, the reader already familiar with the ecological effects of oil and gas development will find Chapter 3 to be a summary of existing information of which he is probably aware; he may wish to refer directly to the discussion of unique activities (Chapter 4) after reading the Summary of Findings (Chapter 2).

Of necessity, this analysis includes only a generalized description of impacts; it focuses on predicting, controlling, and monitoring ecological effects. Thus, an understanding of all the detailed and subtle ecological interactions is not stressed. However, the most relevant site-specific variables have been identified for more detailed consideration in a case-by-case assessment. Ultimately, such a site-specific assessment would provide the basis for regulation of each proposed resource development program.

Finally, it should be noted that geothermal resource development is new to the Texas coast. Many of the analogies and generalizations drawn from geothermal development experiences in other regions remain to be refined as resources in Texas are explored.

2. SUMMARY OF FINDINGS

- 1. Many geothermal resource production activities are identical or similar to typical oil and gas development activities. These activities are:**
 - a. Road construction
 - b. Bridge construction
 - c. Dredging
 - d. Spoil disposal and landfilling
 - e. Bulkhead construction
 - f. Plant construction
 - g. Plant operation and maintenance
 - h. Geophysical surveys
 - i. Levee construction
 - j. Wellsite construction
 - k. Drilling
 - l. Production
 - m. Emergency brine storage
 - n. Brine disposal
 - o. Electrical and telephone line construction
 - p. Pipeline construction

Many of these "nonunique" activities have been extensively studied. Site-specific techniques for minimizing the ecological impacts of these activities have been identified. These techniques include location, design, and construction procedures.

- 2. Certain aspects of the above activities have been identified as unique to geothermal resource development:**
 - a. Well drilling - particularly the release of brine in the event of a blowout; the potential for subsidence
 - b. Production - particularly accidental brine discharges associated with production well blowout or disposal well failure; the potential for subsidence, fault activation, and enhanced seismicity; the potential for subsurface contamination of water, hydrocarbon, and mineral reservoirs
 - c. Pipeline operation - failure of pipeline and accidental brine discharges
 - d. Plant operation - particularly accidental discharges of brine; noise, air pollution, and water consumption
 - e. Brine storage - need for temporary brine storage facilities and problems associated with their design and use

These "unique" aspects were the subject of more detailed analysis in this study.

This analysis indicated that the following have the greatest potential for serious ecological effect:

- a. Accidental brine discharge as a result of a blowout during well drilling
- b. Subsidence
- c. Fault activation and enhanced seismicity
- d. Subsurface contamination of water, hydrocarbon, and mineral reservoirs, resulting from well production

3. A study of the potential effects of the unique activities provided the following findings:

- a. Upland ecological systems are more sensitive to brine discharge than marine systems, due to the long recovery rates. Wetland systems are more sensitive than estuarine systems because much less water is available for dilution, and flushing is slow. This has important implications for the design of well fields, production systems, and spill control strategies.
- b. In the Matagorda geothermal fairway, the greatest ecological effect of increased subsidence will be the expansion of brackish and salt marsh into adjacent coastal prairie and fluvial woodland. Some fresh marsh would also be created. Erosion rates along the Gulf beach would be increased.
- c. In the Corpus Christi fairway, subsidence would cause grassflats to be created in wind tidal flats, with corresponding losses of grassflats in deeper areas. Beach erosion would also increase on the islands. On the mainland, oak groves and coastal prairie areas would be converted to wind tidal flats and salt marsh.
- d. Subsidence effects in the Brazoria fairway will include the expansion of brackish marshes, fresh marshes, and flooding of agricultural areas.
- e. One important aspect of controlling subsidence is the ability to predict it. This study concluded that subsidence modeling for geothermal resource development is not adequate. The most reliable prediction method at this time appears to be the use of oil and gas production analogies. Prevention and control of subsidence can be achieved with some success through proper well spacing and density, siting of production facilities in areas least sensitive to elevation losses, judicious use of permeability-enhancement techniques, minimizing fluid pressure drop during fluid withdrawal, and fluid reinjection.
- f. Early detection of subsidence and fault activation can play an important part in preventing serious impacts. Aerial and ground surveys are useful in monitoring elevation changes during geothermal resource production.
- g. Contamination of potable groundwater and valuable minerals and hydrocarbons can result from the movement of geothermal brine into other geologic formations. Such contamination can be caused by movement along faults, through a failing well casing or uncased well intervals, from contiguous strata, or by infiltration from the surface. These impacts can be prevented by the use, proper installation, and maintenance of high quality materials, and through monitoring both at the geothermal well and in neighboring wells.
- h. Depending on the cooling technique employed, water requirements for a geothermal production plant may range from 38 acre-feet per year per megawatt (MW) to 113 acre-feet per year per MW. High water requirements pose potential use conflicts in areas of water scarcity as well as the

threat of increased subsidence and subsurface contamination if ground-water is used. Saline water can be used for once-through cooling systems; however, cooling ponds must be carefully designed and located to avoid contamination of fresh water sources.

4. In virtually every aspect of the present study, information specific to Texas geothermal resource development was found to be inadequate. Thus, the potential for such effects as subsidence, fault activation, brine discharges, excessive noise, gas emissions, and water consumption were identified largely by analogy to other geothermal production regions and oil and gas production. These analyses should be refined as more Texas-specific geothermal resource data and production experience become available.
5. Each geothermal resource production site will contain features that must be considered on a case-by-case assessment. This study has indicated general variables that are relevant to an assessment.

3. ECOLOGICAL IMPACTS OF NONUNIQUE ACTIVITIES

This section includes short descriptions of geothermal resource development activities that are the same as or similar to other energy development activities, particularly oil and gas development. These activities are:

1. Road construction
2. Bridge construction
3. Dredging
4. Spoil disposal and landfilling
5. Bulkhead construction
6. Plant construction
7. Plant operation and maintenance
8. Geophysical surveys
9. Levee construction
10. Wellsite construction
11. Drilling
12. Production
13. Emergency brine storage
14. Brine disposal
15. Electrical and telephone line construction
16. Pipeline construction

The description of each activity includes a listing of associated activities, or "sub-activities." Subactivities are phases of an activity that directly interact with an ecological system.

Following each activity description is a summary of the ecological effects of the activity. This information is abstracted from existing literature and will be used in conjunction with the analysis of nonunique activities to recommend ecological standards of operation for geothermal resource development on Public Free School Lands.

The method used to identify these activities and the ecosystems in which they would take place is described in Appendix A.

ROAD CONSTRUCTION

Information for this section is from the following references: Gustavson et al., 1977; Longley et al., in press; Texas General Land Office, 1978a; U.S. Department of the Interior, Fish and Wildlife Service, 1976; White et al., 1978.

Description

Road construction is sometimes necessary to provide adequate access for land vehicles moving to and from construction and operation sites. Duration of road construction depends upon the desired quality and length of the road and site characteristics of ecosystems the road will traverse. Road construction often takes place in terrestrial environments. If aquatic ecosystems must be traversed, fill material is emplaced, creating made lands, or bridges are constructed. Subactivities of road construction may include: vegetation clearing, placement of protective structures (for erosion control), substrate removal, mounding, filling (loose earth materials), shell-gravel (roadbed) placement, compaction, paving, revegetation (of disturbed areas along the right-of-way), fertilization, and vehicular movement/operation. Temporary board roads are sometimes used in marshes.

Environmental Effects

The impact of road construction on upland environments is generally localized (confined to the linear road corridor) but may be more widely felt as soil erosion and other degrading effects worsen. Construction of roads in insular/eolian environments may have a particularly severe impact because of resulting disturbance of the vegetation-stabilized substrate. Road construction results in disturbance of soil and vegetation and increased noise, dust, soil erosion, and stream sedimentation. Consequently, there may be damage to vegetation, overt disturbance to wildlife, and loss of habitat. In addition, paving introduces toxic substances, decreases surface permeability, and increases runoff, which, in turn accelerates erosion and increases water turbidity. This may upset the aquatic nutrient balance, thereby affecting phytoplankton, emergent and submergent plants. Board roads crush vegetation. But where temporary roadways are needed, board roads are often preferable to fill roads since the boards may be later removed, the vegetation can recover, and drainage is only temporarily disrupted. Raised roadbeds may, in some cases, interfere with overland water drainage.

BRIDGE CONSTRUCTION

Information for this section is from the following references: Darnell et al., 1976; Texas General Land Office, 1978a.

Description

A bridge is a support structure to provide pedestrian or vehicular access across a bay, stream, drainage swale, sand dune, or other unsuitable substrate. Duration of construction will vary with the expanse to be bridged, the types of materials used, and site characteristics encountered. Bridges may be constructed over waterways or larger water bodies and over easily disturbed, unstable surfaces such as sand dunes.

Pile-supported expanses of bridges are built on pilings or caissons emplaced at intervals. Bridge abutments, however, often consist of mounded and compacted fill materials which may be surfaced with concrete, rock rubble, or other protective surfacings, or they may simply be revegetated. Subactivities include: vehicular movement/operation, substrate removal, permanent spoil placement, placement of piles and support structures, mounding, revegetation, and fertilization.

Environmental Effects

Pile placement for bridge supports results in minor direct losses of vegetation on land and vegetation and/or benthic invertebrates in aquatic ecosystems. Local increases in erosion and turbidity may result. Filling for abutments buries some organisms, may increase turbidity because of erosion and current distribution of the fill, and may locally alter drainage patterns. Gasoline spills and other minor accidents may have limited effects.

DREDGING

Information for this section is from the following references: Barnard, 1978; Benefield, 1976a, 1976b; Darnell et al., 1976; Espey, Huston and Associates, Inc., 1976; Gustavson et al., 1977; Longley et al., in press; Texas General Land Office, 1978a.

Description

Dredging is a method for deepening streams or coastal waters, or for extending waterways inland, by scraping and removing benthic solids or contiguous subaerial substrate. The operation may last only a few hours in preparing the footing of a small pier, or for several years when maintenance dredging of a large channel or harbor is required. The time span over which dredging will occur varies with the amount and type of material to be dredged and with the type of equipment used. Dredging occurs primarily in aquatic ecosystems but may be extended into contiguous upland ecosystems. Subactivities include: vehicular movement/operation, vegetation clearing, pumping water, substrate removal, and permanent spoil placement.

Environmental Effects

Aquatic organisms are particularly susceptible to injury during dredging operations because of direct removal, high levels of turbidity, and/or burial by dredged

material. Spawning grounds, breeding areas, oyster reefs, and areas with restricted water circulation may be adversely affected by dredging. Dredging operations resuspend bottom sediments. Dredging also removes aquatic vegetation essential to many fish and game species using these areas as nursery or breeding grounds. Habitat of many species may be affected. Circulation patterns and salinity may be significantly altered.

SPOIL DISPOSAL AND LANDFILLING

Information for this section is from the following references: Brown et al., 1972; Espey, Huston and Associates, Inc., 1976; Gustavson et al., 1977; Lindsey and Supton, 1975; Longley et al., in press; Texas General Land Office, 1978a.

Description

Spoil disposal is the deposition of generally water-saturated dredged material in water or on land. Disposal sites may be contained (diked or ditched) or open (e.g., broadcast disposal in a bay). Landfilling is the disposal of dry excavated substrates on low-lying, unstable soils in order to increase elevations or provide firm foundations, making the filled areas more suitable for subsequent development. The areal extent of spoil disposal or landfilling may vary from less than one acre for small projects to hundreds of acres for a major harbor or channel dredging project. The rate at which a disposal site is filled varies, depending on the number of dredging projects contributing spoil or landfill materials, the water content of the spoil which is deposited, treatment methods such as compaction, etc. Spoil disposal and landfilling may occur in any ecosystem. Subactivities may include: vehicular movement/operation, substrate removal, pumping water, spoil discharge, mounding, compaction, revegetation, and fertilization.

Environmental Effects

The disposal of dredged or landfill materials on land may have a number of direct and indirect impacts. Productive vegetation and wildlife habitat may be covered and permanently eliminated. Drainage patterns may be altered. Plants and grazers may be harmed by heavy metals, sulfides, ammonia, or other substances contained in sediments. Fluids from dewatered estuarine spoil can cause degradation of vegetation and aquatic fauna intolerant of high salinity. Sustained spoil disposal on land may also increase soil salinity in adjacent areas which are affected by groundwater seeping from the disposal site. Spoil or landfill banks may impede normal water flow and/or result in more frequent inundation.

BULKHEAD CONSTRUCTION

Information for this section is from the following references: Darnell et al., 1976; Texas General Land Office, 1978a; U.S. Army Coastal Engineering Research Center, 1973.

Description

Bulkheads are linear structures of timber, steel, concrete, rock, or other materials backed by earth and located along a shoreline. The purpose of bulkhead construction is to prevent shore erosion by wave action. Size and design details of bulkheads vary with site conditions. Duration of bulkhead construction depends on the size of the bulkhead needed, the type of construction materials used, and characteristics of the site. Bulkheads may be constructed in any aquatic ecosystem and in terrestrial ecosystems adjacent to water. Subactivities may include: vehicular movement/operation, substrate removal, mounding, placement of protective structure, and compaction.

Environmental Effects

Bulkheads generally afford protection only to the land immediately behind them. For example, when bulkheads are built on a receding shoreline, the recessing will continue and may be accelerated on adjacent unprotected shores. Any prior tendency toward loss of beach materials in front of such a structure may also intensify. The construction of bulkheads involves permanent elimination of valuable intertidal and subtidal habitats which often comprise the most productive zones of estuaries. Dredging to obtain fill for bulkheads removes additional shallow or deeper water habitat. The hard sloping to vertical surfaces of these structures create reflection waves which further disturb sediments in the adjacent water. When bulkheads are built in groups, they may create blind channels where circulation is poor and where anaerobic conditions readily develop.

PLANT CONSTRUCTION

Information in this section is from the following references: Berkshire County Regional Planning Commission, 1974; Gustavson et al., 1977; Lindsey and Supton, 1975; Underhill et al., 1976; U.S. Department of the Interior, Fish and Wildlife Service, 1976; White et al., 1978.

Description

Each power plant will require approximately 10 acres of cleared and suitably prepared land surface or filling. The plant may be located on an upland site near an aquatic ecosystem, possibly requiring associated bulkheading, spoil dredging and disposal, and landfilling in order to establish a firm, secure, elevated foundation for the plant. Water would have to be pumped from low-lying areas. The construction of geothermal power plants may occur in insular/eolian, grassland, woodland, or artificial/unstable ecosystems. Subactivities are likely to include: vegetation clearing, permanent spoil placement, substrate removal, mounding, compaction, pumping water, vehicle movement/operation, building construction, equipment installation, revegetation, and fertilization.

Environmental Effects

The major impact of plant construction is that the area of the development site is withdrawn from the natural system. Construction of the plant will also result in a temporary increase in local noise levels, largely due to the operation of construction equipment. Clearing of land will result in the destruction of soil and vegetation, accelerated erosion, disturbance of wildlife, and increased turbidity and sedimentation in contiguous water bodies. Surface permeability will be decreased and runoff increased because of clearing, mounding, compaction, and paving. Revegetation may stabilize disturbed soil and fill materials, eventually reducing erosion. Fertilizers applied to soils to enhance revegetation may spread to contiguous water bodies, affecting aquatic vegetation.

PLANT OPERATION AND MAINTENANCE

Information in this section is from the following references: Berkshire County Regional Planning Commission, 1974; Gustavson et al., 1977; U.S. Department of the Interior, Fish and Wildlife Service, 1976.

Description

Operation of the plant will include electrical power generation and transmission, brine transmission from production wells to the plant and from the plant to disposal wells, production processing (methane separation, etc.), methane transmission to the gas distribution systems, venting steam into the atmosphere, and possibly fresh water consumption for cooling. Fresh water from a suitable surface and/or shallow groundwater source may be pumped to the plant. Plant and equipment maintenance may involve a variety of procedures generally similar to those required for plant construction.

Environmental Effects

Gas separation and conversion of geothermal energy to electrical energy yield certain waste byproducts in quantity. Water vapor, methane, nonmethane hydrocarbons, hydrogen sulfide, heavy metals, boric acid, and ammonia are among the possible air, soil, and/or water contaminants derived from the release and processing of geothermal fluids, and they must be contained at the plant site or in pipelines. Accidents at the plant site or along brine transmission lines could result in the discharge of effluents causing pollution of the air, soils, surface water, and groundwater. Fire and explosions are hazards concomitant with gas separation. In addition, noise, odors, light, and activity associated with plant operation may disturb wildlife. Water vapor from cooling towers may also contribute to increased fog in the immediate area of the power plants. Routine operations may require a large quantity of fresh water for cooling.

GEOPHYSICAL SURVEYS

Information in this section is from the following references: Texas General Land Office, 1978a; U.S. Department of the Interior, Fish and Wildlife Service, 1976.

Description

Geophysical surveys identify characteristics of subsurface strata which may indicate geopressured-geothermal resources. Gravity measurements, explosive charges, and thumpers may be used in conducting a typical geophysical survey. Geophysical surveying is a short-term undertaking compared to other activities; they may be performed in any ecosystem. Subactivities may include: vehicular movement/operation, vegetation clearing, substrate removal, geophysical testing, and filling.

Environmental Effects

Geophysical surveys may cause disruption of the environment locally through soil disturbance and compaction, removal of vegetation, and noise. Off-road vehicle travel can enhance soil erosion. There may also be minor impacts from gasoline spills, litter, etc.

LEVEE CONSTRUCTION

Information in this section is from the following references: Gustavson et al., 1977; Texas General Land Office, 1978.

Description

A levee is a linear embankment built to protect land from inundation. Levees are often used in low-lying coastal areas subject to periodic tidal inundation or along the banks of tidal streams. The period over which levee construction may extend will vary with the extent of construction (length, height, and width of the levee), the type and source of earth materials used, the method of compaction, the choice of equipment, and certain site conditions. Subactivities may include: vehicular movement/operation, vegetation clearing, substrate removal, mounding, compaction, placement of protective structure, revegetation, and fertilization.

Environmental Effects

The construction of levees may affect insular/eolian, wetland, riparian woodland, or artificial/unstable ecosystems. Major effects of levee construction are habitat and vegetation loss over the area occupied by the levees. In marshes, in particular, natural drainage is often interrupted and water levels are raised or lowered locally. Aquatic and terrestrial plants may be adversely affected. Fluctuating water levels may also release nutrients and oxidize sulfides to sulfuric acid. Changes in water chemistry may result, including concentration of heavy metals. Increases in turbidity levels and oxygen demand may also occur. Subaerial habitat is created by levee-building.

WELLSITE CONSTRUCTION

Information in this section is from the following references: Longley et al., in press; Petroleum Extension Service, 1951.

Description

Wellsite construction is the process of preparing the site for drilling and installation of the rig and drilling equipment. Subactivities include: vehicle movement/operation, vegetation clearing, substrate removal, permanent spoil placement, pumping water, compaction, and installation of the rig and drilling equipment.

Environmental Effects

Site preparation (excavation, including vegetation removal) normally produces the major immediate impacts of wellsite construction. Minor spills of gasoline, diesel fuel, lubricating oils, and disposal of various expendable construction materials can be expected, but these would ordinarily produce extremely localized effects. Substrate removal and water pumping may drain aquatic areas (such as marshes) lacking regular contact with a larger water body, and it may disrupt an elevated water table locally.

Spoil placement and, if necessary, compaction may bury vegetation and/or aquatic organisms, may locally restrict surface and/or shallow groundwater movement on land, and may contaminate aquatic ecosystems with suspended solids and a variety of toxic materials. Soil erosion from upland sites by wind and flowing water may be enhanced because of groundbreaking and removal of groundwater.

DRILLING

Information in this section is from the following references: Longley et al., in press; Petroleum Extension Service, 1951.

Description

Drilling is the operation of a drilling rig and equipment, and it ordinarily involves a variety of subactivities which may be repeated throughout the drilling operation. Drilling may take place in any ecosystem. Subactivities of drilling include: vehicle movement and operation; drilling mud circulation; power generation; bit rotation; pipe insertion; crew boarding; well monitoring, testing, and sampling; well stimulation; pumping water; and well completion or abandonment.

Environmental Effects

Drilling, under ordinary circumstances, is a comparatively benign phase of any geothermal production effort in terms of environmental impact. Rig construction, which alters the site initially, may supercede the impact of a normal drilling operation. Only during accidents of varying degrees of severity is drilling an important cause of environmental impact. However, accident conditions may very adversely affect ecosystems in the vicinity of the well. Spills or leaks of brines, acids, or other toxic materials may occur. Contamination of potable groundwater or other producing formations by migrating brines or mud losses can result. Most serious, perhaps, are the blowouts, in which formation fluids, drilling muds, and sometimes the pipe are blown from the hole by excessive downhole pressures. Blowouts can result, as well, in major brine and hydrocarbon discharges, fires, and, occasionally "cratering," the instantaneous collapse of the ground surface around the rig into a subterranean void. Storms may also cause well damage and equipment failures that may lead to blowouts.

PRODUCTION

Information in this section is from the following references: Gustavson et al., 1977; Underhill et al., 1976.

Description

Production involves the extraction of fluids (brine and natural gas in solution) from a completed well. These fluids are then pumped to the power plant for hydrothermal electrical generation and gas separation. Subactivities of production may include: installation of pumping equipment at the wellhead, production of geopressured-geothermal fluids, vehicle movement/operation, equipment maintenance, and well testing.

Environmental Effects

Normal production operations involve little added environmental impact at the wellsite beyond that incurred during wellsite construction. Minor fluid spills during routine equipment maintenance and the pollution and activity associated with vehicular movement are the only direct effects at the surface. However, long-term production may initiate or encourage subsidence and possible fault activation in the well area. These effects can produce adverse environmental impacts and represent an important hazard associated with geothermal production. Accident conditions, as well, may bring about serious consequences. Blowouts, as described under the effects of drilling, can occur during production. Possible impacts resulting from a blowout at a production well include pollution of surface and potable groundwater, contamination of other producing formations penetrated during drilling, explosions, fires, and cratering. Geothermal fluids are hot (325°F, 168.2°C, or higher) as well as toxic and may thus inflict very serious damage to wildlife and vegetation at the wellsite and in contiguous ecosystems. Other brine losses due to leaks are also possible.

EMERGENCY BRINE STORAGE

Information in this section is from the following references: Gustavson et al., 1977; Lindsey and Supton, 1975; White et al., 1978.

Description

Emergency brine storage would be necessary during system failures, and appropriate storage facilities would have to be constructed near production and disposal wells and the power plants. A storage facility would probably consist of a lined pit and/or dikes to contain spilled brine.

Environmental Effects

Emergency brine storage facilities could affect any environment. The chemical composition of geopressured-geothermal brines is not completely known. In general, construction of emergency brine-holding structures would cause damage to local

terrestrial plant life and disruption of animal behavior patterns in the immediate area. If brines escaped into freshwater areas, there might be severe problems for organisms intolerant of increased salinity or temperature changes, resulting in degradation of vegetation and aquatic fauna. Downstream drainage areas such as marshes and estuaries might also be affected.

DEEP REINJECTION BRINE DISPOSAL

Information in this section is from the following references: Gustavson et al., 1977; Underhill et al., 1976.

Description

Brine disposal by deep reinjection is the pumping of "spent" (low temperature and pressure) brine from a completed well back to the production reservoir. Pumps at the surface force the brine into the permeable formation at a point still within the production reservoir but at a distance from the production well. By "flooding" the reservoir in this way, production is enhanced as geothermal fluids containing gas in solution are forced toward the production well. Reinjection also provides an ordinarily safe means of disposing of toxic brines, and may control subsidence and fault activation to some extent. Brine disposal (deep reinjection) may take place in any ecosystem. Subactivities may include: installation of pumping equipment at the wellhead, reinjection of spent brine, vehicle movement/operation, equipment maintenance, and well testing.

Environmental Effects

Normal brine disposal operations involve little added environmental impact at the wellsite beyond that incurred during wellsite construction. Minor fluid spills during routine equipment maintenance and the pollution and activity associated with vehicular movement are the only direct effects at the surface. However, long-term reinjection can in some instances cause hydrostatic lifting of the ground surface in the well area. It is not known whether this effect might result from deep reinjection in the Gulf coastal geothermal fairways, but it has occurred because of reinjection operations elsewhere. Accident conditions, as well, may bring about serious consequences. Blowouts are probably an unlikely effect of reinjection but cannot be eliminated entirely. In particular, storms which may cause well damage and equipment failure could lead to blowout conditions. Other causes of brine leaks or spills below ground or at the surface could occur, possibly contaminating surface water and potable groundwater. Contamination of other producing formations penetrated by the well is another possibility. Blowouts, though unlikely, could cause explosions, fire, loss of brine, and cratering.

ELECTRICAL AND TELEPHONE LINE CONSTRUCTION

Information in this section is from the following references: Berkshire County Regional Planning Commission, 1974; Gustavson et al., 1977; Robinette, 1973; Texas General Land Office, 1978a; U.S. Department of the Interior, Fish and Wildlife Service, 1976.

Description

Electrical and telephone lines above ground are usually elevated on metal towers or wooden poles ranging in height from 50 feet (15 meters) to over 150 feet (45 meters). Generally, the higher the towers or poles the greater the spacing between them. The width of a transmission line right-of-way is typically between 190 feet (58 meters) and 330 feet (100 meters). The rate at which lines above ground on towers or poles can be installed depends on the size of the tower, the number and types of lines to be strung, and the ecosystems in which construction is undertaken. Subactivities may include: vegetation clearing, substrate removal, permanent spoil placement, pumping water, mounding, filling, substrate displacement, compaction, pole or tower erection, revegetation, fertilization, and vehicular movement and operation. Buried electrical or telephone lines are very similar to pipelines in terms of construction requirements, and the necessary subactivities are essentially those which would be associated with pipeline construction.

Environmental Effects

The construction of electrical and telephone lines could affect any ecosystem. On upland sites, construction produces localized impacts initially; these effects are often prolonged, however, by clearing and maintaining corridors along the rights-of-way. Major impacts include vegetation removal and soil erosion. Associated turbidity and sedimentation in contiguous water bodies can have adverse effects on aquatic organisms. Open burning of vegetation along the right-of-way may cause air pollution and introduce risks of uncontrolled burns. Clearing of the right-of-way, by whatever means, would cause temporary disturbance of wildlife. Rights-of-way are typically maintained by mowing, although herbicides may be used around towers and poles. Maintenance of the right-of-way may have the positive effect of creating habitat diversity. Aerial lines are often struck by night-migrating birds, resulting in deaths or the crippling of birds. The electromagnetic field created by high voltage lines may affect wildlife, although this phenomenon has not been studied extensively. In addition, construction and maintenance and the aerial lines and supports mar the visual aesthetics of otherwise attractive landscapes.

PIPELINE CONSTRUCTION

Information in this section is from the following references: Barnard, 1978; Benefield, 1976a, 1976b; Darnell et al., 1976; Gustavson et al., 1977; Longley et al., in

press; Texas General Land Office, 1978a; U.S. Department of the Interior, Fish and Wildlife Service, 1976.

Description

Pipeline construction is a complex activity. It can occur in both aquatic and upland environments and may involve many different subactivities. Factors affecting the choice of subactivities include characteristics of the ecosystems within the pipeline corridor and the general method of construction employed. The specific size and type of pipe used is contingent upon the distance to be traversed, type and amount of liquid or gas to be carried, and site conditions to which the pipe will be exposed. Construction could last as long as several months if a long section of pipeline is constructed. Subactivities may include: vegetation clearing, vehicular movement/operation, substrate displacement, substrate removal, mounding, permanent spoil placement, shell/gravel (pipe bed) placement, water flow diversion, compaction, pumping water, chemical waste disposal, pipe laying, pipe welding, filling, revegetation, and fertilization.

Environmental Effects

Pipeline construction could affect any ecosystem. On land, burying a pipeline results in direct environmental impacts, which include disturbing the soil and the vegetation along the pipeline's route. Generally, however, vegetation can be reestablished along the pipeline within a few months. Right-of-way maintenance can create habitat diversity. Noise during construction may be disturbing to wildlife, particularly in the vicinity of breeding grounds. Construction of pipelines through wetlands, bays, estuaries, or the Gulf of Mexico, however, may result in significant local environmental impacts such as loss of habitat and vegetation, direct removal of benthic organisms, and increased turbidity during construction. Leakage or rupture of the pipelines may result in heated brine discharge or gas explosions and fire. Brine pipelines could heat adjacent substrate and effectively sterilize the soil if not properly insulated.

4. ECOLOGICAL IMPACTS OF UNIQUE ACTIVITIES

This chapter discusses the unique aspects of activities related to geopressured-geothermal resource production. These are unique in that they are not similar to other energy development activities (particularly oil and gas development), nor have they been extensively investigated in previous studies. They have potential for serious ecological effect and warrant special attention.

In keeping with the goals of the study, the focus of this analysis is on the aspects of these activities and their effects that are relevant to prediction, control, and monitoring. As mentioned previously, the objective was not to provide a detailed explanation of the effects and their causes, but to provide sufficient information to identify techniques for managing the effects to minimize ecological degradation.

The aspects of geothermal development activities that were identified as unique and warranting further investigation in this study are:

1. Well drilling - particularly the release of brine in the event of a blowout; the potential for subsidence
2. Production - particularly accidental brine discharges associated with production well blowout or disposal well failure; the potential for subsidence and subsurface contamination
3. Pipeline operation - failure of pipeline and accidental brine discharges
4. Plant site operation - particularly accidental discharges of brine; noise, air pollution, and water consumption
5. Brine storage - need for temporary brine storage facilities and problems associated with their design and use

In the process of the analysis, these activities were grouped according to the nature of their ecological effects. Three major categories were considered:

1. Brine discharges associated with drilling, production, and pipeline and plant operation; brine storage
2. Subsidence, fault activation, and subsurface contamination associated with drilling and production
3. Noise, air pollution, and water consumption associated with production and plant operation

Each of these categories of effect is discussed separately.

BRINE DISCHARGES

Summary of Effects

The most important factors in immediate impact of brine spills on an ecosystem are the ecosystem's dilution characteristics and sensitivity to salinity and boron. Thus, the medium salinity bay is relatively insensitive, while upland systems such as the coastal prairie and agricultural areas are highly sensitive. Long-term recovery rates depend on the types of producer and consumer communities and flushing characteristics. The planktonic communities can recover very rapidly in the medium salinity and other bay systems, but a minimum of one yearly cycle will be required to reestablish systems based on rooted plants. Tens of years would be required to restore tree-based systems such as fluvial woodlands. Soil type is an important factor in all upland systems because it controls the processes which can flush salts out of the root zone of plants.

In general, estuarine systems are expected to be less sensitive than freshwater aquatic or upland systems for both immediate and long-term impacts. Wetlands systems are considerably more sensitive than estuarine systems because much less water is available for dilution, and flushing is slow.

The details of flushing rate and drainage pattern are expected to control long-term recovery of fresh aquatic systems, especially ponds and fresh marshes.

These factors suggest that for spills which cannot be confined to a small area and disposed of by reinjecting, it may be desirable to route the brine to the nearest estuarine system, avoiding fresh marshes, ponds, salt marshes, and brackish marshes as much as possible. Of course, this strategy must take into account the relative value of ecological systems, particularly with regard to habitat of rare and endangered species, etc. Disaster plans for each well should detail possible drainage routes in the event that a blowout cannot be quickly contained.

Detailed Discussion of Effects

This discussion of the effects of brine discharges first characterizes the types of brine discharges that could be expected in a geothermal development program. The important environmental variables that can influence the magnitude or duration of effect, such as topographic features or soils characteristics, are also described. A "worst-case" brine discharge scenario which still has a reasonable chance of occurring is then outlined for use in the impact analysis. Finally, the impacts of brine discharges in various types of ecosystems are discussed.

Characterization of Accidental Brine Discharges

The purpose of this section is to determine the probable characteristics of accidental brine discharges during the construction and operation of a geopressured-

geothermal energy production facility in Texas. Planning to reduce the detrimental impact of accidental or random events requires the selection of impact cases which have a reasonable probability of occurring. For example, the 100-year flood is frequently used in floodplain planning, although there is a small probability of a higher water level. The more serious types of brine discharges which have a reasonable probability of occurring will be used to analyze the adverse environmental impacts on ecosystems within state-owned lands in and near the geopressured-geothermal fairways.

Unfortunately, there does not appear to be a usable body of statistics on accidental brine discharge probabilities for the major operations involved in geopressured-geothermal energy development. Therefore, precise calculations are not possible. The following analysis draws generalized conclusions concerning the probability and potential for serious impacts resulting from brine discharges under four cases: blowout during well drilling, blowout of a production or disposal well, pipeline break, and plant operation.

Well Blowout During Drilling of a Production Well. During deep drilling, the pressure in the borehole must be balanced against the pressure in the geologic strata by controlling the density of mud which is pumped through the drill string. Blowouts occur when pressure control is lost and formation fluids (gas, oil, or water) force their way to the surface. Modern oilfield technology provides many methods for blowout prevention and control, but human error and equipment failure cannot be eliminated. It seems reasonable to expect that geopressured-geothermal production wells, which involve drilling deeper and into higher formation pressures than the average oil and gas wells in Texas, will carry a greater risk of blowout.

Statistics on blowouts under various conditions appear to be rather sparse; moreover, definitions of blowouts vary. A recent summary of the impacts of outer continental shelf drilling (Kash and White, 1973) calculated a ratio of 1 blowout per 500 wells drilled on the continental shelf, and 1 per 2,575 on land. A recent Environmental Impact Statement (Bureau of Land Management, 1977) gave a frequency of 1 blowout per 245 wells drilled. Professor Myron Dorfman of The University of Texas Petroleum Engineering Department estimated a frequency of 4 blowouts per 60 wells drilled per year into geopressured formations in Texas.

The "optimistic" development scenario calls for up to 174 production wells in the Brazoria, Matagorda, and Corpus Christi fairways. The number of deep reinjection disposal wells required would be 348, giving a total of 522 wells drilled to geopressured depths. Based on the range of blowout frequency estimates given above, between 0.2 and 35 blowouts may be expected during the drilling of these wells.

Control of blowouts in oil and gas wells can be achieved in anywhere from a few hours to several months. Under good conditions, blowout preventers can be used to shut in the well with little or no discharge. Under the worst conditions, it may be necessary to drill relief wells while the blowout flows unimpeded. Fire is frequently a hazard at oil and gas well blowouts; the dissolved methane content of geothermal brines may also present a fire hazard.

The greatest rate of brine flow from a blowout would occur if control were lost after the hole had been drilled to near maximum depth. In a flowing well, the formation pressure is balanced by friction within the pipe, friction in the producing rack, and hydrostatic pressure. Graphs of flow rate as a function of pipe size, formation permeability, and wellhead pressure presented in Podio et al. (1976) can be used to estimate flow rate under blowout conditions, with wellhead pressure close to zero. Example flow rates under various conditions are shown in Table 1, in barrels per day, acre-feet per day, and millions of gallons per day for wells normally producing about 40,000 barrels per day.

The most optimistic scenario of Zinn (1977) postulates single wells producing about 120,000 barrels per day. The graphs given in Podio et al. (1976) do not extend to this flow range, but can be extrapolated to indicate that a well capable of producing 120,000 barrels per day with a 2,000 psi wellhead pressure would require 7-inch OD pipe and would flow at least 140,000 barrels per day with zero wellhead pressure. This is the equivalent of 5.88 million gallons per day or 18.0 acre-feet per day.

The temperature and methane content of the resource are also relevant to predicting blowout characteristics. Geothermal brine is supersaturated with methane and superheated with respect to surface pressure. The heat content of 300° F (149° C) brine is sufficient to vaporize about one tenth of the water volume into steam. The production scenario used in this study calls for a methane content of 50 standard cubic feet (SCF) per barrel. Most of this methane would be released as soon as the brine reached the surface.

In summary, the rate of flow of a blown-out well depends primarily on the formation characteristics and the pipe size. Various well configurations lead to blowout rates on the order of 42,000 to 140,000 barrels per day of brine which would release 2.1 to 7.0 million cubic feet of methane. About 38,000 to 126,000 barrels of brine at boiling temperature would be released at the surface while the remainder flashed into steam. This volume is equal to from 4.9 to 16.2 acre-feet of brine per day.

Well Blowout During Production or Disposal. After a well has been completed and is being used for production or disposal of geothermal fluids, the chance for a blowout per unit of time is greatly reduced. However, the well must remain in use for a number of years, carrying corrosive fluids under high pressure. In addition to the corrosive nature of the brines, small particles of sand carried along by the brine may erode pipes and valves. Subsidence may place additional strains on the casing of the well, possibly leading to a subsurface blowout.

Little information is available for the evaluation of the probability of blowouts during operation of a geothermal well. Data from the continental shelf suggest that accidents with production wells are not uncommon (Kash and White, 1973).

Velocity-sensitive blowout prevention valves are required on offshore oil and gas wells, but they have exhibited a 40 percent failure rate due to erosion by sand. The time required to control a production well blowout will depend on the condition of the valves, casing, etc.; it could be from a few days to several months.

Table 1

ESTIMATES OF GEOTHERMAL WELL FLOW RATES UNDER BLOWOUT CONDITIONS*

Pipe Size	Production Thickness (Feet)	Wellhead Pressure at 40,000 bbl/Day (psi)	Flowrate at Zero Wellhead Pressure		
			bbl/day	acre-ft/day	MGD
4½" tubing (3.826" ID)	100	500	42,000	5.40	1.76
	200	1,600	46,000	5.92	1.93
	400	1,850	47,000	6.04	1.97
	800	2,100	48,000	6.20	2.02
5½" tubing (4.67" ID)	100	3,600	66,000	8.50	2.77
	200	4,200	73,000	9.39	3.06
	400	4,600	77,000	9.91	3.23
	800	4,900	80,000	10.31	3.36

* From figures in Podio et al (1976) pp. 14-19. Wellhead pressure is assumed to be near zero during blowout, formation pressure is 11,713 psi, depth is 13,000 feet, brine temperature 300 degrees Fahrenheit. A permeability of 50 millidarcies is assumed, as in the Brazoria development scenario (RPC, 1978).

Brine flow rates for a production well blowout would be similar to those estimated in Table 1. The flow rate for disposal wells would depend on the depth and pressure of reinjection, but it would likely be less than the flow from production wells. The composition of the brine from a disposal well blowout would also be different: it would be cooler, have less methane content, and may have had other chemical modifications during geothermal power plant operations.

Pipeline Failure. The pipelines carrying geothermal brines will be short compared to those operated in the oil and gas industry, but they will be operating under fairly high temperature and pressure. Pipelines from production wells would operate at about 320° F (160° C) and 300 to 2000 psi; pipelines from the plant to disposal wells would operate at about 160° F (71° C) and 240 psi (Brown & Root, 1976). Flow rates could range from about 40,000 to 120,000 barrels per day in production pipelines. Most of the length of the pipelines would be underground.

The most likely causes of pipeline breaks appear to be internal corrosion, vehicle-related accidents, and stresses due to subsidence or flooding. Presumably the wells and pipelines will be sufficiently well instrumented (e.g., staged automatic shut-down valves) that the changes in pressure and flow accompanying a major break would be detected quickly and the pipeline would be shut down. A slow leak could remain undetected, but since the pipelines would be short, it would be easy to inspect them frequently.

It seems likely that the maximum brine spill from a pipeline break would be no larger than one day's flow — 40,000 to 120,000 barrels, or about 5.1 to 15 acre-feet.

Plant Site Discharges. A large number of geothermal production plant configurations is possible. Therefore, a detailed analysis of brine discharge possibilities at the plant site cannot be made at this time. However, it is reasonable to assume that the instrumentation and control facilities will be sufficient to detect any accidental brine spill with little delay, and the equipment involved could be shut down promptly. The plant design will presumably provide for routing spilled brine to a holding pond for eventual disposal, probably by reinjection.

Environmental Variables Which Influence Impact Magnitude

There are a number of environmental variables within any ecosystem which may affect the response of the system to a brine discharge. This section outlines the range of influence of these variables.

Climate. One of the most important variables is weather, especially rainfall, prior to a spill. A spill may be preceded by months without rain or by the intense precipitation associated with hurricanes. The tendency of brines to soak into the soil will depend to some extent on the soil moisture content. Brine entering streams or rivers during periods of high runoff may be diluted, so that aquatic systems escape damage. During low to normal flows, much less dilution will be possible, and greater damage will occur.

Soils. Soil characteristics are also extremely important in determining the response of an ecosystem. Soil permeability can vary over two orders of magnitude, depending mainly on the clay content. Table 2 shows some examples of soil properties within the three geothermal fairways. Although a more permeable soil will absorb more brine, it will also leach out the undesirable ions more quickly. One of the adverse effects of brine is expected to be the displacement of desirable cations from ion exchange sites in the clays. This alters soil structure and may further reduce permeability. Some soils may also have impermeable layers (hardpan) which could restrict the penetration of brine.

Season. Season of the year is also expected to be a significant factor, especially when considering thermal effects in wetlands and aquatic systems. The water temperature in ponds, marshes, and other shallow water bodies tends to follow air temperature closely. Texas water quality standards call for a maximum allowable increase in temperature of 1.5° F over ambient conditions during summer and 4° F in other seasons for estuarine waters (Texas Water Quality Board, 1976). The absolute maximum temperature allowed varies from one water quality segment to another. Obviously, a high-temperature brine would require much more dilution to reach a safe temperature during the summer.

Another important aspect of season is the number and species of organisms present in various habitats. For example, migratory birds may winter along the Texas coast or pass through the Texas coast in the fall and spring. Even full-time resident organisms use different habitats for different purposes depending on the seasons. Obviously, disturbance of a population of birds is more damaging during nesting season than before or after.

Topography. All of the geothermal prospect areas along the coast are in very flat areas. Small-scale relief features will be very important in determining the extent to which a geothermal brine spill can spread and the potential for enclosing a spill with emergency dikes. The distance from the spill to major streams will be of considerable importance in upland and fresh aquatic systems.

In the estuarine systems, features such as spoil banks, oyster reefs, and channels will significantly affect the rate of dilution of a spill. For these reasons, a detailed site-specific analysis would be necessary to predict the area affected by a given size of spill.

Brine Composition. A final major variable is the composition of the brine. Examples of the variability in concentration of the major ions in brine are given in Figure 1 and Table 3. These data indicate that the predominant ions are always sodium and chloride. Calcium can vary by almost three orders of magnitude, from 50 to 40,000 parts per million. In contrast, boron varies only from about 20 to 80 parts per million.

Table 2

PROPERTIES OF SOILS REPRESENTATIVE OF THOSE
IN GEOTHERMAL PROSPECT AREAS*

<u>Soil Series</u>	<u>Depth (Inches)</u>	<u>Permeability (Inches/Hour)</u>	<u>Description</u>
Bernard	0- 6	0.06 - 0.2	clay loam
	6-60	<.06	
	60-78	<.06	
Clareville	0-11	.63 - 2.0	loam to clay loam
	11-38	0.2 - .63	
	38-64	.63 - 2.0	
Galveston	0- 4	6.0 - 20	fine sand
	4-70	6.0 - 20	
Katy	0-25	0.6 - 2.0	fine sandy loam
	25-44	0.06 - 0.2	
	44-86	0.2 - 0.6	
Lake Charles	0-20	0.06 - 0.2	clay
	20-70	<0.06	
	70-80	<0.06	
Orelia	0- 5	0.2 - 0.6	fine sandy loam
	5-25	0.06 - 0.2	
	25-60	<0.06	
Victoria	0-72	<0.06	clay

* Derived from U.S. Soil Conservation Service Soil Series Descriptions.

Figure 1

DISTRIBUTION OF DISSOLVED IONS FROM 37
GEOPRESSURED FLUID SAMPLES FROM LOUISIANA AND TEXAS

*From Gustavson, et al., 1977.

Table 3

CHEMICAL COMPOSITION
OF SELECTED FORMATION WATERS
FROM THE TEXAS GULF COAST*

	Sample Number		
	76GG17	76GG58	76GG63
Well number	Gardiner #1	May Owens #1	Portland #A-3
Field	Chocolate Bayou	East White Point	Portland
County	Brazoria	San Patricio	San Patricio
Production zone	Lower Weiting	Owens	Morris
Perforation interval <i>m</i>	3,588-92	3,138-55	3,511-6
Fluid production rates			
Oil and condensate <i>m</i> ³ / <i>day</i> (<i>barrels/day</i>)	2.1 (13)	3.0 (19)	4.8 (30)
Water <i>m</i> ³ / <i>day</i> (<i>barrels/day</i>)	48 (301)	1.3 (8)	7.5 (47)
Gas 1,000 <i>m</i> ³ / <i>day</i> (1,000 <i>ft</i> ³ / <i>day</i>);	2.7 (96)	14.5 (513)	25 (882)
Temperature			
Measured °C	129	112	126
Quartz °C	128	84	130
Na-K-Ca °C	124	100	120
Original bottom hole pressure 10 ⁶ <i>kn/m</i> ² (<i>psi</i>)	172 (7,589)	188 (8,333)	191 (8,455)
Chemical composition <i>mg/l</i>			
TDS <i>calculated total dissolved solids</i>	68,000	24,900	17,800
Na	24,000	9,250	6,500
K	300	70	68
Rb	0.80	0.30	0.30
NH ₃	26	11.0	5.8
Mg	235	31	15
Ca	2,000	200	89
Sr	380	25	7.0
Fe	8.0	70	2.3
Mn	2.7	1.4	0.16
Cl	40,500	14,000	9,270
HCO ₃ <i>field titrated alkalinity</i>	520	1,200	1,600
SO ₄	0.6	22	84
H ₂ S	0.32	—	—
SiO ₂	87	34	93
B	30	24	62
pH	6.3	6.7	6.8

*From Gustavson, et al., 1977.

Selection of Reasonable Worst Case

This section compares the potential magnitudes of impact of various types of accidents and isolates the most relevant environmental variables. This information will be used to select a "worst case" brine discharge scenario which still has a reasonable chance of occurrence. This scenario will be used to characterize the ecological impacts in the various coastal systems.

Holding pond dike failure or overflow could result in release of a large quantity of brine. However, such a failure is most likely to occur under high rainfall conditions, when soils will be saturated and drainage pathways will be carrying large volumes of dilution water.

Pipeline accidents and plant site accidents could release brine at a high rate, but it seems reasonable to expect that the release would rapidly be brought under control. Well blowouts, on the other hand, may remain out of control for months.

Well blowouts thus appear to have a higher potential for adverse impact than other types of accident. During the development of a geothermal power facility, when a holding pond and reinjection wells are in place, it is likely that an emergency brine disposal system could be improvised to handle any reasonable volume of brine from a blown out well. Thereby the damage would be restricted to that caused by the first few days of brine discharge. Thus, the potential for the greatest impact would occur during early stages of development, during drilling of the first production wells.

Analysis of Impacts of Brine Spills

Methodology. For the purposes of this analysis, coastal ecosystems have been aggregated into four major categories on the basis of various common properties. These categories are summarized in Table 4. The aggregations have been created on the basis of expected ecosystem responses to brine discharges. Thus, the soil characteristics of low salinity and frequent lack of saturation distinguish between coastal uplands and shallow estuarine areas with high salinity and saturated soils.

The next step in the analysis is to determine the types of ecological alterations that can occur in each category of ecosystem as a result of brine discharge accidents. Finally, the magnitude of each type of alteration is considered, and is related to short- and long-term changes within the ecosystems. This analysis draws heavily on the recent report by Gustavson et al. (1977).

Ecological Alterations. Ten major categories of ecological alterations that could be caused by brine discharges have been identified using the methodology set out in the Activity Assessment Routine Activity Analysis (GLO, 1978a). As shown in Table 5, the effects will vary according to the type of ecosystem in which the accident takes place. Furthermore, any one of these types of alterations can stimulate other changes in the ecosystem, particularly over the long term. The most direct and initial alterations resulting from brine discharges are summarized below. A further elaboration of these effects and related long term changes will follow.

Table 4

AGGREGATION OF COASTAL ECOSYSTEMS FOR ANALYSIS OF ACCIDENTAL SPILLS
WITH THE MAJOR UNIFYING ASPECTS LEADING TO THE AGGREGATION

<u>Environment Type</u>	<u>Ecosystems Included*</u>	<u>Unifying Aspects</u>
Coastal Uplands	Coastal prairie Fluvial woodland Brushland Oak mottes and groves Agricultural	Rooted vegetation, little standing water, soils not saturated
Fresh Aquatic	Ponds Streams and rivers Freshwater marsh	Adapted to low levels of dissolved ions, sediments; saturated, standing water; rooted plants and planktonic production
Shallow Estuarine	Brackish marsh Salt marsh Wind tidal flat Grassflat Bay transition area	Adapted to moderate to high levels of dissolved ions; significant production by rooted plants or benthic algae; soils saturated
Estuarine	River-influenced bay Restricted Bay Medium-salinity bay Channel Reef and reef-flank area	Planktonic productivity; adapted to moderate to high dissolved ion levels

* Nomenclature generally follows previous Texas Coastal Management Program practice.

Table 5

TYPES OF ECOLOGICAL ALTERATIONS OCCURRING IN AGGREGATED ECOSYSTEMS
AS A RESULT OF BRINE DISCHARGES

<u>Type of Ecological Alteration</u>	<u>Ecosystem</u>			
	<u>Coastal Upland</u>	<u>Fresh Aquatic</u>	<u>Shallow Estuarine</u>	<u>Estuarine</u>
Destroy vegetation, complete*	X		X	X
Destroy consumers, partial*	X	X	X	X
Add water to soil	X			
Add inorganic material to soil	X		X	
Add toxic material to soil	X		X	
Add inorganic material to water		X	X	X
Add toxic material to water		X	X	X
Add toxic material to air	X	X	X	X
Add heat to water		X	X	X
Add heat to soil	X		X	

* Both by fire and direct contact with brine

1. A complete vegetation removal could occur both through fire and through the direct contact with hot brine. Presumably, large trees might be able to survive short contact with hot brine just as they survive the short-lived heat of small brush fires. Smaller and less motile consumers would be killed by direct contact with hot brine, while more motile forms could escape.

2. Alterations affecting the soil include the addition of water, toxic materials, heat, and various inorganic materials. Inorganic materials are considered to include all dissolved salts not directly toxic to plants and animals.

3. Alterations affecting surface waters include the addition of heat, toxics, and inorganic materials. In addition to dissolved salts in the brine, well blowouts and pipeline accidents may cause the release of large amounts of suspended solids as the high-pressure brine disturbs the soil or sediment.

4. The release of significant amounts of toxic material into the air, as gases or suspended spray particles, may be of importance in those systems having emergent vegetation.

Clearly, the magnitude of most of these alterations is related to the composition of the brine. In the subsequent discussion of these alterations, the high end of the reported range of salinity and toxic materials will be assumed.

Impacts on Coastal Uplands. This coastal uplands ecosystem type includes coastal prairie, fluvial woodland, brushland, oak mottes and groves, and agricultural systems. Productivity in these systems is entirely by rooted plants, with the type of plant varying according to soil, soil moisture, and successional factors. In general, the fluvial woodlands and oak mottes would be found on the sandy soils, while the coastal prairie, brushlands, and agricultural systems are predominantly on the clay to clay loam soils. The actual plant and animal species vary considerably along the Texas coast in response mainly to climatic factors. The impact of brine spills on an ecosystem has been considered in terms of the following factors: the areal extent, soil penetration, soil structure and chemistry, heat, toxics, and long term recovery.

Areal extent of impact. Land surface slope in coastal upland systems tends to be rather low, except near streams. Slopes from 1 to 2 feet per mile (19 to 38 m/km) or less are not uncommon. Thus, accidental brine spills could spread for a considerable distance if not controlled by dikes or ditches. Recalling the calculations of the probable magnitude of well blowouts, a pool of brine averaging 6 inches (152 cm) in depth could spread at the rate of 10 to 36 acres (4 to 15 hectares) per day. The brine would cool rapidly as it spread over the land in a thin layer, so that heat effects would cover a smaller area than salinity effects during a prolonged spill.

Soil penetration. The amount of brine which actually sinks into the soil will depend on soil type, soil moisture, and the length of time of exposure. If the soil is already saturated due to rain or irrigation, the rate of penetration could be quite slow. Under these conditions, salts, heat, and toxic materials would enter the upper layers of soil by diffusion.

Examples of soil characteristics in representative soil series in the geothermal prospect areas were given in Table 2. In addition to the wide range of permeabilities between soils, this table illustrates typical occurrences of layers with reduced permeability within the lower horizons.

Under the worst case conditions of a dry sandy soil, with a permeation rate on the order of 6 to 20 inches (15 to 50 cm) per hour, the soil could become saturated with brine within a few hours. Even the least permeable soils could absorb significant amounts of brine if exposed for several days. Many of the clay soils crack to depths of several feet when dried. These cracks could permit rapid penetration of moderate amounts of brine deep into the soil profile before sufficient moisture was absorbed to swell the cracks shut.

Soil structure and chemistry. The effect of brine on normal soil structure and chemistry would be substantial. The high sodium content would displace most of the more desirable ions from cation exchange sites. If a substantial amount of brine was adsorbed, most shallow rooted plants would be killed or stunted.

As an example, consider the concentrations of various materials in the soil moisture which would result if a typical soil, starting with half its capacity for water, absorbed 1 inch (2.5 cm) of brine and the components became distributed within the upper layers of the soil profile. Table 6 shows some of the concentrations calculated for a soil with a saturated capacity of 0.2 inches (5 mm) of water per inch (25.4 mm) of soil, a typical value, and a moisture content of 0.1 inch (2.54 mm) of water per inch (25.4 mm) of soil. The values for salinity and boron are well above the tolerance limits of typical terrestrial plants.

In addition to plant loss, soil bacteria, insects, and other organisms would also be killed by the high salinity. Thus the consumer community in the soil which is responsible for regeneration of nutrients and improvement of soil structure would largely cease to function.

Heat. Heat effects in soil would initially be confined to a shallow surface layer in direct contact with the brine. Since the brine would lose heat rapidly to the air, the intensity of heating would decrease with distance from the spill site. The main effect of the heat would be to kill vegetation and soil organisms, but no lasting effect would result from the heat alone.

Toxics. Toxic materials which could be added to the air include hydrogen sulfide and fine droplets of salt spray. Few analyses of hydrogen sulfide in geopressured brines are available; Gustavson et al. (1977) cite one measurement of 0.32 ppm. Hydrogen sulfide is highly soluble in water — 4000 ppm in fresh water at 20° C and one atmosphere of pressure. The solubility in hot brine is certain to be much less, but still substantial. Thus, only a small amount is expected to be lost to the air. Salt spray would be produced by a violent blowout and would be deposited on downwind vegetation, possibly with lethal results. See Gustavson et al. (1977) for a discussion of this effect. It is impossible at this time to predict the amount of spray produced by any given accident.

Table 6

APPROXIMATE CONCENTRATIONS OF VARIOUS BRINE CONSTITUENTS
IN PPM AT VARIOUS DEPTHS OF SOIL RESULTING FROM EVEN
DISTRIBUTION OF ONE INCH OF BRINE IN SOIL HAVING A
MOISTURE CONTENT OF 0.1 INCH (2.54 mm) OF WATER PER INCH (2.54 mm) OF SOIL*

<u>Name</u>	<u>Concentration of Brine Constituents</u>	<u>Concentration of Soil Moisture Constituents at Various Depths</u>		
		<u>1 Foot (3.8 m)</u>	<u>2 Feet (.61 m)</u>	<u>3 Feet (.91 m)</u>
Salinity	75,000	33,750	21,750	16,500
Sodium	30,000	13,500	8,700	6,600
Calcium	4,000	1,800	1,160	880
Boron	50	22.5	14.5	11

*Mixing depth of soil X moisture content = dilution volume; calculations
assume that soil water is at one-half of saturated capacity.

Long-term effects on coastal uplands. Without active intervention by man, recovery of most soils after a brine discharge is expected to be slow. Gustavson et al. (1977) show still-barren areas in East Texas which were exposed to oilfield brines 30 to 80 years ago.

Displacement of sodium from ion exchange sites within the soil can be encouraged by addition of gypsum (calcium sulfate), but this process is slow (John Matoka, personal communication). Since high sodium content typically causes loss of soil structure, water infiltration rates are slower than for normal soils. Even if an adequate supply of fresh water could be applied to the soil, the major problem of removing salt-laden waters from deep in the soil profile would remain.

Replanting with salt-tolerant species such as *Spartina spartinae* could help accelerate the process of restoring a soil. The work of the Army Corps of Engineers on vegetation planting techniques for spoil banks could be useful in this operation (Kadlec and Wentz, 1974).

Impacts on Fresh Aquatic Systems. This general ecosystem classification includes ponds, streams and rivers, and freshwater marshes. Most geothermal plants and wells would not be expected to be located within these systems, but they would receive the drainage from a blowout on upland systems. Pipeline breaks could also be a source of accidental brine discharge in freshwater systems.

Productivity in these systems is based on rooted plants, phytoplankton, benthic algae, and imported organic matter. Important consumers include insects, fish, birds, and mammals. Substrates are saturated with water and are typically anaerobic below the upper few centimeters. In ponds, marshes, and slowly flowing streams, the sediments typically contain high amounts of organic matter. Impacts in fresh aquatic systems will be considered in terms of flow regimes and dilution, salinity effects, heat effects, toxic effects, and long-term recovery.

Flow regimes and dilution. A major distinction must be drawn between flowthrough systems and static systems. Many ponds and marshes are topographically isolated from major drainage systems. Such closed or semiclosed systems receive water from local groundwater and runoff and lose water to evaporation and percolation. They are flushed only during floods, if at all. On the other hand, water in flowthrough systems has a short residence time.

Within the project study areas, the Colorado is the only major river; all other streams are strictly dependent on coastal drainage basins for their flow. In general this means that flow rates are low except during periods of local rainfall. Although these smaller streams are not usually gauged, some flow rates taken by the USGS in special studies are available (Ratzlaff, 1976). Flow rates in the small streams typically range from 0.0 to 10 cubic feet (0.0 to 0.28 cubic meters) per second. For the sake of comparison, a 80,000 bbl/day blowout flows at about 5.2 cubic feet (0.15 cubic meters) per second. Calculations of the dilution provided by various streamflow rates are shown in Table 7. The significance of these calculations in terms of ecological effect are discussed subsequently.

Table 7

DILUTION OF A GEOTHERMAL BRINE WITH TYPICAL FRESHWATER STREAM FLOW^a

Constituents				Concentration After Mixing at Various Stream Flows		
Name	Units	Brine Conc.	Stream Conc.	1 cfs	10 cfs	100 cfs
Temperature	deg. F	212 ^b	86	192	129	92
Salinity	ppm	75,000	470	63,000	26,000	4,200
Sodium	ppm	30,000	100	25,000	10,000	1,600
Calcium	ppm	4,000	60	3,400	1,400	250
Boron	ppm	50	0.25	42	17	2.7
H ₂ S	ppm	1	0.0 ^c	0.84	0.34	0.049
Ammonia		26	0.1	22	9.0	1.4

^a Brine flow rate is 80,000 barrels per day and brine concentrations are from the high end of reported values. Stream concentrations are from the middle of the range reported for Chocolate Bayou, except that the temperature is the top of the range (White et al. 1978).

^b Assume excess heat is lost by flashing to steam.

^c No measurements available, assumed to be essentially zero.

Salinity effects. The calculations of Table 7 indicate that a substantial salinity increase would result from a large geothermal brine spill, even in fairly large streams. The salinity of 26,000 ppm calculated for a 10 cfs stream is greatly in excess of the salinity range tolerated by fish and freshwater marsh plants. Salts in the water would diffuse and percolate into sediments, eventually killing all rooted plants if the spill continued for a long period.

Recovery from salinity effects could be rapid in flowing systems, especially if an upstream population of organisms could resettle the area. Salt trapped in closed systems could persist for many years. In such situations, it may be possible to establish salt-tolerant vegetation to provide a productivity base.

Heat effects. The rapid temperature rise resulting from a geothermal brine spill could be fatal to many organisms, especially when combined with stresses due to high salinity and toxic materials. However, heat loss to the air would reduce the temperature as water flowed through the system. Both high temperature and salinity reduce the solubility of oxygen in water, thus creating another stress on organisms.

Effect of toxics. Ammonia and hydrogen sulfide are toxic at the levels shown in Table 7, with the exact toxicity depending on the pH of the water. Ammonia is more toxic at high pH levels (as NH_3) and hydrogen sulfide is more toxic at acidic pH levels (as H_2S). However, both compounds can be dissipated by natural processes. Hydrogen sulfide is rapidly oxidized in aerobic waters, and ammonia can be taken up by phytoplankton and higher plants.

The boron content would not be toxic to fish, but it could be toxic to terrestrial plants on continuing exposure. Salt marsh plants are more tolerant of boron, since it is present in seawater at 4.6 ppm.

Long-term recovery. The prospects for long-term recovery appear to be directly related to the flushing rate of the system. Flowing streams will probably recover without special measures, but isolated ponds and fresh marshes would probably require flushing to reduce the salinity and possibly the boron levels.

Impacts on Estuarine Systems. As a general class, estuarine ecosystems are characterized by a productivity base of phytoplankton plus organic matter added from surrounding uplands and wetlands. Benthic consumers constitute a major component, but most economically important species are motile. The major exception is the oyster in the "reef and reef flank" systems. All estuarine species have a wide salinity tolerance to cope with the high variability of their environment, although various species do exhibit preferences for various salinity ranges.

The importance of heat, dissolved inorganics, and toxic materials is evaluated by computing the dilution required to reach "normal" or safe values of these parameters. Other factors which are discussed are the effects of suspended solids and the potential for long-term recovery.

Dilution calculations. Table 8 shows sample calculations based on normal estuarine waters diluting a hot concentrated brine. The "target" concentrations are: normal seawater for total salinity, sodium and calcium; Texas Water Quality Standards for temperature rise (summer conditions); and suggested Environmental Protection Agency (USEPA) water quality criteria.

The dilution calculations indicate that heat, boron, and hydrogen sulfide may be the most sensitive parameters. Estuarine phytoplankton do not appear to be as sensitive to boron as terrestrial plants, tolerating up to 10 ppm (Antia and Cheng, 1975). Hydrogen sulfide is naturally present in estuarine waters in small quantities due to release from anaerobic sediments, but measurements at these low levels are difficult (Bella et al., 1972). Hydrogen sulfide is not stable in aerobic waters and would be oxidized rapidly.

A detailed treatment of the sulfur cycle in estuaries is presented in Bella (1975). He found that under favorable conditions, estuarine sediments could release 0.2 to 1.0 gm of H_2S per square meter per day. In order to compare the magnitude of a blowout as a sulfide source with natural processes, consider the amount of H_2S in 80,000 barrels per day of brine with a concentration of 1.0 ppm sulfide. Such a blowout could release about 12.2 kg (27 pounds) of H_2S per day. About 6 hectares (15 acres) of sediment producing H_2S at $0.2 \text{ gm/m}^2/\text{day}$ would produce an amount equivalent to the blowout. Thus, it appears likely that the hydrogen sulfide added to an estuarine system would not be an excessive load on the natural system if mixing is fairly rapid.

The calculations of Table 8 indicate that the heat from a geothermal brine blowout could be one of the most significant dangers to the ecosystem. Texas estuaries tend to be quite hot in the summer, especially in the shallower areas, and many organisms may be near the upper end of their temperature tolerance. Although salinities are usually less than that of seawater, restricted bays may experience a buildup of salinity during prolonged periods of low runoff.

In the open areas of estuarine systems such as medium salinity bays, the existing circulation would be entirely adequate to rapidly dilute the five to ten acre-feet per day of a geothermal well blowout. However, in the smaller and shallower systems, such as a restricted bay or river-influenced bay, salt and other nonreactive components of brine could build up during a prolonged blowout, if it occurred during a low runoff period.

Suspended solids. A blown out well may release large amounts of suspended solids, especially if the surface casing is ruptured and a "crater" is produced. These solids settle out in the vicinity of the well and can smother the benthic community. This problem is particularly acute in the vicinity of oyster reefs.

A blown out gas well in the Cedar Lakes area of the central Texas coast produced measurable silt deposition out to a distance of 325 meters from the well (Belaire and Knudson, 1974). Approximately 7.9 acres (3.2 hectares) of oyster reefs near the well were significantly affected.

Table 8

DILUTION RATIO REQUIRED WHEN MIXING
TYPICAL ESTUARINE WATER WITH A GEOTHERMAL
BRINE TO REACH SPECIFIED WATER QUALITY CRITERIA

<u>Constituent</u> <u>Name</u>	<u>Unit</u>	<u>Brine</u> <u>Conc.</u>	<u>Estuarine</u> <u>Conc.</u>	<u>Target</u> <u>Conc.</u>	<u>Dilution</u> <u>Ratio</u>
Heat	deg. F	320 ^a 212 ^b	95 95	96.5 ^c 96.5	149 77
Salinity	ppm	75,000	25,000	35,000 ^d	4
Sodium	ppm	30,000	7,500	10,000 ^d	6.5
Calcium	ppm	4,000	286	400 ^d	14
Boron	ppm	50	3.3	4.6 ^d	35
Hydrogen sulfide	ppm	1	0.000	0.004 ^e	249

^aAssume direct mixing with estuarine water without flashing.

^bAssume all excess heat removed by flashing to steam.

^cTexas Water Quality standards, rise of 1.5° F.

^dSeawater concentration.

^eUSEPA Water Quality Criteria, 1976.

Long-term recovery. In most estuarine ecosystems, the prognosis for long-term recovery is excellent. Due to rapid reproduction, phytoplankton, zooplankton, and benthic invertebrates will reestablish normal populations in a few days to a few months. The more motile sports fish and other higher consumers would also return to the area quickly. Damaged oyster reefs may require one or two years to reestablish commercial populations. The only chance for permanent loss could occur if an oyster reef is covered with mud after a cratering type of blowout. Without a hard substrate for spat settlement, a reef might not become repopulated. However, dumping of oyster shell "cultch" can provide the needed substrate.

Impacts On Shallow Estuarine Systems. The shallow estuarine group of systems includes brackish and salt marshes, grassflats, wind tidal flats, and bay transition areas. This grouping is based on the presence of significant production by rooted plants and moderate to high salinity. Soils are generally saturated but are occasionally exposed to air to varying degrees. Frequency of exposure is greatest for wind tidal flats, intermediate for brackish and salt marshes, and low for grassflats and bay transitional areas. Exposure to air and drying tend to cause soil salinities to be higher than that of overlying waters. These areas, especially brackish marshes, salt marshes, and grassflats are significant as habitat for the juveniles of many important estuarine species.

Dilution. The dilution calculations made for estuarine systems (Table 7) are also pertinent here. Circulation and dilution rates are much slower in shallow estuarine systems than in more open systems such as the medium salinity bay. One reason for this is the shallower depths. Tidal flats, brackish marshes, and salt marshes typically have very shallow water depths from 0 to 2 feet (0.61 m) -- except in distributary channels and ponds. Grassflats and bay transitional areas typically have depths from 0 to 5 feet (1.5 m).

The effect of a lower dilution rate will be a great increase in the area covered by high temperatures and high salinities. The area affected will be highest in the shallowest systems -- tidal flats, salt marshes, and brackish marshes. A marsh or tidal flat with a water depth of one-half foot could be covered with brine at a rate of 10 to 30 acres (4 to 12 hectares) per day. Local relief and drainage features will play an important role in controlling the spread of brine.

Salinity. Plants and animals in the shallow estuarine ecosystems are generally subjected to a wide range of salinities. Table 9 summarizes some upper salinity limits for growth from various sources. In most cases, these upper limits are far from the optimum salinity conditions. Obviously, some dilution would be needed before these plants could withstand one of the more saline geothermal brines.

Heat and toxics. In general, the dilution calculations discussed under estuarine systems can also be applied in the shallow estuarine systems. A considerable degree of dilution would be required to reach acceptable levels of temperature and hydrogen sulfide.

Table 9

SOME UPPER SALINITY LIMITS FOR BRACKISH MARSH (BM),
SALT MARSH (SM), AND GRASSFLAT (GF) PLANTS

<u>Plant Species</u>	<u>System</u>	<u>Upper Salinity ppm</u>	<u>Ref.</u>
<u>Spartina alterniflora</u>	SM	49,700	a
<u>Batis maritima</u>	SM	49,700	a
<u>Juncus roemerianus</u>	SM	44,000	a
<u>Salicornia sp</u>	SM	42,500	a
<u>Distichlis spicata</u>	SM	49,700	a
<u>Spartina patens</u>	SM	42,500	a
<u>Scirpus americanus</u>	BM	28,800	a
<u>Thalassia testudinum</u>	GF	60,000	b
<u>Halodule beaudettei</u>	GF	52,500	c
<u>Cymodocea filiformis</u>	GF	35,000	c
<u>Ruppia maritima</u>	GF	46,000	b

(Typical concentration of geothermal brine is 75,000 ppm;
see Table 6.)

References:

- ^aChapman, 1960.
- ^bMcMillan and Moseley, 1967.
- ^cMcMahan, 1968.

Long-term recovery. Depending on length of exposure, roots and rhizomes may not be killed and may recover within a few months. Restoration of vegetation in brackish marsh, salt marsh, and grassflat areas after longer periods of exposure to heated brine (e.g., greater than a few days) will be slow and uneven unless aided by transplantation. Initial colonization by the annuals such as *Salicornia* sp. will occur in the spring following the brine spill. However, *Spartina alterniflora* and the seagrasses normally expand into a new area by runners at the rate of several meters per year. Resumption of productivity by the benthic algae which predominate in tidal flats and bay transition areas would be rapid, but recovery of the low-density seagrasses in bay transition areas would be slow.

Resettlement by benthic invertebrates could be rapid, but the full species diversity would not be restored until the plant community also recovered. Juvenile fish, shrimp, and crabs would be able to return to the area within a few days, but without the production and shelter offered by the plants, the population density and diversity would be lower.

A general range of rapidity of recolonization of shallow estuarine vegetation is:

Wind tidal flat > Brackish Marsh > Saltmarsh $\approx$ Bay Transition > Grassflat
 few months $\xrightarrow{\quad 1 \quad 2+ \text{ years} \quad}$ $\xrightarrow{\quad 2 \text{ years} \quad}$

GEOLOGIC ALTERATIONS

Summary of Analysis

The second major category of unique effects of geopressed-geothermal resource development includes the related geologic alterations -- subsidence, fault activation, induced seismic activity, subsurface contamination, and hydraulic lifting. These impacts are relevant in that they affect the recoverability of geologic resources, including groundwater, and can have serious effects on the surface. Major study findings concerning the effects of related geologic alterations are these:

1. In the Matagorda geothermal fairway, the greatest ecological effect of increased subsidence will be the expansion of brackish and salt marsh into adjacent coastal prairie and fluvial woodland. Some fresh marsh would also be created. Erosion rates along the Gulf beach would be increased.
2. In the Corpus Christi fairway, grassflats would be created in wind tidal flats, with corresponding losses of grassflats in deeper areas. Beach erosion will increase on the barrier islands. On the mainland, oak groves and coastal prairie areas would be converted to wind tidal flats and salt marsh.
3. Subsidence effects in the Brazoria fairway will include the expansion of brackish marshes, fresh marshes, and flooding of agricultural areas.

4. An important aspect of controlling subsidence is the ability to predict it. This study concludes that subsidence modeling for geothermal resource development is not adequate. The most reliable prediction method at this time appears to be the use of oil and gas production analogies. Prevention and control of subsidence can be achieved with some success through proper well spacing and density, siting of production facilities in areas least sensitive to elevation losses, judicious use of permeability-enhancement techniques, minimizing fluid pressure drop during fluid withdrawal, and fluid reinjection.
5. Early detection of subsidence and fault activation can play an important part in preventing serious impacts. Aerial and ground surveys are useful in monitoring elevation changes during geothermal resource production.
6. Contamination of potable groundwater and valuable minerals and hydrocarbons can result from the movement of geothermal brine into other geologic formations. Such contamination can be caused by movement along faults, through a failing well casing, or uncased well intervals, from contiguous strata, or by infiltration from the surface. These impacts can be prevented by the use, proper installation, and maintenance of high quality materials, and through monitoring both at the geothermal well and in neighboring wells.

Detailed Discussion

In this section, the effects of subsidence; fault activation and induced seismic activity; subsurface contamination; and hydraulic lifting are discussed in detail. Subsidence and fault activation in particular have the potential for large-magnitude impacts. Thus, separate discussions of prediction, management, and monitoring of subsidence and fault activation follow the detailed discussion of effects.

Subsidence

For purposes of this discussion, subsidence is assumed to be a gradual lowering of the ground surface attributable only to withdrawal of fluids from a subsurface reservoir. Small horizontal movements of the surface may occur simultaneously.

The probability that subsidence will result from geopressured-geothermal resource production, as well as the magnitude and rate of subsidence, are dependent upon several factors:

1. The geologic properties of the reservoir and surrounding strata
2. The volume and rate of fluid withdrawn

This discussion will describe each of these factors and how they relate in influencing subsidence.

Geologic Properties of the Reservoir and Surrounding Strata. Two geologic conditions are of particular importance in controlling reservoir behavior and

subsidence potential. These are the presence of (1) shale beds with low permeability and (2) faults.

Low-density, high-pressure shales typically surround the permeable sandstones containing the geopressured-geothermal reservoir. The shales act as hydrologic barriers, restricting the movement of reservoir fluids. These shales are thus responsible for maintaining high reservoir fluid pressures. The cumulative thickness of the confining shale beds may exceed 1,300 feet (396 m) (Gregory, 1977).

Faults may serve a similar function. Permeable aquifer strata may be sealed against impermeable strata which are displaced during faulting. Either of these processes can form a geopressured-geothermal reservoir. (See Figure 2.)

Fluid withdrawal from these confined reservoirs can alter the hydraulic balance between the reservoir fluid pressure and the stress on the reservoir created by overlying strata ("overburden"). A decline in fluid pressure will result in the compaction of reservoir strata and their adjacent confining shale beds. Subsidence occurs when this compaction is transferred upward to the ground surface. This relationship is probably nonlinear; that is, the amount of compaction at the depth of the reservoir may not equal the surface displacement. A thick overburden is more capable of dissipating the effects of compaction at the reservoir depth, thereby lessening the effects at the surface (Geertsma, 1973).

The compaction process. The compaction of a geopressured-geothermal reservoir results from the following series of events:

1. Withdrawal of the fluid
2. Reduced fluid pressure in the production zones of the reservoir (Bebout et al., 1978)
3. An increase in vertical stress on the web framework, or "matrix," of the reservoir as the fluids are withdrawn

The extent to which the matrix may undergo "strain," or stress-induced deformation, is variable. In sandstones such as those comprising the Frio reservoirs of the Texas coast, the stress is more likely to affect the "cement" or mineral overgrowths binding the individual sand grains than the grains themselves. The ability of the cement to resist strain is thus one of the limiting factors controlling compaction.

Even more important in a geopressured system is the possible compaction of low-density shales associated with the reservoir sandstones. The withdrawal of fluid from the reservoir may cause the adjacent shale beds to expel water into the porous reservoir sandstone, even though these shales have low permeability (Gutavson and Kreitler, 1976). As the shale beds "dewater," they become more compacted.

Shale bed thickness is greater than that of the reservoir sandstones in many areas (Bebout et al., 1978), and the shales, once dewatered, are more readily compacted. Thus, compaction in the shales may be volumetrically greater than in sandstones, as long as the shales can transmit water into the sandstone beds (Bebout et

Figure 2

TYPICAL GEOPRESSURED-GEOTHERMAL
RESERVOIR CONFIGURATIONS

al., 1978; Gustavson and Kreitler, 1976). High stress resistance in the cemented reservoir sandstones might actually increase the total amount of compaction by maintaining sandstone porosity, thus allowing the shales to continue to dewater. Compaction of shales nearest the sandstone may eventually limit the transfer of water, but the importance of this effect is not known.

Limits of effect. Compaction of either the reservoir sandstones or the contiguous shales would almost certainly be transmitted upward into the overburden. Stress resistance, or "load-bearing strength," of the overburden then becomes important, but at least some subsidence may eventually be experienced. In one test Gustavson and Kreitler (1976) estimated that approximately 37 percent of the expected reservoir compaction would be transferred to the surface. They report a subsidence rate of 0.12 feet (0.04 m) per year from production of oil and gas in the geopressed portions of the Frio Formation; this is the formation that is currently being studied for geothermal resource production. The rate of fluid withdrawn per well under oil and gas production is considerably less than (e.g., one-fourth) prospective geothermal development rates.

Reservoir characteristics affect not only the amount of elevation loss at the ground surface, but also the rate and areal extent of subsidence. The decline in reservoir pressures resulting from fluid withdrawal may initially be quite rapid. To some extent, dewatering of the adjacent shale beds may slow the rate by maintaining pressures in the reservoir. Reservoir and overburden strata respond differently to these conditions, and the rate of net compaction may vary through time.

Thus, subsidence rates would probably be erratic as well. Rates calculated by Gustavson and Kreitler (1976) for various time intervals in the production history of the subsiding Chocolate Bayou oil field, Brazoria County, Texas, indicate fluctuations of up to 600 percent between two intervals. There may also be a time lag between a pressure decline, the onset of compaction, and subsidence, as postulated by Atherton et al. (1976, v. 1). However, Gustavson and Kreitler (1976) argue against such a delay.

Volume and Rate of Fluid Withdrawal. The areal extent of subsidence is controlled not only by the size of the reservoir (if comparatively small or if fault-bounded) and the direction of fluid movement toward the production well(s), but by the rate and period of withdrawal.

Bebout (1976) stated that a potential geothermal production zone 300 feet (91 m) thick would have to cover an area of 50 square miles (130 sq. km) to provide adequate groundwater supplies over the desired life of the field. Zinn (1977) suggests that withdrawal from such a large reservoir would probably be successful only with the assistance of extensive fluid reinjection, and reinjection might limit the compaction of the reservoir strata. However, some compaction would almost certainly occur and would be felt over most or all of the reservoir. Distal portions of the reservoir would contribute fluids later in the field's life than would the areas nearest the wells. At any one time, then, the reservoir area undergoing compaction and subsidence in Bebout's (1976) example would be smaller than 50 square miles (130 sq. km). Over the life of the project, however, the entire reservoir could experience compaction and create subsidence over a 50 square-mile (130 sq. km) surface area.

Ecological Effects of Subsidence. As discussed previously, geopressured-geothermal energy development on the Texas coast may result in or enhance subsidence. This may take the form of general depression of a wide area, or there may be some irregular depression due to movement on fault lines.

The dynamic processes of coastal ecosystems have responded to subsidence and sea level changes over recent geologic history, but the relative rate of change has been slower than that anticipated in this case. The system responses due to localized subsidence are expected to be similar to those which have occurred due to general sea level changes.

The discussion of the impacts of subsidence will be organized around the four general ecosystem groupings used in analysis of brine discharges, with the addition of the special case of barrier islands. The method of analysis will be to identify the changes in ecosystem processes induced by subsidence, then predict the resultant changes in ecosystem components. Finally these generalized changes will be related to the specific study areas.

Subsidence effects in estuarine systems. For purposes of this discussion, estuarine systems include river-influenced bay, restricted bay, medium salinity bay, channel, and reef and reef-flank area ecosystems. In general, subsidence will permit increased circulation in all systems causing a slight decrease in extremes of salinity and temperature. In the deeper water, the disturbance of sediments by wave action will be reduced, leading to lower turbidity and increased sedimentation rate. The supply of sediments to the gulf from the bays will be reduced slightly.

Subsidence will cause little dramatic change in these systems. Increased circulation will reduce the extent of areas considered to be river-influenced bay or restricted bay, converting them to medium-salinity bay. The net change in phytoplankton productivity resulting from the opposing tendencies of increased productivity (due to improved light penetration) versus decreased productivity (due to reduced recycling of nutrients from bottom sediments) is impossible to predict at this time, but it is probably small.

Subsidence effects in coastal uplands. In coastal uplands, subsidence is expected to change drainage patterns and reduce the speed of drainage. The frequency of flooding and the level of soil moisture will increase. Near the coast, there will be increased saltwater intrusion, especially during storm tides.

Near the coast, the increased salt water and increased soil moisture may cause conversion of coastal prairie and other systems to marsh. In areas of high fresh water supply, this may be brackish marsh. Ultimately, the extent to which salt marsh, brackish marsh or tidal flats result from changes in elevation will depend on several factors, including tidal immersion, soil texture and drainage, water logging, soil salinity, and others. (The literature in this area leaves some uncertainty as to the dominant or controlling factors. Zieman and Odum (1977) suggest that plant growth is controlled by tidal inundation, with little influence by salinity. Mahall and Park (1976, Part III), however, note the exclusion of Spartina foliosa from topographically higher locations because of higher soil salinities in the growing season.)

Away from the areas of saline intrusion, poorly drained soils on coastal prairie will be converted to fresh marsh and, depending on topography, fresh water ponds. Poor drainage in agricultural areas will make cultivation difficult. Fluvial woodlands and oak mottes and groves will experience shifts in species to more water-tolerant plants, forming swamps in some cases.

Subsidence effects in fresh aquatic systems. Ecosystems considered in the fresh aquatic systems group are ponds, streams and rivers, and freshwater marsh. Subsidence is expected to increase the extent of saltwater intrusion, both as a salt wedge in normal weather and as saltwater flooding during storms. The increased water depth is expected to reduce the amount of light reaching the bottom in ponds, marshes, and streams. The present equilibrium of erosion and deposition in stream beds will be upset, causing more deposition in areas which have subsided and more erosion in upstream areas.

As fresh marshes become deeper, emergent plants will be eliminated from the deepest areas creating open ponds. Near sources of salt water, brackish marsh species will increase. As more salt water reaches coastal ponds and extends further up streams, incidence of juvenile estuarine organisms will increase at the expense of freshwater species.

Subsidence effects in shallow estuarine systems. Shallow estuarine ecosystems include brackish marsh, salt marsh, grassflats, wind tidal flats, and bay transition areas. Subsidence will increase the frequency of inundation in wind tidal flats and brackish and salt marshes, in many cases, causing permanent inundation. Greater circulation will occur, decreasing the amount of salinity and temperature variation. The deeper water will decrease the amount of light reaching the bottom and will permit further penetration of wave energy into previously shallow areas.

The importance of depth changes on the order of a few inches and the resulting frequency and duration of inundation in determining plant zonation in salt marshes is well known (see Chapman, 1960 for examples). In Texas salt marshes, the lowest levels are occupied by Spartina alterniflora; higher levels by Batis maritima, Distichlis spicata, and Salicornia sp. Further up, Monanthachloe littoralis and Borrchia frutescens are representative species. The effect of subsidence will be to shift these zones, with S. alterniflora being forced out of deeper areas and the high marsh species invading wind tidal flats, brackish marsh, or other systems. Similar shifts will occur in fresh marshes.

As the water becomes too deep for emergent plants, the type of system which takes over will depend on such things as substrate type, wave energy, and water turbidity. Low wave energy will tend to favor development of grassflats. Otherwise a bay transitional area with only sparse seagrasses will probably develop.

Grassflats are found mainly in depths of 1 to 5 feet (0.3 to 1.5 m), with a definite vertical zonation of species. Increased water depth will cause loss of the deepest areas due to reduced light penetration, with species changes in the other areas, and encroachment on marshes in the shallows.

Vegetation on wind tidal flats is limited by a number of factors, including soil salinity. Increased frequency of submergence will permit the development of salt or brackish marsh plants, with grassflats or bay transitional areas in the deeper locations.

Effect of subsidence on barrier islands. In addition to those ecosystems discussed previously, barrier islands have beach and dune systems which are extremely important. Subsidence will increase the rate of shorefront retreat and the frequency of hurricane washover. Saltwater flooding will increase around the bay to some extent. Longshore sand transport through the newly subsided area may also be out of equilibrium with the neighboring coastline.

Although the average width, and thus area, of beach ecosystem will be reduced, the major impact will be due to increased hurricane washover. Sediments carried over the barrier island during a washover cover and eliminate grassflats and salt marshes on the bay sides of the islands, while shoreline retreat eliminates dune and barrier flat ecosystems. Although these systems may recover to some extent between storms, the net result is decreased productivity.

Subsidence effects in the Matagorda fairways. These fairways involve the Colorado River delta, Caney Creek, and East Matagorda Bay. There are large areas of brackish marsh and salt marsh with numerous streams and fresh to brackish ponds. East Matagorda Bay is considered a restricted bay: the small inlet connecting it to the Gulf of Mexico is outside the geothermal prospect area.

The greatest impact of subsidence would probably be expansion of brackish and salt marsh into adjacent coastal prairie and fluvial woodland. Additional coastal prairie and fluvial woodland areas would be converted to fresh marsh and swamps. Shoreline retreat rates along the Gulf of Mexico beach in the eastern prospect area, which are already high, would be increased.

Subsidence effects in the Corpus Christi fairway. The Corpus Christi fairway includes parts of Corpus Christi Bay, Redfish Bay, Aransas Bay, Port Bay, Mustang Island, Harbor Island, St. Joseph Island, and the mainland. Significant areas of grassflat, salt marsh, bay transitional area, wind tidal flat, medium salinity bay, coastal prairie, and oak mottes and groves ecosystems are present.

The greatest impact of subsidence would probably be felt in the grassflat, salt marsh, wind tidal flats, and bay transitional areas. Moderate subsidence could permit the extension of grassflats over areas which are presently wind tidal flat, with some loss of grassflats in deeper areas. A detailed study of existing topography would be required to determine the net balance of ecosystem changes.

Shoreline retreat would increase on the barrier islands, with increased chance of hurricane washover. This would be especially important biologically on St. Joseph Island, which does not have well developed dunes and already has large washover areas. It could also be of great economic significance to the resort community of Port Aransas.

On the mainland, oak groves and coastal prairie areas would receive more frequent saline intrusion, possibly converting these areas to salt marsh or to wind tidal flats.

Subsidence effects in the Brazoria fairway. The Brazoria geothermal fairway extends from the Brazos River to Galveston Bay and includes most of West Bay plus Chocolate Bay and Bastrop Bay. Most of the area is coastal uplands, but large areas of brackish and salt marsh exist along West Bay. There are also numerous fresh to brackish ponds and streams.

In general, subsidence will favor expansion of salt marshes along West Bay into brackish marshes with expansion of open water areas. Brackish marshes will encroach on present coastal prairie to some extent. Deepening will produce little change in West Bay, because it is already well mixed.

Agricultural areas, which are predominantly planted in rice, will experience additional difficulties in drainage control. Inland coastal prairie areas will probably experience expansion of fresh marshes.

Fault Activation and Induced Seismic Activity

Fault Activation. As defined by Gustavson and Kreitler (1976), fault activation is the initiation or acceleration of movement along a fault, or fracture, in the earth's crust. A fault is an indication of unequal relative movement or "displacement" of adjacent rock masses separated by the fracture. Surface expression of a fault, the "fault trace," typically ranges from an obvious topographic escarpment or "fault scarp" to a poorly indicated geomorphic "lineation." A lineation is a subtle linear topographic feature of geologic origin (Kreitler, 1976). In the Gulf coastal region, a fault observed at the land surface or at a shallow depth is generally formed by the upward extension of a preexisting fault in older, deeper strata.

Normally, natural movement along these faults is so gradual that detection may be very difficult. Activation of the fault implies an increase in the rate of movement on at least one side of the fault. Movement at the surface tends to exaggerate topographic relief across the fault.

Occurrence. Faults are common features of the Gulf coastal region, both surface and subsurface (Hardin and Hardin, 1961). Natural adjustments within the unconsolidated sedimentary deposits that underlie the coastal plains and coastal waters have produced an extensive network of faults, many of which are apparently active today. Superimposed on these natural faults are effects of man's activities which enhance faulting. In all, over 7,000 miles (11,263 km) of surface fault traces and lineations have been mapped along the Texas coast (Kreitler, 1976).

Natural fault movement represents only a limited hazard for geothermal development in coastal Texas. Movement along these faults is extremely slow, and careful aerial photo reconnaissance effectively detects faults in this area. Faults so identified can generally be avoided during facility siting (Kreitler, 1976).

Causes of fault activation. Of greater concern are the faults which are influenced by coastal development. Acceleration of fault movement in the Houston area has caused extensive structural damage at some locations. The principal cause of this accelerated displacement is directly related to heavy demands on groundwater resources (Kreitler, 1976).

Fault activation on the Texas Coastal Plain may be brought about by geothermal resource development in at least three ways:

1. Fluid withdrawal from a fault-bounded geopressed reservoir may cause compaction that is then transmitted along the fault to the surface.
2. Injection of fluids into the geothermal reservoir, or into permeable beds at shallower depths, may cause overpressuring and hydraulic lifting of the overburden along a fault.
3. Induced seismic activity may cause liquefaction of easily disturbed clay strata, promoting movement along faults.

Fault activation on the Texas Coastal Plain is very often the result of groundwater withdrawal or oil and gas production. The activation process is identical to production-related subsidence. Extensive withdrawal of fluids (potable water at shallow depths, liquid or gaseous hydrocarbons, or deep geothermal brines) from confined reservoirs reduces pore pressures, causing compaction of the reservoir rocks and/or associated strata. When the reservoir is bounded by faults, forming what is called a "fault block," the faults often serve as hydrologic barriers, preventing movement of fluids across the fault. For this reason, fluids which are outside the reservoir either cannot reoccupy pore space in the reservoir rocks or are unable to do so at a rate sufficient to prevent compaction after the reservoir fluids are withdrawn. The resulting compaction is, therefore, confined to the fault block, so that movement along one or more of the bounding faults is increased. When these faults extend to the surface, a lineation or a scarp may form or gain prominence.

Effects of fault activation. Producing geopressed geothermal reservoirs along the Texas coast will most often be found within fault blocks (Gustavson and Kreitler, 1976). Fault activation at some production sites is, for this reason, quite possible. The rate and cumulative extent of fault movement at a given location is closely related to local subsidence.

Surface effects of faulting include damage to buildings and other structures and to installations such as pipelines. Awareness and detection of surface faults and proper facility siting offer effective means to prevent serious damage.

Induced Seismic Activity. Seismic activity is detectable vibration in a part of the earth's crust, usually described as an earthquake or earth tremor (American Geological Institute, 1962). The Gulf Coastal Plains of Texas are generally considered to be virtually aseismic (Coffman and von Hake, 1973; Sheets, 1947). That is, no appreciable earthquake activity is expected in the area. However, the low frequency of natural seismic events has in recent years been overshadowed by man-induced seismic activity. Three potential causes of earthquakes which may be important along the Texas coast are:

1. Fluid withdrawal from geopressured-geothermal reservoirs
2. Disposal of spent geothermal brines by deep reinjection
3. Impoundment of artificial lakes

Each of these causes and their relative importance is summarized below.

Fluid withdrawal from geopressured-geothermal reservoirs. The major potential cause of earthquakes resulting from geothermal resource development on the Texas coast is fluid withdrawal. Atherton et al. (1976, v. 2) reported eight discrete earthquake events in coastal and east Texas, and seven others in nearby areas of Louisiana and Oklahoma, which were clearly or possibly associated with fluid withdrawal at oil and gas fields. These earthquakes ranged in intensity from II to V on the Modified Mercalli scale. A rating of V is used to indicate the minimum magnitude at which slight structural damage may be experienced (Wood and Neumann, 1931). Geothermal resource development would require extensive withdrawal of groundwater from densely spaced wells.

While neither the frequency nor the magnitude of earthquakes reported by Atherton et al. was great, the fact that they would be experienced at all in the Gulf coastal region is surprising. No major repositioning of the earth's crustal "plates" such as that presently occurring in California has been detected in coastal Texas. In addition, geologic strata underlying the Texas coast are largely "unconsolidated" and exhibit a somewhat plastic response to deformation. The sudden release of energy which characterizes earthquakes in other parts of the world is generally not observed in this area.

For this reason, slow but continual faulting along much of the Texas coast is common, but seismic activity remains comparatively rare (Brown et al., 1974). But the occurrence of even rare man-induced seismic activity suggests the activity of geologic processes, the significance of which is not limited to earthquakes. Earthquakes triggered by fluid withdrawal may thus serve as indicators of more important effects such as acceleration of subsidence and fault activation.

Deep reinjection brine disposal. Fluid reinjection may be required as a means of disposing of the toxic groundwater that would be produced at geothermal wells. Reinjection may also be used to enhance production and has been suggested as a means of retarding subsidence.

Few examples of increased seismic activity resulting from fluid reinjection are known. Healy et al. (1968) provided an account of radioactive waste isolation measures at the Rocky Mountain Arsenal Disposal Well in Colorado from 1962 to 1966. Approximately 165 million gallons of liquid waste were pumped into permeable strata at a depth of 12,000 feet (3,658 m). Shortly after injection began, small earthquakes were recorded from the vicinity of the arsenal. Earthquakes continued in the area even after injection was curtailed. Results of seismic monitoring efforts have confirmed that the earthquakes were induced by deep fluid injection. Healy et al. (1968) also described earthquake inducement by water injection to enhance oil recovery at a site in western Colorado.

Impoundment of artificial lakes. The third cause of earthquakes to be dealt with here is impoundment of artificial lakes. This effect has been noted in many areas of the world (NAS-NAE, 1972). Impoundment-induced earthquakes have also been observed in the general area of the Texas Coastal Plains. Henley (1966) reported several minor seismic events following impoundment at two East Texas reservoirs. These seismic events probably resulted from surface loading. Substrate in the area of each reservoir consists of loosely consolidated sedimentary rock. As the weight of impounded water increased with reservoir depth, stress on the flooded substrate very likely induced consolidation. In addition, water may have penetrated the submerged strata, lubricating fractures and enhancing minor movements. Readjustment of the substrate to the stress produced by inundation probably triggered these minor earthquakes (Bolt et al., 1975). Similar instances of seismic activity can probably be expected at any newly constructed reservoir on the Texas Coastal Plain.

Reservoir-induced earthquakes are not directly related to the development of geopressured-geothermal resources in Texas. However, the possibility of their occurrence should be considered when siting facilities for developing geothermal resources.

Effects of induced seismic activity. The possible importance of seismic events in coastal Texas may not be limited to direct structural damage. Woodward-Lundgren and Associates (1974) stated that one cause of fault activation with at least theoretical importance is the spontaneous liquefaction of so called "quick clays." The clays have a highly unstable structure consisting of weakly bound layers. Vigorous, prolonged vibration such as that produced by intense earthquakes disrupts this structure, temporarily suspending the disaggregated clay particules in their "interstitial" water. The result is instantaneous "failure" of the incompetent clay mass. The clay may then flow like a liquid under the force of gravity or a small confining pressure (Youd, 1973). Movement of faults along failed clay strata could be significantly accelerated.

Although clays of a type similar to those described by Youd are present in thick beds along the Texas coast (probably in association with geopressured reservoirs), no known instances of liquefaction because of earthquake activity in the Gulf coast region were reported by Woodward-Lundgren and Associates (1974). An awareness of this potential hazard should nonetheless be reflected in the siting process for geothermal energy facilities.

In summary, there is no clear indication that geothermal resource development along the Texas coast would either result in or be seriously affected by induced seismic activity. Little data are available on which to deny absolutely the possible occurrence of a significant earthquake. Drilling experience throughout the Gulf coast region has, however, failed to indicate an important increase in seismic activity in conjunction with either fluid withdrawal or injection flooding. Impoundment-induced earthquakes are localized and have low intensities. Although small earthquakes from all causes are probably more common than is indicated by published accounts, the seisms are probably less important as hazards than as indicators.

Compilation of a detailed seismic history of prospective geothermal development areas and continuous seismic monitoring could indicate linked responses

between changing fluid pressures at depth, compaction, subsidence, fault activation, and seismic activity. Earth tremors could then be used to anticipate important changes in reservoir geohydrology, so that appropriate actions could be initiated. Seismic data, combined with other information on dynamic reservoir behavior, would be a useful tool for management of geothermal resources.

Subsurface Contamination

Contamination of Other Producing Horizons. For this discussion, contamination of other producing horizons is the introduction of geothermal brine into economically important substances. These substances include oil and gas or mineral (such as sulfur and halite or rock salt) deposits from which materials are being extracted (or could be extracted, using existing technology).

Geopressured-geothermal reservoirs underlying the Gulf Coastal Plains may be reached only by drilling through an overburden as much as 3½ miles (5.6 km) thick. The stratigraphic section represented in that overburden may include formations containing potable groundwater and valuable minerals or hydrocarbons. When these formations are penetrated by geothermal wells, contamination of the resources by brine becomes a threat.

Drilling, production, and reinjection for geothermal development can affect the recoverability of geologic materials in penetrated strata. High-pressure brine may escape the geothermal well (production or disposal) and enter other formations, either along fault systems or wherever the rock is sufficiently permeable. These flooded beds may then be more difficult to produce. Water, particularly dense brine, would displace the lighter hydrocarbons, and could contaminate solution mining operations for sulfur or salt.

No well documented examples of interformation brine contamination of recoverable minerals or hydrocarbons in Texas were found during a brief literature survey. However, Hamilton and Meehan (1971) reported the "breaththrough" of reinjected brine into producing wells from damaged disposal wells at the Inglewood Oil Field in California. Texas Railroad Commission rules (051.02.02.009E-1) expressly forbid brine disposal in a manner which "will cause damage to oil, gas, or geothermal resources, or fresh water resources."

The Texas coastal region is a major source for a wide variety of valuable geologic materials. Potential effects of geothermal brine production on the recovery of these materials must be considered whenever these resources occur in proximity to the geothermal production.

Potable Groundwater Contamination. Potable groundwater is subsurface water contained in a producible aquifer which can be rendered suitable for human consumption by ordinary treatment practices. An aquifer containing potable groundwater could become contaminated if foreign substances were introduced in concentrations sufficient to degrade water quality below an acceptable standard. Geothermal brine and other saline waters are potential contaminants which could enter an aquifer along faults, through failing well casings or uncased intervals, from contiguous

strata, from other portions of the aquifer, by infiltration from the surface, and by other means.

In the Texas coastal region, potable groundwater can generally be found at depths of less than 1,000 feet (305 m) (Wood et al., 1963). Shallow aquifers throughout the region provide most of the potable water for large municipalities and industries, and part of the water needed for irrigation agriculture. (Texas Water Development Board, 1970). Contamination of potable groundwater supplies would thus have serious consequences anywhere in the area.

Development of the geothermal resources of the Frio Formation could adversely affect potable groundwater supplies in several ways:

1. Toxic brine from an underground leak in a geothermal well could migrate along faults and through porous zones into freshwater aquifers.
2. A blowout, a leaking or ruptured pipeline, equipment failure at a well or generating plant, or other accident at a geothermal facility could release brine at the ground surface or into surface water.
3. Excessive withdrawal of fresh groundwater to provide cooling water for the geothermal plant could encourage seawater encroachment.

Underground leaks. Drilling pipe, production or injection casing, or cement plugs (in abandoned wells) may corrode or rupture below ground under stress. There is a high probability of pipe, casing, or plug failure over and beyond the life of a production or disposal well. Oil field brines and other saline groundwater have been responsible for many such failures (Krieger, 1961; Webster, 1971; and White, 1970, 1973). Hot, hypersaline water under high pressure is extremely corrosive, making permanent containment of geothermal brine even more difficult.

Subsidence and fault activation may also contribute to well failure and underground brine discharge (Hamilton and Meehan, 1971). Faulty injection wells have even been observed to overpressure the disposal beds, so that fluids migrated into freshwater aquifers (White, 1973) or to the ground surface along faults (Hamilton and Meehan, 1971).

Blowouts, pipeline leaks or breaks, equipment failure, or other accidents. Blowouts, pipeline leaks or breaks, equipment failure at wells or at the generating plant, and other accidents may release particularly large quantities of brine above ground. The brine can then enter surface waters directly or through the surface drainage network. Brine may also permeate the soil and overburden and enter potable groundwater reservoirs. Where aquifers lie at or just below the surface (recharge areas), the probability of significant brine contamination from the surface is quite high. The area affected could be limited, however, if the discharge were detected near its source.

Blowouts may produce a wide range of environmental effects. A blowout may damage the pipe or casing, allowing penetration of reservoir fluids into the freshwater aquifer. High concentrations of natural gas were detected in shallow water wells following two blowouts at a nearby gas well in Jackson County, Texas (Ginn, 1973). Brine contamination may represent an even more serious problem. Geothermal brines

are under high pressure and have densities much greater than fresh water. These highly saline waters could easily displace fresh groundwater which would be under hydrostatic pressure only.

Excessive withdrawal of fresh groundwater. An efficient cooling water system for a geothermal power plant may necessitate use of fresh to slightly brackish water. If this water is delivered from wells drilled into shallow coastal aquifers, local groundwater supplies could be impaired. Cooling water needs at a geothermal plant vary in quantity and quality for different types of plants. Projected water needs in an electrical generating plant are 100 acre-feet per year per megawatt of continuous generation (Rios-Castellon and Underhill, 1976).

Excessive rates of withdrawal to provide cooling water could lower water levels in the aquifer and reduce fluid pressures. Fluid pressure reduction has the potential to cause subsidence and saltwater intrusion and to limit or interrupt the water supply to other users. Reduction of the water supply at the depth of wells operated by other users of the aquifer can generally be avoided by proper assessment of the resource and continued monitoring. The problem can become more severe, however, in areas where fresh groundwater is scarce.

Saltwater intrusion is a very serious concern in coastal areas. Often, coastal aquifers may be continuously infiltrated or "charged" with seawater. Saline and fresh groundwater may thus occur in close proximity within the same aquifer with little mixing. This condition is ubiquitous along the coast and threatens seawater contamination of freshwater resources.

The interface between these waters shifts seaward or landward, depending upon the relative pressures of the salt and fresh waters. Normally, freshwater pressures in the aquifer are sufficient to expel the heavier salt water from inland sites. However, when fresh water is removed from the aquifer for use or when fresh water flowthrough is otherwise interrupted, salt water may encroach inland (Ballentine et al., 1972). A comparable problem can exist along canals dredged inland from coastlines (Jorgensen, 1977).

Hydraulic Lifting

Hydraulic lifting is the process whereby a portion of the earth's crust may be elevated by excessive subsurface fluid pressure. Excessive pressure can be caused by injecting a fluid at high pressures into permeable strata. When the fluid is injected faster than it can be distributed through the reservoir matrix, pressures will increase. The reservoir may then become locally overpressured, such that hydraulic forces within the matrix are greater than the vertical force of the overburden. The reservoir then "lifts" the overburden. Under certain conditions, the lifting effect may be felt even at the surface. Disposal of spent geothermal brines at reservoir (or shallower) depths could, at least theoretically, cause hydraulic lifting.

Effects of Hydraulic Lifting. Hydraulic lifting may have two important effects at the land surface: (1) "rebound" or a generally uniform increase in elevation over a

comparatively large surface area; or (2) differential (upward) movement along a fault. The latter effect is analagous to fault activation. Only a few detailed accounts of hydraulic lifting are available. However, each of these effects has been observed in connection with reservoir injection programs.

Gates et al. (1977) reported that attempts to retard production-related subsidence at the Wilmington Oil Field in California had in fact resulted in hydraulic lifting. Brine that had been extracted with the oil was supplemented with saline groundwater from a shallow aquifer and reinjected into the petroleum-producing reservoir. This flooding program arrested subsidence at the oil field and eventually resulted in surface rebound of as much as one foot at some sites. Reinjection also enhanced oil recovery and provided an apparently safe means of disposing of a large volume of oil field brine. The area had long been the scene of subsidence and no additional structural damage was attributed to the rebound. However, more serious consequences might have been expected in a different setting.

Hamilton and Meehan (1971) described quite different results of a reinjection effort at the Inglewood Oil Field in California. Reservoir flooding (brine reinjection) was undertaken at roughly the same time as similar efforts at the Wilmington Oil Field as recounted above. Injection at the Inglewood field was successful in improving oil recovery. However, many technical difficulties were experienced, including well maintenance problems (such as casing failures), "breakthroughs" of injected brine into oil producing wells, and surface leaks of injected brine.

The most serious problem associated with fluid injection measures at the Inglewood field was differential lifting, causing exaggerated movement along a surface fault.

Occurrence on the Texas Coast. No recorded occurrences of hydraulic lifting in Texas could be found during a brief, intensive literature search conducted for this study. Depth to the geopressedured zone would make such an occurrence unlikely in response to flooding of the Frio Formation. However, Woodward-Lundgren and Associates (1974) stated that injection of waste fluids "into deep disposal wells in the Texas coastal area (have) a potential to lift the ground surface hydraulically and cause differential surface displacement." These authors advised careful well siting practices, including estimation of the potentially lifted area as a means of preventing structural damage in the vicinity of injection wells.

While the importance of hydraulic lifting in deep reinjection programs has not yet been demonstrated in Texas, consideration should be given to this hazard in designing waterflood programs and selecting disposal well sites.

Prediction of Subsidence and Fault Activation

Subsidence and fault activation, often man-induced, represent significant environmental hazards in the Texas coastal region. Production of shallow groundwater and of deeper oil and gas reserves has greatly accelerated modest rates of natural

subsidence and fault movement along much of the coast. Development of geothermal resources may increase the severity of this already threatening problem.

Because geothermal resource development could further accelerate subsidence and fault activation (in urban as well as rural areas), methods for accurately predicting these effects have been sought. These methods should provide estimates of the:

1. Rate and maximum amount of subsidence
2. Size of the area potentially affected
3. Total amount of displacement which can be expected along a fault
4. Width of the zone affected by the fault
5. Activation of previously immobile faults

The predictions should be based on defined geohydrologic properties of the area in question and should not have inordinate requirements for data and data manipulation.

As observed by Hubbert and Rubey (1959), any departure from hydrostatic pressures in a groundwater reservoir represents a disturbance of equilibrium conditions. Since the geopressured gradient within deep Frio reservoirs exceeds hydrostatic pressures by a factor of two or more, the reservoirs may be considered inherently unstable. Fluid extraction may thus be expected to initiate some adjustment of a reservoir's pressure field, and compensation may be most directly achieved by sediment compaction. Subsurface compaction is almost certainly an antecedent condition for subsidence. The extent of subsidence is, however, controlled by other essentially independent factors, as well.

Modeling Production-Related Subsidence. A number of investigators have described the effects of compaction and other factors on subsidence, and several attempts have been made to model production-related subsidence. Atherton et al. (1976, v. 1), Finnemore and Gillam (1977), and Appel and Bredehoeft (1976) reviewed existing models and commented on their applicability for various uses. More recent models were examined during the present study.

Efforts to use these models to estimate subsidence have been hampered to date by the fact that Frio geopressured aquifers are largely untested. Therefore, the type of parametric data useful in predicting elevation losses is scarce and generally unreliable. In addition, considerable uncertainty surrounds each of the proposals for operational drilling and production programs published thus far.

Principal workers in the field attending a recent, informal workshop on production-induced subsidence reached the unanimous conclusion that the state of the art of subsidence modeling for geothermal resource development is not adequate. They concluded that "it is premature to model deep production-related subsidence (R.K. Gabrysch, U.S. Geological Survey, Houston, Texas; personal communication, November 20, 1978).

The problem in trying to devise a subsidence model is not only one of interrelating contributing factors accurately, but of even recognizing the contributing

factors, according to Gabrysch. The assumptions inherent in existing models are unrealistic, and the data needed to validate assumptions are generally unavailable. Geertsma (1973), for example, assumed simple inverse variation between expected subsidence and horizontal distance from the downhole end of the well. That is, the center of the predicted symmetrical subsidence bowl always lies above the nucleus of production. However, observed subsidence at existing geothermal fields does not consistently follow this pattern. The realities of preferential fluid migration and subsidence along faults negate Geertsma's assumptions.

Prediction Methods. Three approaches to predicting subsidence and fault activation caused by production of geopressed-geothermal reservoirs are available:

1. The analytical method
2. The empirical method
3. The analogy method.

The analytical method relies on theorems of hydrology and soil mechanics to explain reservoir behavior, compaction, and subsidence in terms of simplified equations. However, the lack of data and an incomplete knowledge of reservoir-overburden behavior limit the reliability of any analytical method presently available. This fact is important particularly with respect to the Texas Gulf geothermal fairways. Testing of the reservoir matrix and overburden has not been performed and little information can be gained from the analytical models without data on compressibility.

The empirical method uses observations of fluctuated water levels in wells to continuously recalibrate a basically analytical model. The empirical method recognizes the difficulty of obtaining the great variety of information needed for the more ambitious analytical models. For this reason, a select number of empirically determined parameters are used to constantly recalibrate the model, in the hope that the model will become a better predictor with experience.

In the case of one of these empirical models (Jorgensen, 1975), however, an inherent flaw prevents the predictions from becoming more accurate: no preferential movement of fluids or rock masses along faults is allowed. Kreitler (1976, 1977) argued convincingly that faulting is intimately related to subsidence and that a description of reservoir behavior which fails to account for this complex relationship cannot make accurate predictions. Most of the empirical models examined in the present study, because they encompassed only a few dynamic parameters, also contained visible flaws.

The analogy method seeks to compare geohydrological conditions at a prospective wellsite with conditions at a similar site which has experienced subsidence and associated faulting. An analogy is then made between the prospective site and the existing well, and a prediction of effects at the prospect site is made. When available, empirical data can be incorporated into the analogy method.

The analogy method is the most subjective of the three approaches. With this method, the overall behavior of the geopressed reservoir and its overburden is taken

into account without attempting to quantify the details of the contributing interactions. This method was used by Gustavson and Kreitler (1976) in their study of the Armstrong geothermal fairway in South Texas. The method is simple and does not fail to account for major patterns of subsidence in the coastal region. This method, too, is largely untested, however, and reevaluation of it and the other approaches may be necessary in the future.

The well histories prepared by Bebout et al. (1978) for oil and gas wells producing from the Frio Formation can be used as a basis for predicting subsidence and fault activation. Essentially, one would start with the simplest, most readily observed factors and attempt to provide an orderly appraisal of subsidence and faulting potential based on existing data. Subsidence and faulting potential would be determined simultaneously.

Management of Subsidence, Fault Activation, and Interformation Fluid Movement

Among the most serious potential impacts of geothermal development along the Texas coast are subsidence, fault activation, and contamination of economically important subsurface resources with geothermal brine. Techniques for reducing these effects or mitigating their impact are discussed below.

Subsidence. The most important factors influencing subsidence are:

1. Compaction of the reservoir
2. Compaction of the confining beds
3. Compaction of the overburden
4. Declining reservoir fluid pressures
5. Geometry of the reservoir

Little can be done directly to alter the actual geometry of the reservoir (in order to avoid subsidence in a particular sensitive area) or to prevent compaction in the overburden. However, measures to reduce or prevent compaction at depth may control overburden compaction indirectly, and well spacing can create a more favorable "effective" reservoir geometry in a large reservoir over at least part of the reservoir life. Also, careful siting of production facilities with respect to topography, to other structures and installations, and to sensitive natural environments (particularly those near present shorelines) can minimize the hazard of elevation losses. The great thickness of the overburden should limit the degree of subsidence, but it would not eliminate the effect entirely.

Compaction. Compaction of the reservoir occurs as fluids are withdrawn. Nothing can be done by direct means to prevent this effect. However, permeability-enhancement measures such as acidizing and fracturing may exaggerate the problem. These practices should be employed only with knowledge of their effect on matrix competence.

Declining reservoir fluid pressures. Reservoir compaction can be retarded by preventing the reduction of fluid pressures within the reservoir. Several techniques

to achieve this end are available. One such procedure involves scheduling production to minimize the decline in fluid pore pressures. Reducing the rate of withdrawal may meet this objective, but it could limit operations at the generating/separating plant. Increasing the number of wells, each producing at the lower rate, might restore the needed fluid throughput (volume of fluid required for efficient processing), but this practice would cost more. Cost-benefit analyses are used to establish an optimum rate of fluid production from the available wells. Additional costs would impair this relationship economically unless throughput were also increased. This would require additional fluid withdrawal, which would be unacceptable, and, possibly, additional plant capacity, a further expense.

Adjustment of the well density (number of wells per unit area at the surface) offers a similar solution to the problem of pressure loss. This option becomes somewhat more attractive if directional drilling (which also increases expenses) could be used expediently, with the objective of increasing the area over which a given volume of fluid is produced. Well spacing and distribution may also provide a means of altering the effective geometry of the reservoir. However, lower density well spacing also adds costs, for wells, mineral leases, pipelines, and support. Careful cost-benefit assessment of all options is mandatory.

Other techniques for reducing the decline in fluid pressure have also been advanced. The physical state of the fluids may be important. As described previously, recoverable fluids within the Frio geopressured-geothermal reservoirs exist in a liquid state because of high pressure and groundwater salinity which prevent a phase change (i.e., "flash" water vaporization). Methane effervescence because of pressure loss during normal production is not expected or would be negligible (Garg and Pritchett, 1977), despite reduced methane solubility at higher salinities.

Atherton et al. (1976, v. 1) recognized that the risk of subsidence may be reduced by minimizing the fluid pressure-drop per unit withdrawal of fluid mass. Based on estimates of fluid saturation with respect to temperature and pressure at depth, these authors recommend a production program designed to achieve a two-phase reservoir (liquid and steam/gas) rather than a single-phase reservoir (liquid only). Atherton et al. state that, theoretically, this result could be obtained "by simply withdrawing the fluid with no reinjection." Reinjection tends to lower the reservoir temperature, inhibiting effervescence of methane and water vaporization. Without such a temperature reduction, the desired phase change could take place as the pressure is lowered slightly when production begins.

The technical feasibility of an operation such as that described by Atherton et al. (1976) has not been demonstrated with respect to reservoirs of the type existing in the Gulf coastal region. Garg and Pritchett (1977) analyzed two-phase flow in geopressured-geothermal wells in a Frio reservoir. However, in their study, "no evolution of free methane . . . in the pores of the reservoir rocks" was assumed. Garg and Pritchett also postulated the existence of a two-phase regime "only in the cased part of the production hole." Grant (1978) demonstrated that porosity conditions would remain favorable (i.e., minimal compaction) during two-phase production. However, his findings were based on data collected at New Zealand reservoir whose

fluids existed in two phases prior to production. Furthermore, Grant assumed negligible pressure gradients and total pressure changes. Observations cited by Bebout et al. (1978) tend to refute the validity of this assumption in deep Frio reservoirs. These authors noted large pressure declines over the production histories of existing Frio gas fields not practicing reinjection. There appears to be little evidence to indicate that two-phase flow would be initiated in the Frio geopressed reservoirs.

In contrast to the proposal of Atherton et al. (1976), many authors, including Zinn (1977) have encouraged reservoir reinjection as a possible means of forestalling or offsetting subsidence. Wilson et al. (1977) state that "The surest method to prevent subsidence would be to reinject the fluids back into the producing aquifer." These authors, however, question the economic advisability of such a measure in terms of the expense of large-capacity injection pumps and additional wells for disposal. They also express considerable doubt that reservoir injection is technologically achievable. Pritchett et al. (1977), in their reservoir simulation studies, have attempted to demonstrate that a reinjection program is not only achievable but offers an economic stimulus by enhancing methane recovery, as well. They state that potentially ten times as much useful fluid can be produced over the expected life of the reservoir with reinjection than without it. These figures were reiterated by Bebout et al. (1978), who also stated that "By using the reinjection method, higher reservoir pressure and total fluid flow rates can be maintained for a longer period of time." Although both capital and operating costs of a reinjection program would certainly be higher than the cost of production without reinjection, all costs would be amortized over a longer period by extending reservoir life, and profits would presumably be higher because of greater fluid recovery. In addition, some means of disposing of spent brines would have to be found regardless of the capitalization of reservoir reinjection. The cost of an alternate means of disposal would have to be considered and would probably not be offset by any added income. A variety of environmental costs associated with subsidence and related effects of fluid withdrawal would also have to be considered (Mcseley, 1975).

The effectiveness of reinjection as a procedure by which to counteract subsidence has not been clearly demonstrated. While it is reasonable to expect reinjection to prevent or retard compaction of permeable reservoir strata, the compression and dehydration of contiguous, undercompacted shale beds may not be arrested. No direct means of preventing compaction of these shales now exists.

Control of fluid pressures is quite clearly the key to managing subsidence. Generally, comparatively high pressures would indicate maintenance of the status quo within the reservoir. The only flaw in this assumption is the dewatering effect of the shale beds.

Dewatering occurs as the shales are compacted. Much of the total compaction at the depth of the reservoir could take place within the shale beds which may have a cumulative thickness of 1,300 feet (396 m) (Gregory, 1977). However, fluid pressures within the reservoir rock would actually be maintained to some extent by this effect, which indeed has been relied upon as a condition which may help sustain reservoir

yields (Bebout et al., 1978). The objective, then, would be to prevent an initial strong decline in fluid pressure to retard dewatering and compaction and, ultimately, subsidence. Long-term economic recovery may be seriously hampered by such a measure.

The only other method of controlling fluid pressures may be reservoir re-injection. Reinjection has three primary benefits:

1. It may enhance economic recovery at the geothermal field by functioning as a "waterflood" program.
2. It would provide a means of disposing of brines which, with rigorous safeguards, might be "safer" than other available options.
3. It may help to maintain reservoir pressures and thus, to an unknown extent, discourage subsidence.

As seen in previous discussions, however, some risk and doubt surrounds each of these benefits.

Geometry of the reservoir. Careful well and facility siting (particularly with respect to proximity to water bodies), and avoidance of sensitive natural environments and areas of development would limit the potential impact of subsidence. Selective siting may offer the only feasible approach to reduction of subsidence risks, but it would not reduce the likelihood of subsidence. The land area potentially affected by a single production well could approach 50 square miles (130 sq. km) (Bebout, 1976), and several production wells would occur in proximity. In addition, most reservoirs will probably be found within fault blocks of irregular shape. Locating wells in order to restrict the risk associated with subsidence can thus become extremely complex.

Fault Activation. Factors causing fault activation are closely related to conditions which may induce subsidence. Efforts to limit or prevent subsidence would be applicable to the problem of fault activation, as well. Unfortunately, few management options seem to be available. Production of geopressured-geothermal groundwater from the Frio Formation in coastal sections of the state carries an inherent risk of accompanying subsidence and fault activation. The probability of occurrence of these effects is not accurately known, but oil and gas production from the same source beds has caused subsidence and faulting in the past, while producing at a much lower rate than is projected for geothermal wells.

Detection and avoidance of active or potentially active faults represent the most reasonable approaches to impact management. Construction of resistant structures, and even modification of existing structures to prevent fault damage may be possible. However, in most cases, advance siting may eliminate the necessity of such expensive measures. Kreitler (1976) noted that:

With the possible development of geothermal-geopressured aquifers in the Texas Coastal Zone for geothermal energy, land subsidence may occur with accompanying surface faults The potential for continued

subsidence and additional fault activation should not, however, preclude further development of (potable) groundwater resources of the Gulf Coast aquifers or development of geothermal resources. Lineations which are presently passive structural features, and which in the future may become the foci for differential subsidence and active faulting, identify these critical areas of concern. Herein lies the predictive value of lineation analysis and subsidence monitoring.

Interformation Fluid Movement. Despite the implementation of reasonable precautions in geothermal development, subsurface leaks and surface release of toxic brines may be an inevitable consequence of the nature of geothermal brines and the complexity of recovery, transmission, processing, and disposal operations. Insistence on proper installation, operation, and servicing of equipment, and use of high quality materials in every phase of development may reduce the frequency of spill occurrences. Proper monitoring and emergency procedures can prevent or mitigate serious pollution incidents to the extent possible. An awareness of the complex, dynamic geohydrologic processes involved in creating the geopressured-geothermal resources and in making production possible should be a mandatory part of any development program.

Excessive withdrawal of fresh groundwater, if needed for cooling at the processing plant, could reduce fluid pressures in shallow coastal aquifers, thereby permitting seawater encroachment. Freshwater pressure barriers have been successfully used to combat this problem in California (Rancilio, 1977) and elsewhere. Freshwater, treated sewage water, or partially deionized brackish water is injected into an encroached aquifer at a point seaward from the water supply wells, in order to exclude the intruding salt water. Fairchild and Wiebe (1977) described another barrier system used in California, which combines pumping wells with injection wells. The pumping wells are arrayed parallel to but seaward from the injection wells and are used to pump out saltwater. Pumping reduces the salt water intrusion pressure so that a smaller volume of freshwater can be used to form an effective pressure barrier. Intrusion of non-marine or other contaminant waters can also be controlled in this manner.

These methods of preventing encroachment are extremely expensive. Each injection well has only a finite life time (Rancilio, 1977), so that periodic costs of redevelopment or replacement must also be considered in devising a control program. If fresh groundwater must be used at a geothermal plant in the coastal region, careful evaluation must be made of the resource availability and the possibility of contamination due to aquifer pressure reduction.

Monitoring the Effects of Geothermal Resource Development

Major impacts of geothermal resource development in the Texas coastal region include subsidence, fault activation, and contamination of important underground resources (including potable groundwater). These effects may be largely unavoidable even when sound engineering practices are carefully followed. The objectives of conscientious development are (1) to reduce the frequency and/or severity of impacts

through careful planning and design execution; and (2) to ensure early detection and accurate assessment of those effects which are felt, in order to improve mitigation efforts. Resource and impact monitoring can play important roles in meeting these objectives.

Monitoring techniques will vary with the type of impact and the environmental setting. This section discusses procedures which may be useful in monitoring subsidence, fault activation, and interformation fluid movement.

Subsidence. Two types of monitoring would be most useful in evaluating subsidence: aerial surveys and ground surveys.

Aerial surveys. Aerial photography would provide a record of surface features useful in siting geothermal facilities. These photographs would also be useful in establishing a reference datum of conditions at the site prior to development, against which later alterations could be compared. A time-series of large-scale aerial photographs would probably be most useful for this purpose. Positions of surface faults and lineations (which might correspond to faults intersecting the geopressed reservoir, possibly forming reservoir boundaries), apparent relief along faults, proximity of important surface features such as structures to water bodies, distribution and apparent vigor of natural vegetation, and many other features could be readily detected and changes could be noted. Low-altitude, high-altitude, and satellite imagery could be used in various applications. A slightly more exotic type of aerial survey which could prove useful is precision laser ranging from a satellite to land targets of known elevation (Kahn and Vonbun, 1976).

Ground surveys. Ground surveys would consist primarily of establishing and periodically checking a dense network of topographic benchmarks. Local changes in elevation would be noted with accuracy and could be used to indicate differential subsidence (which may be a precursor of fault activation). Time-series observations of groundwater levels in wells in shallow freshwater aquifers could also be made. These data can be used to monitor subsidence attributable to shallow groundwater production (Sato and Watanabe, 1976).

Specialized procedures for determining thickness changes in strata comprising the reservoir overburden have been developed by several investigators, as described by Atherton et al. (1976, v. 1) and Gabrysch and Bonnet (1975). These procedures may be adaptable for use in studying subsidence related to production from the deep Frio Formation.

Fault Activation. As with subsidence monitoring, detection and measurement of faulting would draw upon two primary data sources: aerial surveys and ground surveys. Data needed from aerial surveys for fault monitoring would be identical to those required for subsidence monitoring. Kreidler (1976) indicated that lineations and faults can be mapped easily using enlarged aerial photographic mosaics. The relative displacement along a fault may also be suggested by changes in relief through time, as seen in sequential aerial photographs. Accurate location of faults and lineations is important in the siting of new structures and other facilities, and to identify existing structures which could be affected by fault activation. Woodward-Lundgren and Associates (1974) found that black and white stereo-aerial photography,

color infrared imaging, and thermal (emitted) infrared imaging, were suitable for detection of faults on the Texas Coastal Plain, but that low-sun-angle photographs and side-looking radar images were not.

Ground surveys for fault monitoring would use the same benchmark network needed for subsidence monitoring. In addition, tilt-meters (which indicate changing relative relief) and observation trenches across suspected faults have been used to monitor or detect fault movements, although Woodward-Lundgren and Associates (1974) did not evaluate these methods favorably.

Interformation Fluid Movement. Escape of toxic geothermal brines from production and disposal wells (both below ground and at the surface), transmission pipelines, and the processing plant could adversely affect shallow potable groundwater and mineral- or hydrocarbon-producing formations in the subsurface. Consequences of such accidents could be quite serious economically and in terms of public health and environmental quality. Two approaches to detection and monitoring of contamination are: (1) monitoring at the geothermal facility and (2) detection in affected freshwater, oil, gas, Frasch sulfur, or solution brine wells.

Little direct effort on the part of the geothermal energy developer would be required to detect problems in neighboring wells. These operators would observe and quickly report the existence of brine contamination if present. The geothermal producer should, however, develop a contingency plan by which to respond effectively to such reports.

The geothermal resource developer and his contractors do have a responsibility to continually monitor fluid pressures, fluid composition and temperature, flow rates, and other production parameters, at the wellheads, pipeline pumping stations, and the generating/separating plant. Inspections and pressure tests of systems for brine conveyance should be routine. Monitoring wells may be located at a distance from the geothermal facility to detect brine losses.

WATER CONSUMPTION, AIR EMISSIONS, AND NOISE

During the analysis of unique environmental aspects of geothermal resource development, water consumption, potential air emissions, and noise were identified by several sources as having potentially serious effects. Due to the lack of widespread experience in geopressured-geothermal resource development, the probability or magnitude of these effects is uncertain, particularly as they relate to Texas resources.

The purpose of this section is to present a collection of existing information on these three aspects of development and to make a preliminary judgment (to the extent allowed by existing information) concerning the probability for serious ecological effects.

Summary of Analysis

In summary, water consumption can be a problem associated with geothermal development. Depending on cooling technique, water requirements for a 50 MW plant may range from 38 acre-feet-MW-year to 113 acre-feet-MW-year (Underhill et al., 1976). Depending on reservoir temperature, water requirements will vary from 2070 acre ft./yr./MW (300° C) to 4950 acre-ft./yr./MW (150° C) (Goldsmith, 1978). In areas of scarce groundwater resources, it will be necessary to consider water consumption in the design of the plant.

Studies to date indicate that it is unlikely that H₂S emission will cause significant ecological or health effects, but its odor presents a major nuisance that is unacceptable to the public (USDOE, 1978). The other problem with H₂S is its corrosive properties. Currently, it appears that the most effective method of hydrogen sulfide abatement is injection of oxygen into the brine as discussed in Wilson et al. (1977).

Noise will be a factor during some phases of all geothermal development. Noise levels during different phases of development will range from 40-100 dBA. The average noise level, however, should not be substantially different from natural noise levels along the Texas Gulf. Ecological effects of noise on animals may include disruption of hunting, defense, breeding, rest, hibernation, and/or migration. There is evidence that noise may compress the territories of breeding birds and that certain species may increase in numbers in noisy areas. Additional research is needed to determine the extent to which species can be "conditioned" and to establish definite, direct effects of noise.

Detailed Discussion

Water Consumption

Of the major environmental concerns associated with geothermal development, the Department of Energy has stated that airborne emissions and water use may have research findings adverse to unrestricted commercialization. The amount of water required for development of geothermal energy production depends largely on plant design. For example, a binary cycle plant design would require twice as much cooling water as other types of plants.

Large quantities of cooling water may be required for efficient electric power generation. One MW of continuous power could require as much as 100 acre-feet of cooling tower makeup water per year.

Cooling water can be provided to a geothermal site in three ways:

1. A "once through" cooling system, in which external water, frequently from a river or lake, is used once for cooling and then discharged to its source (direct transfer of heat to a body of water)

2. An evaporative cooling tower, in which the external water is evaporated to the atmosphere
3. A dry cooling tower, in which the fluid is cooled by air and continually circulated in a closed system (direct transfer of heat to the atmosphere)

The water requirements for these systems vary widely. Once-through systems and wet cooling towers require substantial amounts of water. Dry cooling towers require very little water.

For a flash-steam system using once-through cooling, the amount of cooling water will range from 4950 acre-feet/year/MW if the reservoir temperature is 150°C to 2070 acre-feet/year/MW if the reservoir temperature is 300°C (Goldsmith, 1978). The water typically rises 20°F (6.6°C) while passing through the condensers.

In some existing plants, condensation steam is used to make up water in the cooling towers. Thus, there is not a supplemental cooling water requirement. However, there is a net withdrawal of fluid from the geothermal reservoir. If this presents a problem, either the condensate must be reinjected or supplemental water will be required for reinjection. The supplemental water requirements will approximate the steam rate. For every pound of steam condensed, about one pound must be evaporated in the cooling tower (Goldsmith, 1978).

In addition, the condensate is essentially distilled water which has an industrial value for boiler feed water and other process use of over \$2 per thousand gallons. It may, therefore, be more desirable to sell the condensate and use water of lesser quality, such as treated sewage effluent, brackish groundwater, or another raw water source for cooling.

If the salt content of geothermal brine is low, the cooled brine could be used as cooling tower make-up. Water with a high salt content would not be feasible for cooling tower make-up because of salt content in the spray from the cooling tower. If saline water is used for once-through cooling with cooling ponds, the ponds should not be placed in groundwater aquifer recharge zones. If such ponds are located elsewhere, they will nevertheless require liners and leakage detection systems. Other concerns of cooling tower water content are hardness, pH, organic substance, dissolved solids, and nutrients found in the water.

Finally, dry air cooling systems, which do not evaporate any water in the cooling process, can be used. Although these systems would eliminate the need for cooling water, the energy penalty associated with dry cooling systems is large. In the case of a low-temperature process such as geopressured-geothermal energy, the penalty could be as high as 25 percent due to decreased thermodynamic efficiency and energy requirements of the dry cooling system. In addition, the capital costs for such a cooling system are several times higher than for a "once-through" cooling system or an evaporative cooling tower.

The selection of cooling system will depend, in part, on local climate conditions. Table 10 shows water requirements for alternative cooling techniques. The calculations were made on the assumption that the average year temperature would

Table 10

ESTIMATED WATER REQUIREMENTS FOR ALTERNATIVE COOLING TECHNIQUES**
FOR 50 MW(e) [NET] ELECTRIC GENERATION (GEOTHERMAL)

Cooling Technique	Water Requirements			Land Acres
	Thru-Put (Gal/MWH)	Consumption (Per MW)		
		Gal/MWH	Acre-Feet MW-Year	
Once Through	225,000	1384	38	0.0
Cooling Ponds	225,000	1395	39	420
Wet Towers	225,000	4219	113	3.0
Dry Tower	0	--	--	4.5

* Research is being done in order to find a model that will identify the optimum fluid (mixture) for a given reservoir temperature. Fluid properties are evaluated using Starling, 1973.

** Cooling water requirements are based on projections made from data concerned with the cooling water requirements used in geothermal plants in California, with appropriate correlations for the Texas Gulf Coastal Plain climatology and expected geothermal fluids quality. Adapted from Fulton, 1974, and Underhill, 1975.

SOURCE: Rios-Castellon, L. and G. K. Underhill, In: Underhill, et al. 1976

be 70°F (21°C), with a minimum winter temperature of 20°F (6.6°C), and a maximum summer temperature of 105°F (40°C). This temperature range is the annual range expected in the Texas Gulf coast.

Hydrogen Sulfide Emissions

Much of the natural sulfur content of geothermal waters can occur in the sulfide form. It appears that most geothermal wells, especially those already in production in California, will contain appreciable amounts of hydrogen sulfide (H₂S). Hydrogen sulfide is highly corrosive. The potential corrosion of electrical transmission lines, turbine equipment, and power generating equipment are problems which make control of hydrogen sulfide highly desirable. Hydrogen sulfide presents an environmental and odor hazard as well.

The major contribution of air pollutants during the exploration phase of geothermal resources would be the gases and vapors released during drilling and testing of wells. During the operational phase, hydrogen sulfide is carried along with the steam when flashing occurs. Emission controls should be quite effective for condensable and some reactive gases and vapors. In nonflashing systems, such as a binary fluid system, the sulfide may not escape from the water and could be reinjected.

H₂S concentrations in geopressured fluids range from 1.0 ppm in New Zealand to 61 ppm in condensate in Castle Rock Springs, California (Gustavson et al., 1977). Data are available on hydrogen sulfide content of geothermal steam and the problems associated with the H₂S in the steam (Harvey et al., 1976; Wilson et al., 1977; Li et al., 1976). Geothermal steam data may not be relevant to Texas geothermal fluids, however. Samples of formation waters from the Gulf coast indicate an H₂S concentration from the Gardiner #1 well in Brazoria County of .32 mg/l (0.32 ppm). Table 3 in the discussion of brine discharges shows chemical composition of selected formation water from the Texas Gulf coast.

The California standard for ambient air is 0.03 ppm, based on an average odor detection limit. The federal government has a standard emission limit, not an air quality standard. The Occupational Safety and Health Administration (OSHA) standard emission limit is 10 ppm average (20 ppm max) for an eight-hour exposure (Wilson et al., 1977). Figure 3 shows the physiological effects of H₂S on humans.

The hazard from hydrogen sulfide to aquatic life is often localized and transient. Fish exhibit a strong avoidance reaction to sulfide. If fish encounter a lethal concentration of sulfide, there is a reasonable chance they will be repelled by it before they are harmed if there is an escape route open (Jones, 1964). Water containing concentrations of 2.0 mg/l undissociated H₂S would not be hazardous to most fish and aquatic life, but concentrations in excess of 20 mg/l would constitute a long-term hazard (USEPA, 1976).

Investigations of the effects of low levels of H₂S on vegetation suggest that there will be no damage to natural ecosystems unless ambient hydrogen sulfide

Figure 3

PHYSIOLOGICAL EFFECTS OF HYDROGEN SULFIDE

SOURCE: USEPA, 1977b

concentration exceeds 100 ppb for weeks at a time. However, few native plant species have been tested; there may be some components of the natural vegetation, such as lichen, that are highly sensitive to hydrogen sulfide (Leitner, 1978).

Long-term accumulation and effects of hydrogen sulfide on ecosystems are unknown. Many data on toxicity of hydrogen sulfide to fish and other aquatic life have been based on extremely short exposure periods (USEPA, 1976). Sulfide criteria for domestic or livestock water use have not been established because the unpleasant odor and taste would preclude use of the water at hazardous concentrations. Presently available data indicate that vegetation damage due to low concentrations of H_2S will not occur as a result of geothermal operations, but more research is needed to confirm this with additional species and to examine synergistic effects of H_2S with other pollutants. Effects of exposure to low levels of H_2S on human health have not been demonstrated (USEPA, 1977b). Axtmann (1975) states that in a liquid-dominated site such as Wairakei, New Zealand, atmospheric H_2S emissions appear less an environmental issue than one of industry hygiene. The Department of Energy has stated that some studies show that it is unlikely that hydrogen sulfide emission will cause significant ecological or health effects. In addition, even with reliable data on effects of certain concentrations of H_2S , valid sulfide analyses of geothermal fluids are sparse and unreliable due to the difficulty of in situ sampling.

Current technology in H_2S abatement may need to be improved to adequately control H_2S in waste streams (USEPA, 1977a). Many hydrogen sulfide abatement techniques have been studied. Some of these techniques are:

1. Direct oxidation of hydrogen sulfide to free sulfur and sulfate may be accomplished by the injection of oxygen into the brine (Wilson et al., 1977).
2. Continuous injection of aqueous hydrogen peroxide and sodium hydroxide solutions into the geothermal stream. The principal product is sodium sulfate, a neutral salt (Castrantas, Turner, and Rex, 1976).
3. Scrubbing H_2S from geothermal steam with a solution of a metal salt, such as $CuSO_4$, the cation of which yields a sparingly soluble sulfide precipitate (Harvey, Brown, and Turchan, 1976).

Noise

Noise will be generated by a wide variety of activities and operations during all phases of all large-scale geothermal development projects. Significantly high noise levels are thought to interfere with the normal behavior and function of a broad variety of animals. Disruption of hunting, defense, breeding, rest, hibernation, and/or migration are potential impacts which could result from geothermal development (USFWS, 1978).

During exploration, noise is generated by vehicles, drill rigs, construction equipment, and explosives. The drilling operation involves the use of heavy equipment and large diesel engines and occurs 24 hours/day for several weeks or longer; noise

levels of 80-90 dBA can be expected. Drilling noise levels pose less of a problem in hot-water than in vapor-dominated systems because mud rather than air (as in vapor-dominated) is used as the circulating fluid. The most significant noise associated with hot-water wells is that emitted during production testing for power generation, when 20-25 percent of the hot water would be flashed to steam. If unmuffled, the noise of the expanded steam could reach a level as high as 100 dBA at 50 feet (15.24 m) (USEPA, 1977b). (See Table 11.)

During the well-field development phase, noise will be generated by construction equipment, large-scale drill rigs, compressors, and pumps. Significant noise from venting geothermal wells will be present. The intensity of this noise varies according to the nature of the geothermal resource, with vapor-dominated systems being the loudest. There are periods of development when mufflers are not used during which wells are allowed to discharge freely to clear out debris (USFWS, 1978). During operation of the geothermal project, noise will be generated by wells, inter-connecting piping, the power plant, cooling tower fans, and support equipment.

In general, ambient noise levels for a geopressured-geothermal field would probably be similar to those of a hydrothermal-geothermal field -- in the range of 40 dBA. This is not substantially different from natural noise levels along the Gulf. If it is necessary to release geothermal fluids to holding ponds or as steam, noise levels could increase temporarily to 90-100 dBA at 50 feet (15 m) from the noise source (Gustavson et al., 1977). Impacts resulting from noise will vary from project to project depending on the nature of the geothermal resource; the size and physical proportions of the well field; the adequacy of the noise control program; and the intensity, duration, and timing (time of day and time of year) of noise emissions. OSHA noise standards require limited exposure of workers to noise levels above 95 dBA. Persons in the vicinity of a geothermal site may be exposed to continuous noise at levels varying from 40 to 120 decibels, depending on stage of development and distance from noise source (Table 12).

Ecological response to sound varies from species to species and from individual to individual. This is due to the auditory system of the individual and the individual's prior conditioning. Table 13 compares levels of geothermal development noise with noise levels of familiar situations. Effects of noise appear to be greater on smaller wildlife species. Noise may compress the territories of breeding birds which advertise their territories by singing, but this has not been supported by research (Thompson, 1977). Big game animals may become conditioned to a high noise level, such as constant vehicular traffic (Thompson, 1977). At the Geysers, preliminary noise study results indicate that the moderately increased noise levels have not drastically changed wildlife communities (Leitner, 1978). Some evidence exists that in noisy areas certain species may be reduced in numbers, but there is no proof as yet that noise is necessarily the causal factor (Leitner, 1978).

If important species are expected to respond adversely to noise, then noise is an important topic to consider. Noise will likely cause problems when comparatively low baseline sound levels exist and/or important noise-sensitive species live in the area (USFWS, 1978). Studies of noise apparently present methodological difficulties that

Table 11

PREDICTED PROJECT-RELATED NOISE AT 50 FEET

<u>Activity</u>	<u>Noise Level (dBA)* at 50 Feet (15.24 m)</u>
Road building equipment	80-90
Drilling rig (air)	102
Steam exiting a blooie with muffler	60
Steam well venting - standby	60 (at source)
Truck traffic bringing equipment and supplies	100

*Decibel A scale: A decibel is the universally adopted unit for measuring sound intensity. One decibel change in sound is approximately the smallest difference in sound intensity that the human ear can detect.

From: Enviros, 1974.

SOURCE: U.S. Fish and Wildlife Service, 1976.

Table 12

**NOISE ATTENUATION BY DISTANCE ALONE (NO EFFECTS
OF WIND, RELATIVE HUMIDITY, TOPOGRAPHY, ETC.)**

50 ft. (15 m) Base Level	1,000 ft. (304.8 m) -26 dB	½ Mile (.8 km) -34.5 dB	1 Mile (1.6 km) -40.5 dB	1½ Miles (2.4 km) -44 dB	1 ¾ Miles (2.8 km) -45.3 dB	2 Miles (3.5 km) -46.5 dB	3 Miles (5.25 km) -50 dB
60 dB	34	25.5	19.5	16	14.7	13.5	10
70	44	35.5	29.5	26	24.7	23.5	20
80	54	45.5	39.5	36	34.7	33.5	30
85	59	50.5	44.5	41	39.7	38.5	35
90	64	55.5	49.5	46	44.7	43.5	40
95	69	60.5	54.5	51	49.7	48.5	45
100	74	65.5	59.5	56	54.7	53.5	50
105	79	70.5	64.5	61	59.7	58.5	55
110	84	75.5	69.5	66	64.7	63.5	60
115	89	80.5	74.5	71	69.7	68.5	65
125	99	90.5	84.5	81	79.7	78.5	75

$$\text{Sound Level}_2 = \text{Sound Level}_1 - 20 \log \frac{(\text{distance}_2)}{(\text{distance}_1)}$$

+10 dB is normally perceived as being twice as loud. Adding two sounds of the same dB level produces a composite sound +3 dB above individual sound levels.

55 dB interferes with outdoor speech, etc.

70 dB is standard to protect against hearing damage from long-term exposure to noise.

SOURCE: U.S. Fish and Wildlife Service, 1976.

Table 13

COMPARISON OF NOISE PRODUCED DURING GEOTHERMAL
RESOURCE DEVELOPMENT WITH OTHER FAMILIAR SOUND LEVELS*

<u>Geothermal Noise</u>	<u>Level (dBA)</u>	<u>Distance (meters)</u>	<u>Comparative Levels</u>
	100	16.3	Unmuffled diesel truck
Drilling operation	90	15.2	
	75		Street corner in a large city (average)
Ambient noise level for an operational geopressured geothermal field (California)	40		Residential area at night (average)

*Modified from U.S. Department of the Interior, 1976; Weres, Tsao, and Wood, 1977;
and Gustavson and McGraw, 1977.

SOURCE: Gustavson, McGraw and Tandy, 1977.

make data interpretation complicated. There must be adequate predevelopment data on wildlife habitats and noise conditions if accurate interpretation of the impacts of noise can be made.

SUMMARY OF IMPACTS, PREDICTION, AND CONTROL OF UNIQUE DEVELOPMENT ACTIVITIES

The foregoing analysis indicates that subsidence, fault activation, hydraulic lifting, induced seismicity, and accidental brine discharges are the major impact categories of concern in geothermal resource development. These impacts are summarized in this section in terms of their causes, effects, indicators, prediction, and control.

Subsidence

Causes

Withdrawal of geopressured geothermal fluids at projected production rates may reduce reservoir fluid pressures, resulting in compaction of the reservoir strata and contiguous shale and mudstone beds. Compaction of these so-called "under compacted" shales and mudstones would be accompanied by "dewatering" of interstitial and intraparticle fluids. The resulting volume reduction within the mudstones and shales would be greater than the compression of the more "competent" or undeformable reservoir rocks for a given vertical stress. Mudstones and shales generally comprise a greater thickness of the geopressured section, as well, and are thus more important sites of compaction than are the reservoir rocks. Thickness changes in subsurface strata may be transmitted incrementally to the surface, causing subsidence or loss of elevation. Approximately one-third of the total compaction may be experienced as subsidence, by best estimates.

Effects

Subsidence is most serious in areas lying near sea level. Effects may include: (1) encroachment of contiguous water bodies over sites and structures; (2) more frequent or prolonged impoundment of rainwater (pluvial ponding) on poorly drained surfaces, or larger impoundments; (3) more frequent, extensive, or violent inundation of low areas during hurricanes or other flood conditions; (4) increased shoreline or stream bank erosion; (5) submergence of upland, wetland, or bay margin biotic communities, eliminating some species and introducing others; (6) soil salinization within closed depressions in dry areas; (7) elevation of local water tables, including those of saline

waters, relative to the ground surface, "drowning" terrestrial plants rooted in the aerated soil zone or poisoning them with salt; (8) submergence of breakwaters bulkheads, and other protective structures; (9) more inland penetration of seawater up coastal rivers and canals, potentially affecting water supplies; and (10) activation of faults (see separate discussion).

Indicators

Subsidence is indicated by elevation losses over a bowl-shaped area which may be several miles in diameter, as noted by successive geodetic surveys or comparison of topographic maps based on aerial surveys separated by several years. Surrogate evidence may include: (1) shoreline retreat; (2) increased flooding; (3) persistence of standing water; (4) progressive submergence of fixed shoreline objects; (5) changing biological communities, such as transitions from upland to wetland, fresh marsh to salt marsh, or salt marsh to grassflat or open bay biotypes; (6) increased erosion along shorelines and river banks; (7) soil salinization, perhaps producing "salines" or salt encrusted depressions; (8) destruction of terrestrial plant communities caused by a rising water table; (9) seawater intrusion into coastal rivers and canals; and (10) fault activation (see separate discussion). Other subsidence indicators or precursors are: (1) reduced reservoir fluid pressures; (2) declining groundwater levels in producing wells; (3) compaction of beds at depth (indicated by measuring the vertical separation of implanted radioactive tracers, etc.); (4) changing formation fluid chemistry (indicating shale dewatering or other effects); and increased microseismic activity in the vicinity of producing wells (see separate discussion).

Prediction

Techniques for predicting subsidence are in an early stage of refinement, particularly with respect to deep production such as that which would be required in order to develop from Texas' coastal geothermal reservoirs. Three general approaches to subsidence prediction are available, however: (1) the analogy method, which uses case histories of effects of similar developments in comparable geohydrologic settings to predict subsidence (following commencement of field development, a subjective appraisal of subsidence indicators as shown here may be incorporated, as well); (2) the empirical method, which uses observed subsidence or its indicators to project trends and to adjust production and note responses; and (3) the modeling method, which uses surface and subsurface data to develop a digital replica of a reservoir and its overburden on which to apply mathematical representations of geohydrologic processes and production scenarios. These methods are best used in conjunction, and should be reevaluated as new data or development plans become available. In the same manner, several areas can be evaluated simultaneously to select sites at which subsidence is least likely to occur.

Control

Subsidence control probably can be effected only by maintenance of reservoir fluid pressures. High projected rates of production (to 40,000 barrels per day per well, from a closely spaced cluster of 3 to 6 production wells) may result in a rapid decline in pressure, promoting shale and mudstone dewatering into the reservoir host rock. This process may tend to limit the pressure drop, but would not inhibit shale and mudstone compaction, the principal immediate cause of subsidence. Production rates would have to be adjusted to prevent even an initial reduction in pressure, by: (1) decreasing the rate of fluid withdrawal per well; (2) increasing well spacing; (3) reducing production over long depth intervals or from overlapping intervals; (4) reinjecting spent geothermal brine into the reservoir (for pressure maintenance); and (5) limiting reliance on production-enhancement practices such as acidizing, fracturing, and propping, which not only tend to increase flow rates (thereby lowering pressures) but reduce the capacity of the reservoir rock to resist compaction. The objective of each of these strategies is to retard subsidence, rather than correct it, by limiting the amount of section shortening (compaction) in subsurface beds per unit surface area. Reinjection has been used elsewhere to restore elevation losses, but this practice would probably not be advisable in coastal Texas (see separate discussion under "Hydraulic Lifting").

Remarks

Subsidence is both a natural and man-induced phenomenon in coastal Texas. Presently, shallow groundwater and oil and gas production have caused extensive subsidence, approaching a maximum of approximately 10 feet locally, over an area of almost 7,000 square miles throughout the Texas coastal region. This impact represents a severe hazard in an area where hurricane tides of over 20 feet have been recorded and where the 20-foot topographic contour may be 20 miles inland.

Production of fresh to slightly saline groundwater for cooling water needs at the geothermal processing plant could cause subsidence, as well. The potential for this impact should be evaluated in essentially the same manner as is geothermal production-related subsidence. The combined effects of these impacts should be carefully assessed.

Fault Activation

Causes

Fault activation is the initiation or enhancement of movement along a fault, or fracture, in the earth's crust. A fault is an indication of unequal relative movement or "displacement" of the adjacent rock masses separated by the fracture. Fault movement occurs primarily in the subsurface, but it may be expressed at the surface, as

well. Both types of movement are of concern in the Texas coastal region, where there may be at least three causes of fault activation: (1) fluid withdrawal from a geopressed reservoir bounded by faults may encourage compaction of beds on one side of the fault, and that compaction is transmitted along the fault, perhaps to the surface; (2) injection of fluids into the reservoir or into permeable beds at shallower depths, may cause "overpressuring and hydraulic lifting of the overburden along a fault (see separate discussion under "Hydraulic Lifting"); and (3) either induced or natural seismicity may cause "liquefaction" or flowing of easily disturbed clay beds, promoting movement along faults (see separate discussion under "Seismic Activity"). Only differential compaction and subsidence (cause 1, above) can be considered important causes of fault activation in the region. The significance of injection overpressuring and seismicity-induced liquefaction (causes 2 and 3, above, respectively) in activating faults in coastal Texas has not been demonstrated.

Effects

At the surface, faulting may produce topographic escarpments ("fault scarps") and rectilinear drainage systems. Subtle soil moisture differences across the fault may change the character of the soils and may result in differences in vegetation. Direct structural damage to airport runways, roads, and buildings have been attributed to faulting in some areas of the coastal region. Pipelines have been damaged and have had to be relocated, as well, and gravity flow in wastewater lines has in some cases been disrupted. Other surface effects of fault activation are similar to those of subsidence.

In the subsurface, active faulting could damage wells, permitting loss of fluids below ground or at the surface, and may increase seismic activity (see separate discussions under "Brine Discharges" and "Seismic Activity," respectively).

Indicators

Fault scarps and fault-related lineations (subtle linear topographic features of geologic origin) are most easily detected on aerial photographs. Black and white, color, and false-color infrared aerial imaging have been shown to be useful in detecting faults, and side-looking airborne radar (SLAR) may be adaptable to this use, as well. Soil and vegetation changes, stream channel alignment, and the general orientation of landscape elements may be recorded as fault lineations that can be traced for as much as 60 miles. Faulting may also cause fractures to appear on roadways, airport runways, and through structures, and may damage or disrupt buried utility lines. Rapid elevation changes or more gradual zones of relief may be noted along geodetic survey lines. Typically, these features are not represented on topographic maps because the total relief is less than the contour interval. Also, a dense network of topographic benchmarks would be required for adequate registration of fault positions, which generally can be said only to lie somewhere between two benchmarks. Precursors of faulting may include subsidence, increased microseismic

activity, and the indicators of both of these impacts (see separate discussions under "Subsidence" and "Seismic Activity," respectively). When the positions of faults are known, tiltmeters or other monitoring devices can be installed which will record even small displacements.

Prediction

No adequate means of predicting the activation of faults, other than by considering them to be secondary effects of subsidence, is known. The empirical method of subsidence prediction may be particularly adaptable to this purpose, although long experience at the development site would probably be necessary for satisfactory application of the method. In general, prediction of faulting could be accomplished by estimating subsidence and superimposing this estimate on a landscape whose faults have been mapped. Careful monitoring of fault displacements would improve the process of correlating fault movements with more widespread subsidence. Faults which extend from the production reservoir to the surface will often be the sites of greatest displacement.

Control

Faulting can be controlled only by controlling subsidence (see separate discussion). Reinjection to control faulting by selectively inducing hydraulic lifting is an untested procedure in the Texas coastal region and may be difficult to implement.

Remarks

Faults and lineations of both natural and man-induced origin are common features in the Texas coastal region. Approximately 7,000 miles of these features, 96 miles of which are known active faults, have been mapped in coastal Texas. While structural damages have resulted from faulting in the area, proper siting of facilities, based on a search for indicators of preexisting faulting, can eliminate much of the hazard.

Hydraulic Lifting

Causes

Injection of waste fluids, primarily spent geothermal brine, into permeable reservoir beds or into shallower disposal horizons, may be a common method of isolating toxic substances produced by geothermal resource development. When fluid is injected faster than it can permeate through the matrix, pressures will increase. The injected stratum may become overpressured, such that hydraulic forces within the stratum are greater than the confining pressure of the overburden acting on that

stratum. The overburden may then be "lifted." This process is called hydraulic lifting, and under certain conditions, the effect could be felt at the surface, although subsurface effects may be more common.

Effects

Hydraulic lifting could, potentially, elevate the land surface. In some areas, subsidence effects have been offset by intentional hydraulic lifting, although this procedure would probably be inappropriate in coastal Texas. The reason for this is that much of the subsidence in the coastal region would be caused by shale and mudstone compaction, which is not reversible. Surface displacement is not, however, a likely effect of hydraulic lifting. Subsurface displacement of beds or portions of beds is a more probable result. Injection pressures may be so high that fluids escape the disposal site and migrate along faults or through otherwise impermeable barriers and "breakthrough" into freshwater aquifers or valuable mineral or hydrocarbon deposits (see "Accidental Brine Discharge"). Seismic activity may also be increased (see separate discussion).

Indicators

Slight upward elevation changes relative to surrounding areas may be associated with hydraulic lifting, particularly in the vicinity of injection wells. Drainage of shallow estuarine sites, alteration of water courses and shoreline positions, and similar alterations might occur, although these are not likely. More probable indicators are (1) retarded subsidence; (2) contamination of fresh groundwater, economic mineral, or hydrocarbon resources; and (3) increased microseismic activity. These possible indicators of hydraulic lifting are discussed under "Subsidence," "Accidental Brine Discharge," and "Seismic Activity," respectively.

Prediction

Methods to predict hydraulic lifting are essentially identical to those involved in predicting subsidence, except that data concerning injection pressures and disposal well sites would have to be incorporated in the assessment. Injection could affect subsidence, as well, and must be considered in making estimates of subsidence. Seismic activity may give a useful indication of hydraulic lifting and could be incorporated in a practical system of predicting lifting.

Control

Hydraulic lifting can be controlled by many of the same techniques applicable to the control of subsidence, except that injection rates rather than production rates are

adjusted. In practice, both production and injection rates would be regulated in concert to maximize production while minimizing, or at least selectively localizing, adverse effects such as subsidence and hydraulic lifting.

Remarks

No well documented instances of hydraulic lifting in coastal Texas are known. The process of high-pressure injection to geopressured reservoir depths is almost entirely untried. Effects should be carefully monitored to provide adequate data from which to develop suitable prediction and control procedures.

Induced Seismic Activity

Causes

Low natural or "background" levels of seismic activity in the Texas coastal region may give a somewhat misleading impression that earthquakes are of no concern. However, several records of earthquakes having intensities of up to V on the Modified Mercalli Scale of 1931 (corresponding to slight structural damage) have been noted in east and coastal Texas at oil and gas fields. In general, seismic activity and less intense microseismic activity may be induced by any process which changes the internal pressure equilibrium of a reasonably large part of the earth's crust. In connection with geothermal resource development in the Texas coastal region, the major potential inducements to increased seismic activity are: (1) geopressured fluid production; (2) injection of spent geothermal brine into the producing reservoir or another horizon; and (3) impoundment of artificial lakes near geothermal fields.

Effects

Seismic activity resulting from geothermal resource development could cause slight structural damage in the vicinity of the field, and it could, at least theoretically, cause "liquefaction" or spontaneous flowing of so-called "quick" or "sensitive" clays found in the coastal region, which could activate faults. However, the most significant effect, perhaps, would be a sudden surge of groundwater flow either within the geopressured reservoir or at shallower depths. Such an effect could seriously impair the function of production and disposal wells, possibly contributing to an already high risk of a blowout or an uncontrolled flow through a well (see separate discussion under "Accidental Brine Discharge").

Indicators

Except for strong shocks, most seisms can be detected only by monitoring instruments operating continuously. Seismographs and observation wells equipped with sensitive level recorders are best suited to this purpose. Geothermal fields throughout the world are often subject to minor earthquakes, and the geothermal "fairways" of coastal Texas may be no exception.

Prediction

Earthquake prediction is a very active area of inquiry at present, but one which has not, as yet, produced a generally applicable prediction technique, particularly for low-intensity seisms. However, a number of investigators have shown a close correlation between production and injection fluid pressure changes and microseismic activity. An empirical approach may offer the best method of anticipating earthquakes attainable at the present time.

Control

In the same manner that seismic activity might be predicted, so might it be controlled: by adjusting production and injection rates and pressures in various parts of the geothermal field until a correlation can be made and the rates adjusted to permit no more than an acceptable level of seismic activity. Although the process, in practice, would be more complex than is indicated here, there is convincing evidence of the existence of certain dynamic thresholds of pressure change necessary before seismicity is increased. To discover these values at a given development site then becomes a relevant task in preparing an effective control technique. Newly constructed artificial lakes are known to have caused earthquakes in many parts of the world, including eastern and northern Texas. Shocks recorded near these sites are not, generally, of damaging intensity. However, siting criteria for geothermal wells should include consideration of proximity to lakes.

Remarks

The importance of induced seismic activity for geothermal development in Texas is not yet known. Vast experience in oil and gas production and underground brine disposal in the region has not shown that earthquake-inducement is a serious hazard. Yet few, if any, systematic investigations of this problem have been undertaken. The tremendous rates of production and the high pressures involved in injection and production of geothermal brine suggest at least a potential risk, particularly in view of the limited but definite record of induced seismic activity in the area. This record has not, apparently, been very widely noted by professionals engaged in resource development in the state.

Accidental Brine Discharge

Causes

Leaks from pipelines, holding ponds, well casings, and uncased well intervals; well "blowouts"; and brine migration from disposal horizons are the principal causes of accidental brine discharges resulting from geothermal resource development. Brine or other fluids may be discharged at the surface (on land or into water bodies) or underground (into fresh water aquifers, hydrocarbon or mineral deposits, or other permeable strata), with potentially serious consequences. Hurricanes, equipment failures, fault movements, seismic events, corrosion, and human error can result in the unintended release of toxic substances at a geothermal development site.

Effects

Adverse effects of accidental brine discharges above and below ground include: (1) human casualties and property damage, including damage to geothermal development installations; (2) injury to wildlife and wildlife habitat; (3) contamination of surface water or groundwater used for municipal, agricultural, or industrial purposes; (4) salinization of soils; (5) contamination of hydrocarbon or economic mineral resources, or disruption of efforts to recover these resources; and "cratering" or "pitting" of the surface.

Indicators

Possible indicators of brine-related accidents include: (1) loss of fluids or fluid pressures from wells, pipelines, or other facilities; (2) reported contamination of area wells, to a distance of perhaps five miles from the point of discharge; (3) emergence of brine at the surface, either on land or in water bodies; and (4) sudden changes in fluid chemistry or temperature at production or disposal well sites, indicating introduction of foreign materials.

Prediction

Prediction of accidental brine discharges may not be possible. For this reason, monitoring efforts take on special importance. Long experience in developing the geothermal resources of coastal Texas may suggest correlation between seismic activity, faulting, or other conditions which potentially result in blowouts or other fluid discharges. However, no reliable technique exists for predetermining when or precisely under what circumstances an accidental brine discharge might occur.

Control

Preventive controls, including careful monitoring and development of techniques for rapidly detecting, assessing, and controlling discharges, offer the most advantageous approaches to abating accident conditions. Proper installation, testing, and maintenance of well casings, pipelines, blowout preventors and storm shutdown equipment, emergency brine storage and disposal facilities, and all monitoring devices can ensure that the best available technology is employed in preventing and controlling accidental brine discharges.

Remarks

As many as four out of every 60 wells drilled into the geopressured zone may blowout. This figure suggests a very high risk attendant to geothermal resource development. The environmental and economic damage of even a single major release of hot, toxic, high-pressure geothermal brine could be extremely high -- so high that future resource development might be impaired. The need to exercise caution in exploring the potential value of this resource is clearly indicated by fact and logical inference.

APPENDIX A

Study Methodology for Review of Geothermal Resource Development Activities and Their Ecological Effects

INTRODUCTION

This paper summarizes a survey of relevant literature concerning the ecological effects of geothermal resource development activities. On the basis of this summary, activities for which insufficient impact data were available were designated candidates for further analysis. The objective of this task was to make maximum use of existing information, thereby focusing any new analysis on activities unique to geothermal development and/or that have been inadequately studied to date. Ultimately, information compiled from previous research as well as analyses conducted under this study provide the basis for recommending ecological standards of operation for developing state-owned geothermal resources.

The procedure followed in this portion of the study included the following steps:

1. The current technology of geothermal-geopressed energy resource development was described using the activity analysis method. Contributing "activities" were identified, and similar activities were grouped together (Table A1). Ecosystems or "biologic assemblage units" (Brown and Fisher, 1974; Texas General Land Office, 1978b) within State Free School Lands of the coastal geothermal fairways were also identified; similar ecosystems were then grouped into categories (Table A2). The groups of activities and ecosystems were then arranged in a matrix (Table A3). The matrix was completed by indicating the ecosystem groups in which each activity could reasonably be performed.
2. A review and interpretation of pertinent literature was conducted to determine the probable environmental consequences of conducting an activity in each relevant ecosystem group. A condensed summary of effects was prepared. The purpose of this effort was to organize existing impact data in a way that simplified its use for the subsequent proposal of new or modified standards of operation governing geothermal resource development.
3. The compilation of existing impact data was evaluated to identify activities warranting further analysis. Criteria for selecting those activity/ecosystem combinations which warrant further investigation were developed. These criteria are any one or a combination of the following:
 - a. The activity and its impacts are unique to geopressed-geothermal reservoir production.
 - b. Sufficient data concerning the effects of an activity in a given ecosystem were not readily obtainable.
 - c. There must be a reasonable likelihood that further investigations would materially contribute to the existing impact data base within the time constraints of the study.

Table A1

ACTIVITIES ASSOCIATED WITH DEVELOPMENT OF A GEOTHERMAL ENERGY PROJECT

Activity	Project Components						
	A Power Plant	B Production Well	C Disposal Well	D Electrical, Telephone Transmission Lines	E Gas/Brine Transmission Line (from Production Well to Power Plant)	F Gas Transmission Line (from Power Plant to Distribution System)	G Brine Transmission Line (from Power Plant to Disposal Well)
Road Construction	X	X	X	X	X	X	X
Bridge Construction	X	X	X	X	X	X	X
Dredging	X	X	X	1	2	2	2
Spoil Disposal and Landfilling	X	X	X	1	2	2	2
Bulkhead Construction	X						
Plant Construction	X						
Plant Operation and Maintenance	X						
Geophysical Surveys		X	X				
Levee Construction		X	X				
Rig Construction		X	X				
Drilling		X	X				
Production		X					
Brine Storage (emergency)	X	X	X				
Brine Disposal (reinjection)			X				
Electrical and Telephone Line Construction				X			
Pipeline Construction	X				X	X	X

¹ See description of the activity "Electrical and Telephone Line Construction."

² See description of the activity "Pipeline Construction."

Source: General Land Office of Texas (1978). Activity Analysis, Texas Coastal Management Program Technical Paper Number 11 (by RPC, Inc. for GLO). Austin, Texas. 196 pp.

Table A2

AGGREGATIONS OF COASTAL ECOSYSTEMS¹ ON
STATE-OWNED AND CONTIGUOUS LANDS AND WATERS WITHIN GEOTHERMAL FAIRWAYS²

- I. Marine (Nearshore Gulf, Inlet/Tidal Delta)
- II. Littoral (Beach/Upper Shoreface)
- III. Insular/Eolian (Vegetated Barrier Flat, Washover Complex, Active Dune Complex)
- IV. Deeper Estuarine (Medium Salinity Bay, Restricted Bay, River-influenced Bay, Reef and Reef-flank Area, Channel)
- V. Wetland/Shallow Estuarine (Wind-tidal Flat, Salt Marsh, Brackish Marsh, Inland Freshwater Marsh, Coastal Lake, Grassflat, Bay Transitional Area)
- VI. Grassland (Coastal Prairie)
- VII. Woodland - riparian (Fluvial Woodland)
- VIII. Woodland - upland (Brushland, Oak Mottes and Groves)
- IX. Artificial/Unstable (Spoil Deposit - subaqueous, Made Land)

¹Terminology after Brown and Fisher (1974) and General Land Office of Texas (1978).

²Geothermal fairways after Bebout, et al. (1978).

Table A3

**ACTIVITIES ASSOCIATED WITH GEOTHERMAL DEVELOPMENT
AND ECOSYSTEMS IN WHICH THEY MAY OCCUR**

Activities	<u>Ecosystem Types</u>								
	<u>I</u> <u>Marine</u>	<u>II</u> <u>Littoral</u>	<u>III</u> <u>Insular/ Eolian</u>	<u>IV</u> <u>Deeper Estuarine</u>	<u>V</u> <u>Wetland/ Shallow Estuarine</u>	<u>VI</u> <u>Grassland</u>	<u>VII</u> <u>Woodland (Riparian)</u>	<u>VIII</u> <u>Woodland (Upland)</u>	<u>IX</u> <u>Artificial/ Unstable</u>
Road Construction			X		X	X	X	X	X
Bridge Construction			X	X	X		X		X
Dredging	X	X	X	X	X	X	X		X
Spoil Disposal and Landfilling	X	X	X	X	X	X	X	X	X
Bulkhead Construction	X	X	X	X	X		X		X
Plant Construction			X			X	X	X	X
Plant Operation and Maintenance			X			X	X	X	X
Geophysical Surveys	X	X	X	X	X	X	X	X	X
Levee Construction			X		X		X		X
Wellsite Construction	X	X	X	X	X	X	X	X	X
Drilling	X	X	X	X	X	X	X	X	X
Production	X	X	X	X	X	X	X	X	X
Brine Storage (Emergency)	X	X	X	X	X	X	X	X	X
Brine Disposal (Reinjection)	X	X	X	X	X	X	X	X	X
Electrical and Telephone Line Construction	X	X	X	X	X	X	X	X	X
Pipeline Construction	X	X	X	X	X	X	X	X	X

Applying these criteria; five geothermal resource development activities or aspects of activities were identified as warranting further investigation in this study:

1. Plant operation and maintenance (accidents associated with normal operations or routine maintenance procedures at the generating/processing plant, potential for excessive noise, water consumption, and air emissions)
2. Drilling (activation potential for subsidence/fault and accidents associated with normal drilling operations)
3. Production (normal production operations causing subsidence/fault activation, and potential accidents)
4. Brine storage (during emergency conditions involved with drilling, production, plant operation and maintenance, and brine disposal)
5. Brine disposal (normal reinjection operations and associated accidents)

By comparison, the U.S. Department of Energy (1978) has nominated several environmental concerns pertinent to geothermal energy development in a recently prepared "Environmental Readiness Document." This publication identifies the release of airborne and waterborne effluent, noise, subsidence, enhanced seismicity, water use, land use conflicts, disrupted social services, altered community structure, and system safety and occupational health as potential environmental concerns. Of these factors, release of airborne and waterborne effluents, noise, subsidence, enhanced seismicity, and water use were selected for additional study in the environmental portion of the present study.

PLANT OPERATION AND MAINTENANCE

Accidental discharge of large volumes of heated brine could occur during either normal operations or routine maintenance procedures at the electrical generating/production processing plant. Brines accidentally escaping the plant site and connecting pipelines could spread to the contiguous and nearby ecosystems. Overland flow, infiltration of the substrate, and mixed or unmixed subaqueous inflow may result. Analysis of this activity will focus on the effects of brine discharge and measures to prevent such accidents. In addition, the extent and effects of noise, fresh water consumption, and release of gases will be further investigated.

DRILLING

Drilling operations routinely seek to avoid "blowouts" (which may disperse brines, hydrocarbons, and drilling muds; cause fires; and under extreme conditions, cause "cratering"), contamination of other producing zones or shallow aquifers in the subsurface, and other losses of pollutant materials. However, rig and "downhole" accidents can produce conditions under which such serious environmental effects may result. Drilling and reservoir fluids may escape at the surface and into permeable strata in the subsurface. The effects of such accidents will be analyzed and methods of accident prevention and impact mitigation will be investigated.

PRODUCTION

Blowouts and related fluid losses can occur in conjunction with normal production operations; significantly, these accidents are no less common than is the case during drilling, except wildcat drilling to an unproven reservoir (Kash et al., 1973). Hazards associated with production accidents are the same as those which may result from drilling accidents: surface and subsurface contamination with toxic drilling and reservoir fluids, fires, and cratering. Therefore, the analysis of drilling impacts will be applied to production, and methods to prevent such effects will be investigated. In addition, normal production may result in such widespread effects as subsidence and fault activation (Gustavson and Kreitler, 1976). The potential for such effects and methods for measuring and predicting them will be analyzed.

BRINE STORAGE

Because spent production brines are assumed to be reinjected to reservoir depths in the scenarios developed for the present study, routine surface or aquatic brine disposal are not considered. However, emergency conditions at production or disposal wells or at the generating/processing plant will require construction of storage facilities for temporary brine containment. This analysis will consider conditions in which brine storage facilities fail or are inadequate. Examination of the resulting environmental effects tends to emphasize the need for emergency brine storage systems. However, the use of such systems poses certain risks, as well. The environmental impact of emergency brine storage is examined in this study in order to suggest procedures and installation designs which can reduce the environmental hazard to a minimum.

BRINE DISPOSAL

In the current investigation, brines leaving the generating/processing plant are assumed to be reinjected to production depths through remote disposal wells. Fluid losses because of accidents at these wells may produce adverse surface and subsurface effects. In addition, hydrostatic pressures developed during reinjection may cause differential surface displacement, lifting the ground surface locally (Woodward-Lungren and Associates, 1974). Potential ecological consequences of these events are considered in this study.

APPENDIX B

**Methods for Assessment of Environmental
Impacts of Geothermal Resource Development**

INTRODUCTION

Geopressed-geothermal resources in the Gulf Coastal Region of Texas are encountered at great depths in an extremely complex geohydrologic setting. As discussed in detail in this technical paper, development of these resources may be accompanied by an inherent risk of increased environmental impact.

Most serious, perhaps, of all the potential environmental impacts of geothermal resource development are the effects of induced subsidence, fault activation, and accidental brine discharges. Poorly consolidated strata may compress as geopressed fluids are withdrawn, and a portion of that compression may be felt at the surface as subsidence. Where hydrologic barriers cause differential subsidence, faults may be activated, resulting in surface displacement and possible structural damage and microseismic activity. Subsidence may also result in encroachment of surface water over low-lying areas adjacent to major water bodies, and it could increase the likelihood of flooding, particularly during hurricanes.

Accidental brine discharges provide the potential for large-scale destruction of ecological systems, as well as for contamination of groundwater resources and economically valuable minerals. Surface discharges of brine, if allowed to stand for more than a few days, can result in the contamination of ecosystems that may take tens of years to recover.

Accurate assessment of the probability of these types of risks can be done only on a site-specific basis. The following discussion describes some approaches that can be followed in making such assessments. Included in these approaches are discussions of:

1. Data required to perform the assessment
2. Techniques for prediction of the effects and for field monitoring
3. Approaches to management for risk reduction

The assessment methodologies are divided (by type of impact) into three sections:

1. Brine Discharges - Surface and Subsurface Contamination
2. Subsidence - Subsurface and Surface Effects
3. Fault Activation, Seismic Activity, and Hydraulic Lifting

ACCIDENTAL SURFACE AND SUBSURFACE DISCHARGE OF BRINE

CAUSES AND MAGNITUDES

Geothermal brines may be accidentally discharged at the surface due to well blowouts, pipeline leaks or breaks, failure of storage facilities, and through accidents in the gas separation and power generation facilities. The amount of brine discharged is expected to be fairly small for pipelines equipped with valves permitting rapid manual or automatic shutdown when a leak is detected. Rapid detection and shutdown should also be possible for power and gas facilities.

Since brine storage facilities might be expected to hold several days' brine production, a large spill could result from failure of a storage facility. However, it should be possible to monitor storage facilities closely and detect leaks at an early stage. The most likely time for failure of a storage pond would be during high rainfall and flooding, thus the impact would be reduced by rapid dilution.

Well blowouts are the most unpredictable accidents causing surface brine discharge and are potentially of the greatest magnitude. A blowout may remain out of control for months, and under the least favorable circumstances could release tens of acre-feet of brine per day.

Subsurface brine discharges may be brought about by drilling pipe or casing leaks and leaks through uncased intervals in improperly plugged wells. Corrosion, blowout damage below ground, and movement along intersected faults are the most likely causes of leaks. The risk of subsurface brine discharges in conjunction with geothermal resource development is particularly great because of the large volume of brine involved and its toxicity and high pressure.

DATA REQUIREMENTS

In order to evaluate probability and impact of surface and subsurface brine discharges in an area due to geothermal development, a body of data on both the surface and subsurface properties of the development area must be gathered. Some of these data, such as engineering practices to be employed, would most logically be compiled by the developer. Other types of data can be found in the scientific literature, state agencies, and experts in various fields.

Surface Properties of Affected Area

Most of the required data on surface properties can be summarized in map form. The following maps of the area are needed: location of proposed facilities, ecosystems and land use in the area, topography, and hurricane and flood hazard areas.

The topographic map will be used in estimating the spread and dilution of spilled brine, and if possible, should provide contours at one-foot intervals from -5 to +10 feet. USGS 7.5-minute quadrangle sheets provide the proper level of detail and can be used as base maps.

The following data should be available for each potential spill site (well, pipeline, storage facility, etc.). For upland sites, the soil properties, including permeability, shrink-swell potential, and salinity, should be determined. The natural drainage pathways from each site to sea level should be delineated on the base map. In addition, the presence of sensitive areas such as wildlife refuges, bird nesting sites, and habitat used by rare and endangered species should be determined.

Streamflow statistics and water quality data for any stream likely to be affected by brine should be obtained from the USGS or TDWR. Information on the characteristics of all fresh water aquifers in the area should also be obtained.

Subsurface Properties of Affected Area

Information required to determine potential effects on groundwater contamination and contamination of economically important minerals includes (1) the physical and chemical properties of the geothermal fluid; and (2) the formation properties.

These data are typically collected by a developer in forecasting the production program of a field. Supplementary information can be found in TDWR, BEG, USGS, and other scientific literature. The following is a typical data outline:

- I. Physical and chemical properties of geothermal fluid
 - A. Corrosion properties
 - B. Toxicity and salinity
 - C. Temperature and pressure
- II. Formation properties
 - A. Structure
 1. Dip, thickness, and horizontal content of strata
 2. Location and offset of faults
 - B. Porosity and permeability
 - C. Identification of economically important strata
 1. Groundwater aquifers (containing water whose total dissolved solids concentration is 3,000 parts per million or less)
 2. Oil and gas
 3. Other economically important minerals
 4. Existing disposal site

Engineering Description of Proposed Geothermal Development

Since the probability of accidental spills is strongly related to the design of the proposed development, detailed engineering data will be needed. This information should include both the materials and the procedures used according to the following outline:

- I. Well-related materials and practices
 - A. Rig description
 - B. Design depth
 - C. Casing program
 - D. Blowout prevention equipment and procedures
 - E. Emergency shutdown equipment
 - F. Logging program
 - G. Completion and testing program
 - H. Facilities for disposal of brines produced during testing or in the event of accident
 - I. Any planned emergency procedures for coping with blowouts, floods, hurricanes, etc.
 - J. Procedure for plugging in the event of a dry hole
 - K. Expected physical and chemical properties of brine
- II. Pipeline-related materials and practices
 - A. Materials used, strength, corrosion resistance, insulation properties, etc.
 - B. Procedure for excavation and pipelaying
 - C. Procedure for testing pipeline
 - D. Facilities for monitoring and leak detection
 - E. Shutdown procedures for leaks or breaks, with estimated maximum brine spill volume
 - F. Techniques for recovery and disposal of spilled brine
 - G. Anticipated physical and chemical characteristics of brine
- III. Brine storage facilities
 - A. Materials, especially type of liner to be used
 - B. Facilities for leakage detection and control
 - C. Capacity in relation to uses at various stages of project
 - D. Operation, especially during flood and hurricane hazard conditions
- IV. Other facilities
 - A. Layout
 - B. Design capacity
 - C. Operation procedures, especially during floods and hurricanes
 - D. Facilities for leak detection and control

RISK ANALYSIS, PREDICTION, AND ASSESSMENT

Surface Brine Discharge

Risk analysis and impact prediction require several steps: (1) an estimate of spill size vs. frequency must be made; (2) the area of each ecosystem potentially affected by a given spill size must be determined; and (3) the impact of a spill in each ecosystem must be analyzed.

1. Spill Frequency

At the present time, the identification of potential spill size and frequency related to various engineering practices is the least documented part of the analysis. Clearly there must be some consideration of the engineering reliability of materials and practices. This would require an expert petroleum engineer. Additional information on accident frequency could possibly be obtained by analysis of Railroad Commission drilling records. Consideration should be given to the risks involved in flood, hurricane, and other hazard areas.

Obviously, most small spills and leaks could be confined for eventual disposal but at some point in the size spectrum, the spill rate would exceed the capacity of the emergency control procedures. The size versus frequency distribution for these spills is needed for the next step in the analysis.

2. Area Determination

Using the topography and ecosystem maps, estimate the ecosystems and areas affected by the largest spill determined in the first step which has a "reasonable" probability of occurrence. Note that defining this probability requires a policy decision. The areas and ecosystems affected by representative smaller spills should also be estimated.

3. Ecosystem Impacts

Estimate the duration and magnitude of the effects of the brine spill. This could be done using the AAR-ESC procedure or by analogy to the history of known spill sites. Special note should be taken of ecosystem damage in "sensitive" areas.

Summarizing ecosystem impacts due to accidental spills will be more difficult than for normal project assessments because of the probability aspects. This may require some experimentation before a suitable approach is found. One approach might be to state ecosystem impacts as lost productivity in acre-years for each size of

spill. These figures (for each ecosystem type) could then be multiplied by the probability for each size of spill to yield an "expected" ecosystem productivity loss for a given activity.

Subsurface Brine Discharge

Risk analysis and impact prediction for subsurface contamination involves two related procedures: (1) estimate the maximum volume of brine potentially discharged through a ruptured drill pipe or casing, or which may reach the surface to enter an aquifer through surface recharge; and (2) determine the lateral and vertical movement of that volume of brine through potentially affected permeable strata containing important resources. Data needs previously outlined (concerning the depth, thickness, location, and properties of important groundwater aquifers, hydrocarbon and economic mineral reserves, and currently utilized disposal horizons) must be met in identifying and characterizing important subsurface resources in the potentially affected area.

1. Volume of Discharged Brine

The maximum volume of brine that may discharge from a well below ground can usually be determined by pressure-testing the well following completion. Declining reservoir pressure through time may tend to reduce the volume of brine accidentally discharged from production wells. The volume of brine which may escape a disposal well would normally be controlled by the pumping pressure and the response time following fluid loss. In most instances, the volume of brine could be accurately approximated.

2. Movement of Brine Through Permeable Strata Containing Important Resources

Approximation of the movement of high-pressure brine through shallow aquifers, mineral or hydrocarbon deposits, and other important strata may require the use of a mathematical aquifer model of the type described by Appel and Bredehoeft (1976). Ambient fluid pressure projections and data concerning the permeability or transmissibility of the unit may be used in deriving an initial indication of the rate of intrusion. However, mixing phenomena and many other factors related to fluid diffusion through a heterogeneous permeable medium can only be accounted for statistically using empirical data. For detailed assessments, aquifer models incorporating these data must be brought into service.

A more readily implemented, although less precise, means of predicting brine movement requires the subjective evaluation of available geohydrologic data. Proximity of wells to important resources, known stratigraphic and structural trends in the subsurface, and permeability data which may be obtained from core samples or

approximated from electrical logs can be used in making a general assessment of contamination risks in the vicinity of a geothermal production or disposal well. However, this determination is useful only in establishing broad limits of confidence. Casing requirements and well monitoring procedures should ideally be developed through systematic modeling and testing and extensive experience in developing the resource. Modeling can also suggest the probability of natural dilution or other restorative processes important in evaluating the impact on the resource. General regulatory controls over water pollution which may result from geothermal resource development are discussed by Rogers and Oberbeck (1977).

SUGGESTIONS FOR RISK REDUCTION

The first line of defense in reducing the risks of accidental spills will be the engineering design and practices used in the various activities. Drilling to the deep geopressured-geothermal zone is a new and rapidly changing technology. Due to the high financial commitment required, and the huge losses caused by well blowout or pipeline break, it seems reasonable to expect developers of a geothermal project to use the best available techniques to prevent accidents, without excessive agency regulation.

However, for the second line of defense, which is the emergency containment and disposal plan, the goals of the developers cannot be expected to coincide entirely with the goals of the resource management agencies. Maintaining emergency facilities which are seldom used and which serve only to protect the environment will require a large financial commitment without immediate payoff. This would appear to be the area in which resource management agencies should concentrate their efforts to ensure a balance between economic costs and the potential for ecological and socioeconomic losses.

The third line of defense consists of planning the locations and emergency procedures for resource development activities so that, if emergency containment fails, environmental damage is minimized. For instance, rapid draining of brine from an upland ecosystem to a stream (instead of allowing it to spread over a coastal prairie) could minimize damage to a system which would be very slow to recover at the cost of relatively short-term loss of stream productivity. Siting of wells will probably be the most significant decision since this will also tend to control the pipeline locations.

Siting is also important in controlling the risk of subsurface contamination. Whenever possible, geothermal production and disposal wells should be placed to avoid heavily used portions of aquifers. Second priority should be given to avoidance of other resource recovery areas, although compatible development of geothermal resources in proximity to oil and gas and other mineral resources may be possible. Because faults may be activated by geothermal groundwater production, well siting should take into account the probable positions of major faults in the field,

particularly reservoir boundary faults with known surface expression. Possible well damage resulting from movement along intersected faults may thus be avoided to some extent.

SUBSIDENCE

DATA REQUIREMENTS

Assessment of the probability and amount of subsidence and of the nature of associated effects at a development site requires data which are routinely collected in the course of exploring the geothermal field and devising a production program. Most of the data not routinely collected could be compiled from available literature and regulatory agency records. Information needs generally fall into three categories: geological properties, drilling and production data, and ecological properties.

Geological Properties

The following data should be collected for the geothermal field and for a five-mile radius surrounding the field:

1. Historical (prior to geothermal resource development) rate, amount, and affected area of subsidence
2. Location of surface faults and related lineations, erosion and accretion areas, and aquifer recharge areas
3. Stratigraphy and geologic structure, emphasizing the location, depth, structure, and thickness of geothermal reservoirs and associated high-pressure shales or mudstones
4. Porosity, permeability, and petrology (including cementing minerals) of reservoir and associated strata
5. Compressibility of reservoir and overburden strata and dewatering rates of shales under ambient conditions
6. Ambient temperature and pressure
7. Geopressure and geothermal gradients

Drilling and Production Data

The following data should be collected for the geothermal field and for a five-mile radius surrounding the field:

1. Expected production and reinjection rates and field life
2. Number, location, and spacing of existing and projected production wells and injection wells, including water, oil, gas, solution-mining, abandoned, and shut-in wells
3. Location of existing and proposed roads, facilities, structures, pipeline and other utility corridors, and navigation channels
4. Depths of completion of wells
5. Permeability-enhancement measures (depth, interval, type of procedure, permeability and compressibility of affected strata following procedure, approximate area of reservoir affected)
6. Expected pressure decline within the reservoir through time

Ecological Properties

Evaluation of subsidence effects in an area mainly requires data on the relationship of ecosystems to topography. Much of these data will be available in map form. Maps of ecosystem distribution, land use, and topography will be required, with the topographic maps providing one-foot resolution in the range -5 to +10 feet elevation. Other maps required will be for hurricane and flood hazard, tidal and estuarine circulation, and the location of sensitive areas such as wildlife refuges, sanctuaries, rookeries, and rare and endangered species habitat.

It will also be necessary to search the scientific literature on depth zonation in the fresh aquatic, shallow estuarine, and estuarine ecosystems. For the upland systems, information on the relation of rainfall, soil type and moisture, and drainage to plant communities would be desirable.

SUBSIDENCE PREDICTION AND MONITORING PROCEDURES

A number of procedures are available for collecting and interpreting data relevant to subsidence and to the prediction of potential subsidence. Aerial photographs, surface geodesic surveys, and maps or written accounts can be used in reconstructing the predevelopment subsidence history of an area. Declining elevations, persistence and enlargement of impoundments, and progressive encroachment

of standing water over contiguous shallow estuarine areas or uplands through time are excellent indicators of subsidence. Displacement along faults and improved definition of photolineations also provide important evidence of subsidence, and of associated fault activation, as well. Interpretation of aerial photographs taken at regular intervals, perhaps annually, is a very useful technique for monitoring subsidence. Better indications of subsidence are provided by noting elevation changes across a dense network of topographic benchmarks. The rate of subsidence and the affected area can be judged most accurately when these benchmarks are monitored at frequent, regular intervals.

Subsidence can be predicted using data outlined previously. Compressibility of reservoir and overburden strata and the rate of shale dewatering suggest the probable compaction of strata as reservoir pressures decline. The depth and geometry of the reservoir, particularly in relation to the spacing of production and reservoir reinjection wells may help to define the size of the potential subsidence bowl. Faults which interrupt the reservoir and reach the surface may limit or define the area of subsidence. A major objective of prediction is to approximate the percentage of the compaction at depth which may be transmitted to the surface as subsidence.

Three methods of subsidence prediction are available. The analogy method requires a subjective extrapolation of conditions promoting susceptibility to subsidence from areas previously affected to prospective development sites. The empirical method draws upon monitoring data to project trends which can be used in adjusting production and reinjection to limit subsidence. The modeling method makes use of a mathematical representation of the reservoir, its overburden, and the overlying surface to correlate geohydrologic properties of the strata with production and reinjection data. Models for use in predicting subsidence have been reviewed by Atherton et al. (1976), Finnemore and Gillam (1977), and Appel and Bredehoeft (1976).

Analogy Method

Using the analogy method, sites which have previously experienced subsidence are compared to prospective development areas. Similarities and differences between the sites are noted. The most important properties to be compared are (1) the geohydrologic setting for each site, including its stratigraphy and geologic structure; and (2) the production histories or production scenarios of the fields. Similarities suggest that effects at one site may be extrapolated to the other, with equal attention being given to dissimilarities between the areas. This method of predicting impact is very useful when properties of the sites have been adequately described to allow realistic comparison. Ordinarily, a number of detailed case histories to which analogy could be made would have to be available during the assessment. Such an approach was suggested by Atherton et al. (1976, v. 1), and was used by White et al. (1978) in recommending a site for a geothermal test well to be drilled in Brazoria County, Texas. Well descriptions and field data reported by Bebout et al. (1978) are at present probably the best single source of relevant information on which to conduct an assessment by analogy.

Empirical Method

The empirical method relies on constant monitoring of field conditions during reservoir development as the means by which effects are anticipated and, when necessary (and possible), averted. In practice, all geothermal resource production efforts will employ this method of "predicting" impacts. Other approaches simply cannot be relied upon to such an extent that development of the resource could be entirely preprogrammed. However, the empirical method alone may not always allow adequate time in which to avoid adverse impacts. The relationship between a cause, such as a localized decrease in fluid pressures, and an effect, such as subsidence, may not always be immediately apparent either. A clear course of action might not in all cases be presented by the circumstances.

Modeling

Subsidence modeling seeks to develop mathematical expressions for various aspects of subsidence behavior in terms of presumed relationships to reservoir and overburden properties.

For example, the possibility that a finite pressure loss in part of the reservoir could cause subsidence may have to be evaluated. Digital replicas of the reservoir and overburden are tested using formulae representing compaction and fluid migration rates. A prediction of subsidence is then generated.

The validity of such predictions is automatically suspect, because of at least two uncontrolled sources of possible error inherent in every subsidence model. These sources are (1) the accuracy and completeness of the expressions for complex geo-hydrologic relationships, and (2) the precision of data used to calibrate the model. Adequate experience must be gained in using the model in order to adjust the mathematical expressions and to build confidence in the model's ability to predict, before the model can be relied upon in critical situations. Typically, the models never attain accuracy, or do so only after most of the effect has already been felt, despite elaborate "tuning" with monitored data (Atherton et al., 1976, v. 1). These problems were the focus of attention at an informal conference on modeling deep production-related subsidence held in California in 1978. The conference was attended by most of the principal investigators in the field, whose consensus expressed at this meeting was that it is premature to model deep production-related subsidence at the present time because of limitations in the state of the art (R. K. Gabrysch, U.S. Geological Survey, Houston, Texas; personal communication, November 1978).

Despite serious concern over the accuracy of subsidence models in general, some models probably can be used in deriving a first approximation of effects, if that approximation is not relied upon exclusively. Models do have one major advantage over other methods of predicting subsidence: models usually must provide an explicit statement of their assumptions. The validity of those assumptions may be questioned,

but the assumptions are an integral part of the documentation supporting the model's predictions. Similar explicit statements could greatly improve the analogy and the empirical prediction methodologies.

Combined Approach

The most useful approach to predicting subsidence is probably a combination of the three methods of forecasting. A cascading system of prediction methods would probably tend to eliminate most systematic errors and to reduce the number of nonsystematic errors in predictions. Initially, the analogy method could also be employed to assess the general degree of risk at a given site of impact resulting from a stipulated development scenario. The first generation subsidence model would then "come on line" to begin to help refine that prediction. With commencement of reservoir development, the empirical method would also be used. Continued interplay of these methods probably offers the best means of ensuring accurate predictions.

ANALYSIS OF ECOLOGICAL EFFECTS OF SUBSIDENCE

As shown in part one of Figure B1, analysis of the impact of estimated subsidence is divided into socioeconomic and ecological impacts. This paper treats only the ecological impacts in detail; the socioeconomic impacts are discussed in a separate report. Balancing socioeconomic benefits versus ecological changes is obviously a policy decision.

The flow of information required for analysis of ecological impacts is shown in part two of the flowchart. Inputs required include the subsidence prediction as a function of time, the present topography of the region affected, and the present distribution of ecosystem types as outlined in the "Data Requirements" section of this paper. The subsidence values are applied to the present topography to produce a predicted future topography (see "Subsidence Prediction and Monitoring"). This future topography must also be modified by the expected changes due to known active processes, such as erosion and sedimentation.

Next, the distribution of ecosystems in the region should be analyzed with respect to control by elevation, water flow patterns, and other factors. By applying this knowledge to the predicted future topography, a map of predicted ecosystem distribution can be constructed. Such maps should be constructed for subsidence predictions for various intervals.

It is anticipated that subsidence of more than a foot or so would begin to alter significant amounts of existing uplands into shallow estuarine areas, and shallow estuaries into open water systems. A more detailed discussion of the likely ecological changes resulting from subsidence in each of the three geothermal fairways is contained in this technical paper. Since many of the upland areas altered would be in

Figure B1

PROCEDURE FOR DETERMINING ECOLOGICAL IMPACTS OF SUBSIDENCE

Part I

Input: Predicted subsidence versus time from applicant (original production plan) or from GLO-supported modeling effort

Output: Either an agreed production plan or a rejected application

Part II

Input: Predicted subsidence versus time for production plan

Output: Estimates of changes in ecosystem areas

private ownership, it would appear to be extremely important to consider the legal status of the changed ecosystems as well as the relative area changes.

RESOURCE MANAGEMENT FOR RISK REDUCTION

Predictions of subsidence must become an important part of the management program by which the field is developed. The potential seriousness of many of the impacts, including subsidence, which may be associated with geothermal production nevertheless warrant certain actions to reduce risks regardless of the accuracy of predictions. Brah and Jones (1978) discussed institutional arrangements for effective management to halt subsidence resulting from shallow fresh to brackish groundwater production. Some of these and other options are available to developers of geothermal groundwater in their effort to reduce subsidence. Viable options include the management or adjustment of: (1) production and disposal/reinjection well sites; (2) well spacing; (3) the rate of production or injection per well; (4) the total production per unit time from one or more geopressured reservoirs or shallow groundwater (cooling water source) aquifers; (5) the duration of production from one or more production zones; (6) the selection of a disposal horizon for spent geothermal brine (may or may not include the geopressured reservoir); (7) the total injection per unit time into one or more disposal horizons; (8) the duration of injection into one or more disposal horizons; (9) the decision whether to attempt to enhance permeability in a given production or disposal zone; and (10) the selection of a method of enhancing permeability.

Most of these options are related to the maintenance of fluid pressures within the geothermal reservoir. Permeability enhancement concerns the possible reduction of the bearing strength of reservoir rocks. Pressure losses and reduced bearing strength tend to increase the risk of subsidence and should be minimized or eliminated whenever possible.

Ultimately, the best techniques for managing subsidence is through accurate prediction of high-risk areas and monitoring to provide earliest possible indications of subsidence.

FAULT ACTIVATION, SEISMIC ACTIVITY, AND HYDRAULIC LIFTING

Fault activation, seismic activity, and hydraulic lifting are among the more serious potential environmental effects of geothermal resource development. Similarities among these effects and in approaches to their assessment suggest that they are best discussed together. However, where appropriate, the effects are mentioned individually in the sections on "Data Requirements," "Prediction and Monitoring Procedures," and "Resource Management for Risk Reduction."

DATA REQUIREMENTS

The types of data required for predicting and assessing fault activation, seismic activity, and hydraulic lifting are similar, and are generally included in the outline of data requirements for evaluating "Subsidence" and "Accidental Brine Discharge (Surface and Subsurface)." Compilation of the record of elevation changes in the area, which is required for the assessment of subsidence, could indicate a history of fault displacements or hydraulic lifting, as well, although geodetic surveys may not routinely use a network of closely spaced topographic benchmarks such as that necessary for detailed studies of fault movements. See "Prediction and Monitoring Procedures," this section. Seismic activity should be monitored at several seismographs or in observation wells. Records of production and injection rates and pressures should also be carefully maintained for periodic comparison with observed geohydrologic impacts, including those described here, and subsidence. The objectives of these efforts are to detect and measure impacts at specific sites and to relate the effects to the type and rate of field development. A statistical treatment of these relationships can suggest ways to improve impact monitoring, prediction, and risk management practices.

IMPACT PREDICTION AND MONITORING PROCEDURES

Topographic Benchmarks

As noted in the discussion of "Subsidence," routine monitoring of a dense network of topographic benchmarks may provide the most detailed record of local elevation changes obtainable. Proper siting of benchmarks along known major surface faults in particular would ordinarily be needed in order to ensure collection of adequate data concerning fault movements.

Aerial Survey

Photogrammetric interpretation of aerial imagery offers another means of detecting and monitoring fault activation. At certain faults chosen as key indicators of surface displacement, tiltmeters can be installed and observed; these observations would provide confirmation of the initiation and rate of faulting in the area of geothermal resource development.

Seismic Activity Monitoring

An effort to monitor seismic activity around the well field may also be necessary, at least during the early experience with geothermal development. Portable or permanent seismographs, or observation wells equipped to record rapid

changes in fluid levels, are useful tools with which to measure induced seismicity. Care should be taken, however, to establish background levels of microseismic "noise" at a development site prior to development. These vibrations can then be screened to prevent interference in analyzing small-magnitude tremors of the type typically associated with fluid production and injection (see Cappello et al., 1974; Healy et al., 1968; and Hoover and Dietrich, 1969).

Fault Activation Prediction

Fault activation and seismic activity probably cannot be predicted directly. Kreitler (1976) stated that "Lineations . . . are presently passive structural features . . . which in the future may become the foci for differential subsidence and active faulting . . . Herein lies the predictive value of lineation analysis and subsidence monitoring." Kreitler was referring, however, to prediction of the sites of faulting and subsidence, as an aid in properly locating facilities. Rates of movement along faults and the total possible displacement may best be ascertained by monitoring, although empirical prediction, based on a detailed monitoring record, may prove useful. A similar argument may be made for predicting seismic activity.

Understanding of these impacts may be improved by statistically relating observed effects such as increased fault displacement of seismicity to production and reinjection efforts and to one another. Pressure variations within the geothermal reservoir may anticipate more severe responses, including faulting, subsidence, hydraulic lifting, and seismic activity. Similarly, each of these effects may be related to one another in a way that makes prediction of impacts possible. For example, a given drop in reservoir fluid pressure during some time period may promote compaction and detectable subsidence. Subsidence may trigger faulting and a simultaneous increase in seismicity. Hydraulic lifting may follow a dramatic rise in fluid pressure, causing faulting and increasing seismic activity.

Prediction of Hydraulic Lifting

A more direct approach to predicting hydraulic lifting may be feasible. A model of subsidence above a producing reservoir could be applicable in many ways to hydraulic lifting, as well. The model would have to be calibrated for conditions within the disposal horizon, if different from the producing horizon. With certain limitations, hydraulic lifting can then be treated as negative compaction or negative subsidence. The reliability of subsidence models as predictors of lifting phenomena may be no better, however, than as devices for estimating subsidence.

RESOURCE MANAGEMENT FOR RISK REDUCTION

As was noted in the discussion of "Subsidence," the major cause of adverse geohydrologic impacts in conjunction with geothermal resource development is a

marked change in ambient fluid pressures within production or disposal reservoirs and their associated strata.

Maintenance of ambient pressure conditions at depth offers the best means of controlling these effects. Production should be adjusted to limit pressure reductions, although a decline in reservoir pressure could perhaps be compensated by injecting fluids into the reservoir. Reexpansion of compacted shales would not be possible, but higher reservoir pressures might retard dewatering. Injection, particularly into comparatively shallow disposal horizons, must be carefully monitored to prevent overpressuring. Production and injection well siting should also be made in consideration of the likelihood of induced hazards. Proximity to faults is a major criterion to be exercised in choosing sites for wells.

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