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GEOTHERMAL SUBSIDENCE RESEARCH
PROGRAM PLAN AND REVIEW

N.E. Goldstein, J.E. Noble, and T.L. Simkin

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GEOTHERMAL SUBSIDENCE RESEARCH PROGRAM PLAN AND REVIEW

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1. INTRODUCTION

1.1 RATIONALE FOR A REVISED PLAN

Hot water, steam, or a mixture of the two are extracted from geothermal reservoirs for the production of electricity or for the direct use of the heat energy. Because land subsidence can result from this process, the U.S. Department of Energy, Division of Geothermal Energy (DOE/DGE) requested that Lawrence Berkeley Laboratory (LBL) prepare a research plan to study this problem. The resulting plan was published by LBL in April 1977, entitled "Geothermal Subsidence Research Program Plan" (LBL-5983). The revised Geothermal Subsidence Research Plan (GSRP) presented here is the result of two years of research based on the recommendations of a technical advisory committee and on the DOE/DGE's wish to include specific components applicable to the geopressure resources on the Gulf Coast.

This revised plan describes events leading up to FY 1979 and 1980 and the resulting research activities completed for that period. At the time of this writing most of the projects are completed; this document summarizes the accomplishments of the GSRP during FY 1979 and 1980 and includes recommendations for the FY 1981 and 1982 programs.

1.2 RATIONALE FOR RESEARCH

As an alternative source of energy, geothermal energy for electrical conversion or space heating is available in many places throughout the United States. One potential problem with geothermal energy development is that land deformation may accompany removal or injection of fluids from or into geothermal reservoirs. The issue of land deformation, associated with subsurface reservoir compaction, is the focus of this research program plan.

Unexpected and uncontrolled subsidence may have social, environmental, and economic consequences in certain areas. However, predictable subsidence occurring under controlled conditions may be acceptable. Subsidence impacts can vary greatly, depending on the geologic and land-use settings. Damages associated with the subsidence at the Wilmington oil field, California, represent one extreme. The center of that subsidence depression, located within the city of Long Beach, has dropped over 9 m since 1926. Horizontal movements of nearly 3 m have also been measured. These movements have damaged wharves, pipelines, buildings, streets, bridges, and wells, necessitating costly repairs, including the raising of land surface to prevent inundation by the sea. Damages have exceeded $100 million (Mayuga and Allen, 1969). On the other hand, movement as much as several meters due to groundwater withdrawal in agricultural areas of California and Arizona has so far had no significant economic impact (McCauley and Gum, 1975).

Potential geothermal resource areas are found at various depths and in many different geologic and land-use settings. Thus subsidence may or may not be an issue of major concern. The degree of concern that subsidence arouses will depend on a comprehensive assessment of its potential impact at each geothermal site. The research program contained in this plan seeks to enable such assessments to be made with confidence.

1.3 RELATIONSHIP TO OTHER DOE GEOTHERMAL RESEARCH PROGRAMS

One of several geothermal research programs promulgated by DOE/DGE, the GSRP is most closely related to the Geothermal Reservoir Engineering Research Program (GREMP), also managed by LBL, in the sense that both programs are concerned with reservoir dynamics as a consequence of exploitation. Although we normally think of subsidence as an environmental concern, it is extremely important not to lose sight of how subsurface compaction and surface deformation bear on specific issues of reservoir engineering (B.E. Lofgren, personal communication):

1. Precise measurements of ground movement could be an important tool for understanding reservoir boundaries and recharge characteristics.

2. Reservoir compaction must be understood for evaluating how much fluid can be extracted and how reservoir pressure behaves during exploitation.

3. Subsurface damage (i.e., damage to casing and formation) due to compaction may pose far more serious economic problems than the surface deformation.

Within LBL, reservoir engineering and subsidence programs have the greatest overlap in numerical modeling as a means for predicting subsidence. A number of reservoir simulation codes have been modified and exercised for this purpose.

Under separate funding from DOE/DGE, TerraTek, Inc., Salt Lake City, Utah, is studying available cores from geothermal reservoirs to accumulate data on properties of materials. Through the GSRP, TerraTek also receives support for short- and long-term creep testing. The Well Log Instrumentation Program, managed by Sandia National Laboratories, is concerned with the development and testing of electronic components, seals, and cables for high-temperature, high-pressure, and corrosive environments. Because Sandia's program has direct applicability to the Direct Measurement and Monitoring element of the GSRP, parts of the two programs have been coordinated. The Induced Seismicity Program, managed by DOE/Neva Operations Office (NVOO), is also coordinated with the GSRP.

2. FRAMEWORK FOR A REVISED PLAN

The ultimate goals of the subsidence research program are to understand and control subsidence associated with geothermal energy development. These goals may be stated more precisely:

1. Characterize the physical phenomena of land surface subsidence as they relate to geothermal energy production.

2. Assess the economic and environmental impacts of subsidence.

3. Assess the operation of a well field so that adverse impacts will be minimized and geothermal resources can be developed to their fullest potential.

The research framework and the approach for reaching these goals have been revised as a result of (1) accomplishments from the first two years of research, (2) recommendations and comments from scientists and workers at a workshop held to focus on the need for periodic revision of research programs, and (3) specific, up-to-date program needs of the DOE/DGE.

The original Geothermal Subsidence Research Program (GSRP) had an integrated structure with five major elements: (1) characterization of subsidence, (2) physical theory of subsidence, (3) properties of materials, (4) simulation of subsidence, and (5) subsidence control. Each of these elements was divided into specific research categories, defining the direction of the research program. Research categories in turn were composed of individual research projects. In the original Subsidence Research Program, there were five program elements, nine research categories, and fifteen projects, as shown in Table 1.

2.1 ACCOMPLISHMENTS OF THE ORIGINAL GSRP (THROUGH FY 1978)

Four contracts were completed and three contracts were in progress at the end of FY 1978. The completed contracts are as follows:

1. Case Histories. (Grimsrud et al., 1978) Four case histories were completed by Systems Control, Inc. in the following areas: Wairakei, New Zealand; Chocolate Bayou, Texas; The Geysers, California; and Raft River, Idaho. These sites were selected on the basis of their physical similarity to U.S. geothermal sites in terms of withdrawn geofluid type, and overburden characteristics as well as completeness, quality, and availability of data. The case histories are now serving as models for developers and/or regulators in assessing the subsidence potential for their area of interest.

2. Environmental and Economic Effects. EDAW/Earth Sciences Associates produced an assessment of data available from areas that have experienced geothermal and nongeothermal subsidence. A detailed appraisal was made of

Table 1. The Formal Structure of the Original GSRP (1977)

Elements	Research Category	Projects	Subcontractor
Characterization of subsidence	Case histories of subsiding areas and geothermal subsidence potential maps	Land deformation case histories	Systems control
		Geothermal subsidence potential maps	
	Field measurement programs	Criteria to distinguish between potential subsidence caused by a geothermal project and subsidence due to other causes	
		Monitor horizontal and vertical displacement	Woodward-Clyde review
	Direct monitoring instrumentation	Assess the state of the art of measurement	Woodward-Clyde manual
		Develop prototype instruments and conduct field tests	
	Environmental and economic effects	Data collection	EDAW-ESA
		Investigate effects	
Physical theory of subsidence	Physical processes of subsidence	Same as research category	
Properties of materials	Indirect techniques to estimate subsidence at depth	Assess indirect techniques	
		Develop prototypes	
	Laboratory testing	Same as research category	TerraTek CSM
Simulation of subsidence	Subsidence models	Same as research category	Golder
Subsidence control	Reservoir operational control policy	Industry evaluation	
		Guidelines and procedures	

areas with the most comprehensive data bases (Viets et al., 1979). Areas studied included desert basins in central and southern Arizona; Baldwin Hills and Inglewood, California; San Joaquin Valley, California; Santa Clara Valley, California; Wairakei, New Zealand; and Wilmington Beach, California. The quantity and quality of data collected for areas studied were disappointing. No comprehensive study of the effects of subsidence was found for any of the areas; most data were based on estimates rather than actual expenditure records, and in general there was a lack of public awareness of subsidence except in areas where related hazards, i.e., flooding, were serious.

3. Surface Monitoring--Guidelines Manual. A geothermal development program must include monitoring of horizontal and vertical displacements both at surface and at depth before and during production. It should be possible to differentiate subsidence from geothermal operations and subsidence from other human-induced activities or natural causes. Woodward-Clyde Consultants has produced a manual (Van Til, 1979) that reviews various surface monitoring methods and compares their installation, utilization, and accuracy. Utilization of these methods should enable planners and regulators to determine natural subsidence rates. In addition, the manual explains how to establish a system for monitoring induced subsidence during development and production of a geothermal field.

4. Direct Measurements of Changes in Vertical Distances in a Wellbore Another Woodward-Clyde study reviewed instruments available for monitoring vertical and horizontal displacements in a wellbore (O'Rourke and Ransom, 1979), evaluated techniques and materials for improving or developing new instruments, and identified elements of sensor and signal technology with potential for high-temperature monitoring of vertical wellbore changes. Woodward-Clyde recommended hostile-environment testing for the following four components: induction coil with slip-collar well casings, reed switches with magnet emplaced in slip collars; electromagnetic oscillators with magnet emplaced in slip collars; and radioactive logging with tracers emplaced either in slip collars or directly into the formation.

The three contracts that were still in progress at the end of FY 1978 are:

1. An assessment of existing mathematical subsidence and deformation models by Golder Associates, Seattle, Washington.

2. High-temperature and high-pressure compressibility studies of cores from geothermal reservoirs by TerraTek, Salt Lake City, Utah.

3. Centrifuge compaction studies of reservoir materials by Colorado School of Mines, Golden, Colorado.

A more complete description of these three contracts may be found in Section 3 and Appendix A.

2.2 THE ASILOMAR WORKSHOP

A workshop was held in October 1978 at Asilomar, California, to (1) review the results of the completed GSRP research, (2) advise on changes needed to improve the usefulness of ongoing research, (3) assess the adequacy of the original plan, and (4) recommend revisions to the original plan. The workshop consisted of presentations on status and results of ongoing research. The approximately 50 workshop attendees broke into small subgroups to discuss the research and make appropriate recommendations. Oral presentations by a spokesperson from each group were made to the plenary group. At the end of the workshop, each participant was asked to fill out a questionnaire and to put in writing recommendations regarding any of the established research categories. An Executive Summary of the Asilomar Workshop is given in Appendix B.

2.3 TRANSITION TO THE REVISED PLAN

During the Asilomar Workshop, two major issues were raised that influenced the changes in the research program plan. First, DOE representatives asked the participants to consider the DOE/DGE program goal to accelerate geothermal plant construction. This brought about the need to focus on site-specific research, rather than to concentrate on generic or basic research activities. Second, many of the workshop participants felt that the original plan was too highly structured and not as easily comprehended as it should be.

As a result of these two factors, the main structure of the plan was reduced at the workshop to three elements, all of which have a site-specific orientation: (1) monitoring and measurement, (2) prediction, and (3) impact assessment. To these elements we later added a fourth, mitigation. The current simplified classification scheme is shown in Table 2.

Table 2. Current Research Elements and their Categories in the GSRP

Monitoring and Measurement	Prediction	Impact Assessment	Mitigation
Direct-monitoring instrument and technique development	Subsidence models	Case histories	Numerical simulations
Indirect techniques to estimate compaction at depth	Physical processes of subsidence	Environmental and economic effects	Field tests
Field (in situ) measurement			

3. THE REVISED PLAN

3.1 RESEARCH PROJECTS IN FY 1979 AND 1980

As a consequence of the GSRP Asilomar Workshop, a research plan was developed for FY 1979. This plan was modified after review by the DOE/DGE, and it was further refined through discussions with experts in subsidence research. One result of these reviews and discussions was the recognition that several of the research topics could not be comprehensively studied in one year. Consequently, the plan was expanded to include FY 1980. Those research projects planned for FY 1979 and 1980 are described in this section. Detailed Scopes of Work for all new contracts contemplated or issued during FY 1979 and 1980 are given in Appendix A. Table 3 shows the costs by Research Element for FY 1978 to 1981.

3.1.1 Monitoring and Measurement, Direct Surface Subsidence Monitoring

Manual for Monitoring Subsidence

Woodward-Clyde Consultants has produced a manual (Van Til, 1979) that reviews various monitoring methods and compares their installation, utilization, and accuracy. Utilization of these methods should enable planners and regulators to determine the natural rate of subsidence. In addition, the manual explains how to monitor induced subsidence.

Wellbore Measurements to Monitor and Measure Reservoir Compaction

Hostile-environment instrumentation and radioactive bullet logging seem to have promise for monitoring and measuring compaction directly. The Subsidence Program must try to accelerate the development of tools and techniques so that these will be available to industry as needed.

In FY 1978, Woodward-Clyde Consultants reviewed wellbore extensometers and inclinometers. Techniques and materials for improving existing instruments or developing new instruments were identified. Woodward-Clyde recommended that the following components be upgraded for high-temperature use: (1) magnetic materials, (2) electronic oscillators, (3) electronic line drivers, (4) reed switches, and (5) induction coil and tool materials.

Work Planned for FY 1979 and 1980. The Sandia Laboratories' hostile-environment tool-development program has identified for modification many of the same components identified by Woodward-Clyde and already has issued contracts to develop and test high-temperature components. In FY 1979, LBL contributed financially to Sandia contracts that meet the Woodward-Clyde recommendations. To date, LBL has received circuit diagrams for the construction

Table 3. Geothermal Subsidence Research Program Costs (thousands of dollars)

	Fiscal year			
	1978	1979	1980	1981
Program management	150	200	130	100
LBL in-house research	50	125	95	80
SUBCONTRACTS				
Prediction	149	503	255	150*
Measurement/monitoring	189	264	238	130
Impact assessment	196	22	220*	125*
	734	1114	938	585

* Geopressure subsidence research.

of a multiplexer that can withstand temperatures up to 200°C. Work is continuing at Sandia to improve electronic components that can be used in higher-temperature environments.

Assessment of Radioactive Bullet Logging

Radioactive bullet logging has been used with varying degrees of success to monitor vertical formation compaction in oil and gas fields. Although its potential is highly rated by some logging experts, its usefulness in geothermal fields is not known. To judge adequately the usefulness of radioactive bullet logging in geothermal fields, an assessment was made of the current state of the art of radioactive bullet logging and the potential for its utilization in geothermal reservoirs.

Work Completed in FY 1979 and 1980. The current state of the art of radioactive bullet logging was assessed in a report by Dunlap and Dorfman (1980), which includes a detailed bibliography, a review of tool-design principles, and temperature tolerances of such equipment. Systems most promising for geothermal utilization are identified, and suggestions are made on improving tool design. The report concludes that in cased holes the multiple casing collar system provides 10 times the accuracy of radioactive bullet logging. This difference would be particularly significant in hard formations that have low compaction coefficients and may exhibit lower pressure drawdowns.

3.1.2 Monitoring and Measurement, Indirect Techniques

Surface gravity and surface seismic measurements seem to have the most potential for use in monitoring the response of a geothermal reservoir to exploitation.

Precision Gravity Studies

The ability of precise surface gravity measurements to monitor the response of a reservoir to exploitation will be assessed. Gravity methods cannot be used alone to differentiate between elevation changes (surface deformation) and net mass changes within the reservoir. However, used with first- and second-order leveling and water-level monitoring, gravity methods might provide a cost-effective indirect method to indicate net mass changes in the subsurface due to extraction and/or injection of geothermal fluids.

Work to be Completed in FY 1979 and 1980. Professor R. Grannell, California State University at Long Beach, has completed an assessment of surface gravity measurements for monitoring subsidence-related net-mass changes. Her final report serves as a procedural guide for implementing a gravity study to investigate and monitor such subsidence-related formation changes and to identify subsidence study sites. Precision gravity surveys were conducted at a network of monuments over the Huber (Imperial Valley, California) and Cerro Prieto (Baja California) geothermal fields.

Seismic Studies

Reservoir and overburden rocks, particularly competent ones, may emit seismic-acoustic signals as they compact or fail because of stress changes. The objectives of this project are to assess the value of seismic monitoring as a guide to compaction phenomena in the subsurface, to correlate seismic activity with land subsidence, and to evaluate real-time monitoring techniques as a cost-effective means of acquiring and analyzing data.

Work Completed in FY 1979 and 1980. The Automatic Seismic Processor (ASP) has been completed by the University of California, Berkeley, Seismographic Station and was tested at The Geysers geothermal field. A report on the results from The Geysers will be published by March 1981. The Cerro Prieto field will be monitored by the ASP system in December 1981.

3.1.3 Reservoir Compaction and Subsidence Prediction

Assessment of Compaction Theories

Existing compaction and subsidence theories will be assessed and their applicability to geothermal reservoirs evaluated. Most theories were developed to explain the behavior of oil and gas reservoirs in relatively shallow unconsolidated aquifers and may not be adequate for deep, thermodynamically complex geothermal reservoirs. In addition, the inelastic and time-dependent response of rock systems to changes in effective stresses is not adequately understood. Such ignorance severely limits the accuracy of subsidence predictions.

Work Completed in FY 1979 and 1980. Comprehensive assessments of the applicability of existing compaction and subsidence theory to geothermal reservoirs have been completed by Carroll (1979) and Rudnicki (1980). The time-dependent inelastic behavior of brittle rock was examined on the assumption that the underlying mechanism of deformation is slow, environmentally assisted crack growth.

Assessment of Compaction-Subsidence Mathematical Models

Golder Associates, Seattle, Washington, was contracted to assess the adequacy of existing mathematical models for estimating vertical and horizontal deformation. In addition, they have made recommendations for additional research necessary to increase the capability of estimating subsidence.

Work Completed in FY 1979 and 1980. Proficiency assessment has been completed on the following models: (1) hand calculation of 1-D compaction, (2) 1-D coupled stress-seepage model, (3) nucleus of strain, (4) boundary integral equation method, (5) displacement discontinuity method, (6) finite element method, and (7) CCC. This work is reported in a series of four GSRMP reports (Miller et al., 1980). The authors' basic conclusions are summarized below.

1. The development of highly sophisticated, coupled models for reservoir flow and deformation is not desirable at this time. Not only is the use of overly sophisticated models not justified by available data, but, as was shown in the Austin Bayou case study, the coupling of flow and deformation increases cost more than it does accuracy.

2. Conceptual models should be developed to as great a level of sophistication as is permitted by available data. Mathematical models should be selected that are appropriate to the sophistication of the conceptual model.

3. In some situations, where production can be assumed known, reservoir flow modeling may not be necessary. This was true at Austin Bayou.

4. Further theoretical development of reservoir flow models appears to be appropriate. At present, lack of adequate reservoir flow theory places significant limits on prediction of the subsidence of geothermal reservoirs. Current theories have not, in general, been adequately tested. In addition, further theoretical work might be appropriate in the fields of multiphase and fracture/porous media flow.

5. Mathematical models should not be based only on state-of-the-art theoretical developments; there is also a need for models using simplifying assumptions such that they can be implemented by the field engineer. Possible simplifying assumptions include lower dimensionality, restricted physical processes, and limitation of calculation to static equilibrium conditions.

6. Current theory appears to be adequate for all practical deformation modeling problems. Although assumptions of homogeneity, isotropy, and linear elasticity are frequently gross, they often appear to be adequate relative to other inaccuracies introduced by lack of data. No single model is superior to all others. Golder tested six different models and found that each one was valuable in some situations and that none of them was good in all situations.

7. The range of mathematical models now in existence may be sufficient for most reservoir deformation problems. Accessibility, however, can be much improved; many models are in the public domain but are not widely known. Similarly, many can be made more usable by improving documentation, simplifying input and mesh generation, increasing efficiency, improving output format and display, and writing more general computer codes that would cover several different models.

their occurrence in some environmentally fragile coastal areas, there is a special need to begin a separate assessment of the problems and issues facing developers and to develop a research plan.

Work Planned for FY 1980. A survey will be made of the geotechnical, production, and environmental characteristics of geopressure geothermal resource areas. Representative areas will be chosen in Texas and Louisiana, and proposed development scenarios will be investigated to identify potential environmental, economic, and social issues.

3.2 THE INTEGRATED PROGRAM FOR FY 1979 AND 1980

In the context of the GSRP organization shown in Table 2, the research program during FY 1979 and 1980 concentrated mainly on two elements: (1) monitoring and measurement, and (2) prediction. To illustrate how the various projects interrelate, we show in Figure 1 a block diagram with the appropriate interfaces between projects within GSRP and other DOE/DGE Programs. Theoretical and laboratory studies (left side of the figure) deal with predictive elements of subsidence. Field measurements (right side) deal with the monitoring and measurement elements of the program.

There is no one-to-one correspondence between the program blocks in Figure 1 and projects funded under GSRP. Because subsidence is part of the fundamental problem of reservoir dynamics, GSRP projects interface with projects under the DOE/DGE Geothermal Reservoir Engineering Management Plan (GREMP). These are indicated in Figure 1 by asterisks.

3.3 RESEARCH PROJECTS PLANNED FOR FY 1981

The following projects have been recommended for funding in FY 1981 by DGE/DOE.

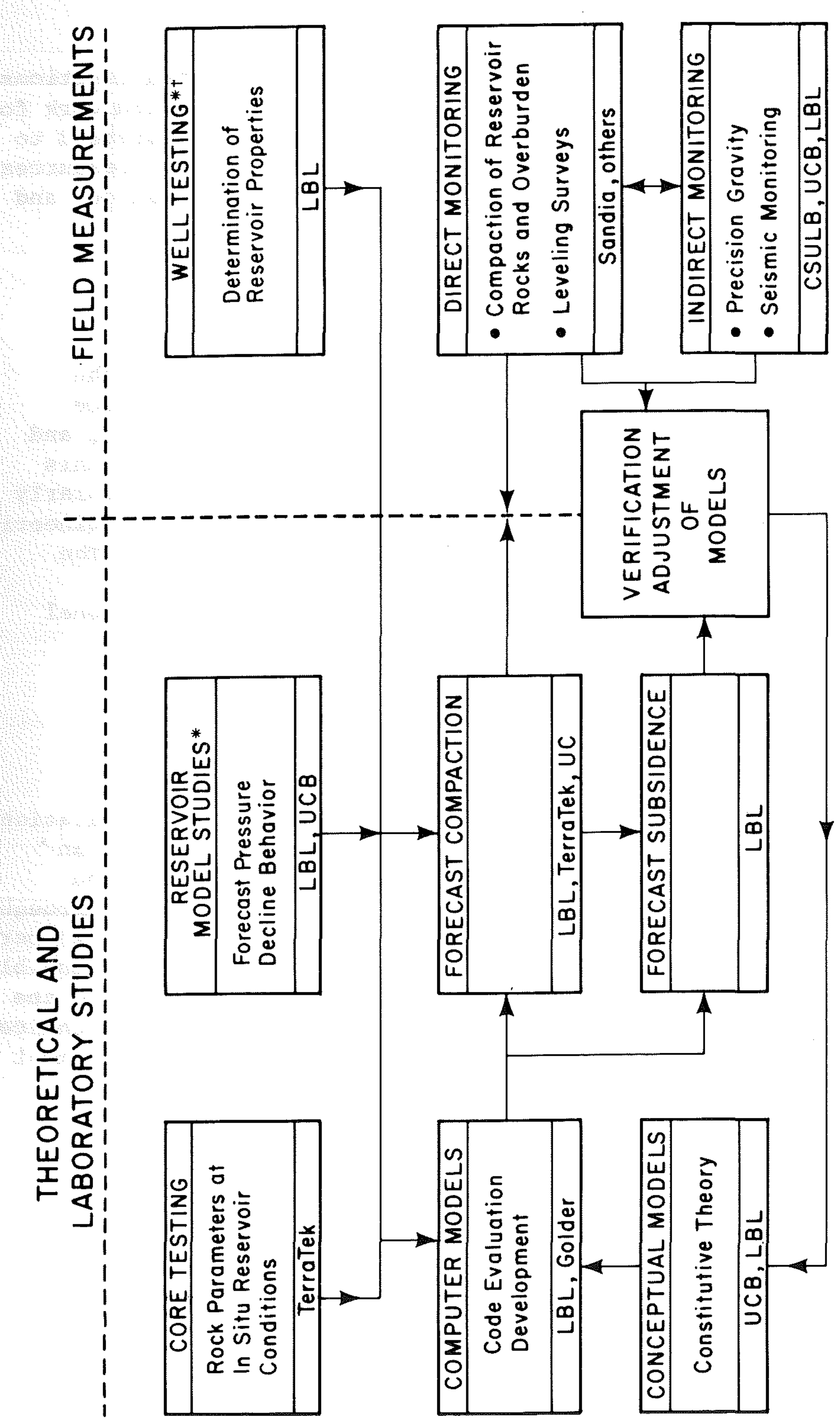
1. Site-specific numerical analysis of subsidence of geopressured and hydrothermal reservoirs.

2. Establishment of the rates and distribution of subsidence in the Gulf Coast area.

3. Releveling of the Imperial Valley.

4. Continuous gravity monitoring at The Geysers by University of California, San Diego.

5. ASP and gravity monitoring at Cerro Prieto.



* Geothermal Reservoir Engineering Research Project
† Geothermal Log Analysis Research Project

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Figure 1. Interfaces between projects within GSRP and other DOE/DGE programs.

4. GSRP MANAGEMENT PLAN

Figure 2 shows the management organization and the associated functions of the GSRP. Although the plan is presently heavily oriented toward work for the Hydrothermal Support Branch within DGE, the program is also intended to serve the Advanced Technology Branch, which has responsibility for resources of the geopressure type. This section describes the GSRP organizations and division of responsibilities during the period FY 1977 to 1980.

4.1 DEPARTMENT OF ENERGY, DIVISION OF GEOTHERMAL ENERGY

The Manager, Environmental Research, acting with the concurrence of the Branch Chief, Hydrothermal Support, and the Director, DGE, will provide overall programmatic guidance for the definition, planning, direction, and control of the program. The Manager is responsible for coordinating this program with the various national geothermal program elements, particularly the research and management plans in Induced Seismicity, Reservoir Engineering, Exploration Technology, Well Logging, and Well-Log Instrumentation. The Manager also is the principal coordinator with the U.S. Geological Survey and other federal and state agencies participating in the national geothermal program.

4.2 LAWRENCE BERKELEY LABORATORY

LBL provides administrative, procurement, and technical support for the Subsidence Research Plan. In detail, LBL is responsible for preparation and periodic revision of the Program Plan and implementation of the plan through (1) selection and procurement of contractors, (2) technical and financial review of contractors' activities, (3) technology transfer through publication of contractors' reports and a Subsidence Newsletter, and (4) periodic workshops to review and help redirect the Plan. LBL is also responsible for an in-house subsidence research project that lends basic support to the Plan, serves to investigate new research directions, and provides a technical bridge between GSRP and the LBL Geothermal Reservoir Engineering Management Plan through research in geothermal reservoir dynamics.

4.3 TECHNICAL ADVISORY COMMITTEE

LBL has put together a Technical Advisory Committee with representation from the geothermal industry; city, state, and federal regulatory bodies; national laboratories; and academic institutions to review periodically the GSRP and research results. The Committee is responsible for helping LBL plan the program, making research recommendations, reviewing technical proposals, reviewing the research plan, and judging the adequacy of results.

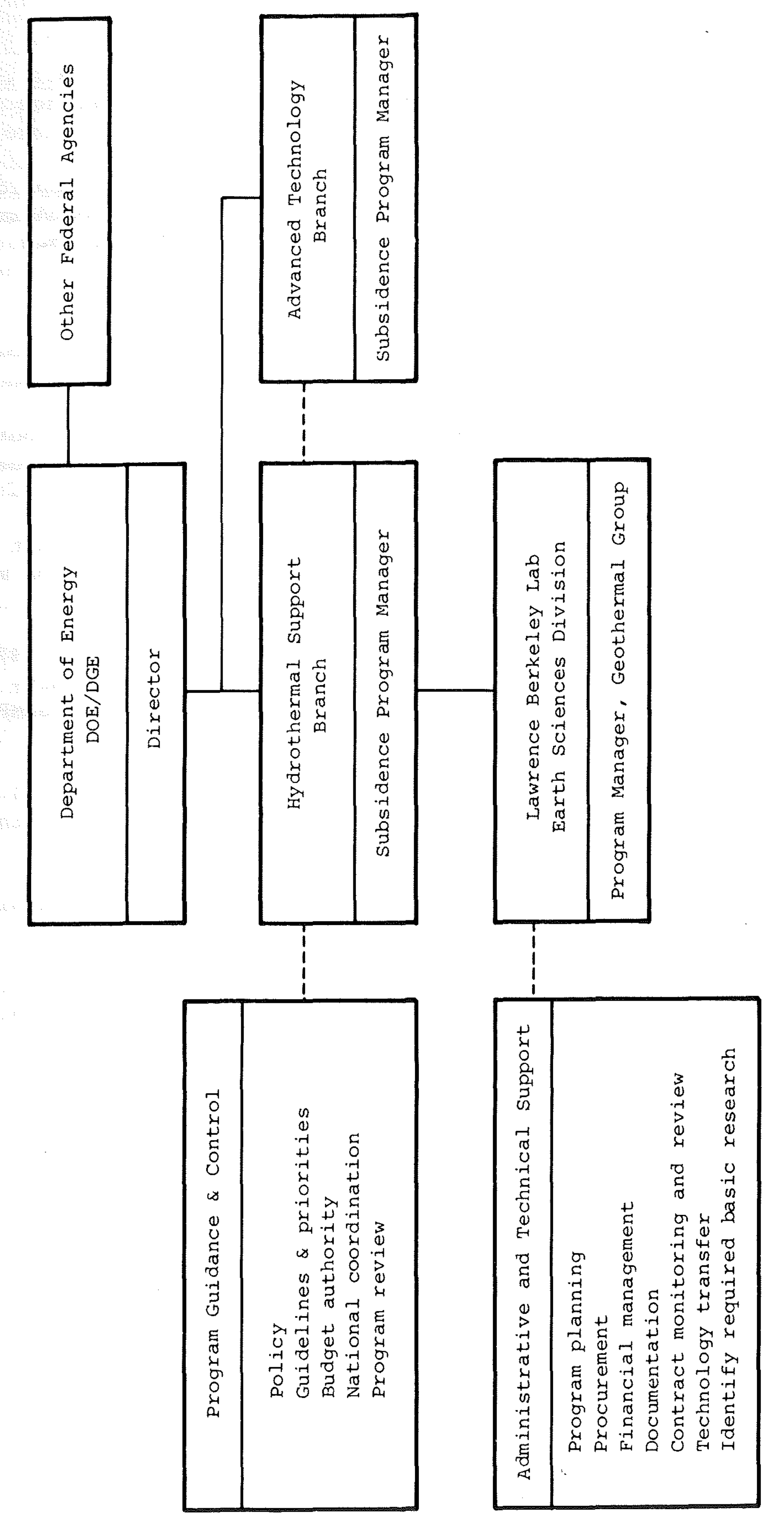

Figure 2. Geothermal subsidence research program management organization and functions.

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APPENDIX A. DETAILED SCOPES OF WORK, FY 1979 TO 1982

In this section we give the detailed Scopes of Work of all projects either undertaken or contemplated from FY 1979 through 1982. The projects are listed in Table A-1.

A.1 DIRECT MONITORING AND MEASUREMENT TECHNIQUES

A.1.1 Hostile-Environment Component Development

Problem Statement

Current logging instruments either cannot operate within the 5,000 to 20,000 ft range required or they cannot withstand the in situ geothermal conditions. Without such measurement capabilities, we have no direct means for monitoring reservoir compaction.

As a necessary precondition for much of the direct monitoring and measurement research, improvements in present instruments or new instruments are required for use at great depths or where high temperatures and corrosive conditions prevail. Instrument concepts should be identified, and prototypes should be built and tested. For example, we must develop the capability to measure the vertical distance between two points in a deep geologic formation with an accuracy of at least 0.05 ft per 100 ft of interval distance. Measurements must be made under hostile conditions of temperature, pressure, and salinity.

Research conducted under the LBL GSRP has identified the following components as the most promising for downhole subsidence monitoring and measurement: (1) electronic circuits, (2) coils and transformers, (3) magnetic materials, (4) reed switches, (5) casing collar locators, (6) instrument housings, and (7) cableheads, cables, and uphole geothermal wireline equipment.

Scope of Work

Several of the above-mentioned items are currently being developed and field-tested through Sandia's Geothermal Logging Instrumentation Development Program. To accelerate the development of these items, LBL is providing funds to Sandia Laboratories for allocation to Sandia subcontractors listed on page 22 to assist in the development of instrumentation.

TABLE A.1. Projects Undertaken During FY 1979 and 1980

Element	Category	Project
Monitoring and measurement	Direct measurement	Hostile environment components (Sandia)
		Radioactive bullet logging assessment (University of Texas)
	Indirect measurements	Precision gravity (C.S.U., Long Beach)
		Seismological investigations (U.C., Berkeley)
Prediction	Theory	Theory of subsidence (Univ. of Illinois & U.C., Berkeley)
		Assessment of numerical codes and theory (Golder Associates)
		Compaction and subsidence modeling (LBL)
	Laboratory studies and physical modeling	Creep tests, elastic modeling of reservoir rocks (TerraTek)
		Centrifuge tests (Colo. Sch. of Mines)
Impact assessment	Case histories	Chocolate Bayou case study supplement (EDAW-ESA)
	Environmental and economic effects	Compilation of environmental and economic effects at specific sites (EDAW-ESA)
		Geopressure-geothermal research plan (EDAW-ESA)

Development Item	Subcontractor
High-Temperature Electronics	Teledyne Philbrick
Line driver	
Pulse shaper	
Voltage-to-frequency converter	
High-Temperature Magnetics	Texas A&M University
Identify suitable, commercially available, long-life magnetic materials	
Identify suitable, commercially available transformer materials and prototype designs	
Mechanical Components	Gerhart Owen
Instrument housings	
Casing-collar locators	
Cable heads	
Sidewall shoes	
Induction coils	

A.1.2 Assessment of Radioactive Bullet Logging for Compaction Measurement

Problem Statement

Although radioactive bullets have been used in oil fields for compaction studies, they have not yet been applied to the geothermal environment. Research is needed to review the state of the art in radioactive bullet logging and its relation to subsurface compaction and to identify ways in which bullet logging can be adapted to monitoring in geothermal wellbores.

Scope of Work (FY 1979 and 1980)

Task 1: Assess the current state of the art of radioactive bullet logging. The assessment included a comprehensive literature review and bibliographic compilation and a detailed review of available tool-design principles, radioactive sources, accuracy and repeatability of wellbore

measurements, commercially available equipment, and the temperature tolerance of such equipment.

Task 2: Evaluate the merits of existing logging systems and identify systems having the most promise for geothermal utilization.

Task 3: Investigate and suggest methods for conversion and enhancement of best present logging system to enable systems to operate in geothermal wellbore conditions and to deliver the desired accuracies.

Scope of Work (FY 1981 and 1982)

Successful completion of the development of hostile-environment components and the identification of radioactive bullet logging systems will be followed by development of prototype instruments.

Task 1: Develop prototypes for most promising concepts. Prototype instruments will be built for laboratory and field testing. The number of prototypes to be built will be determined in this task. Laboratory testing and calibration will also be performed in this task.

Task 2: Field test prototype instruments. The prototypes will be field tested. This includes developing test procedures to assure accurate results and to compare results.

Task 3: Prepare a draft report. The results of the research project to this point should be critically reviewed. A draft report will be prepared and may be presented at a workshop seminar or to a committee of selected professionals. Recommendations for conducting the review are required in the proposal.

Task 4: Prepare a final report. The final report will include descriptions of (1) tabulation of test data, (2) results and conclusions, (3) instrument specifications and design, and (4) recommendations for production and application.

A.1.3 Indirect Surface Techniques to Monitor and Measure Reservoir Compaction

Problem Statement

During geothermal production, bulk properties of rock and fluid change due to changes in pressure and temperature, which, in turn, are affected by:

1. The amount and rate at which the fluids and heat are withdrawn from the reservoir.

2. The fluid and heat recharge.

3. The in situ stress distribution.

To use indirect methods, which depend on small changes in the bulk properties, we must make accurate measurement of those parameters related to subsidence, and we must develop the supporting theory.

Improved field-measurement equipment and new measurement techniques are required for accurate determination of changes in the reservoir bulk parameters. New theories are needed to relate measured parameters to subsidence.

Discussion of a solution

Several bulk properties of the reservoir fluid and rock might be of use in estimating subsidence by indirect methods. They are:

1. Temperature
2. Pressure
3. Fluid flow rate
4. Fracture characteristics
5. Fluid composition
6. Permeability
7. Porosity
8. Density
9. Formation depth and shape
10. Electrical resistivity
11. Lithology
12. Mineralogy
13. Acoustic properties

Possibly no single property can, by itself, be correlated directly with subsidence-related compaction. But, for example, a well test using instruments that measure pressure, temperature, and flow rate might provide accurate estimates of permeability and porosity. These could then be related to subsidence. Fractures, interbed inhomogeneities, varying lithology, mineralogy, and fluid composition complicate the establishment of a theory relating the bulk parameters and subsidence. Nevertheless, because well testing is a highly developed technology, it may be possible to obtain the accuracies necessary to establish such a theory.

Other possibilities include the measurement and correlation of fracture properties with formation compaction and of the differential changes with seismic velocity in the reservoir formation as a function of pressure, temperature, porosity, etc.

In these examples, it is assumed that instruments and techniques can be adapted that have sufficient accuracy and repeatability to achieve correlation between formation bulk properties and the small, but important, changes in the formation. A major requirement of the research will be the derivation of the correlations between bulk properties and the subsidence-related formation movement. Of the indirect surface techniques reviewed, precision gravity and seismological investigations seem to hold the greatest promise for providing useful information.

A.1.3.1 Precision Gravity

The purpose of surface gravity research is to assess the applicability of precise gravity measurements to monitoring a geothermal reservoir's response to exploitation. Gravity measurements, if applicable, could provide a cost-effective indirect method to indicate net mass changes in the subsurface due to extraction and/or injection of geothermal fluids. Net mass changes might also be caused by alteration of the subsurface chemical/thermodynamic environment, changes in the volume of subsurface formations, or changes in formation void ratios. How these changes might be related to subsidence is of paramount interest to the Geothermal Subsidence Research Program.

Scope of Work (FY 1979 and 1980)

Task 1: Assess the applicability of surface gravity measurements to monitoring the various subsidence-related net-mass formation changes that could be caused by exploitation of a geothermal reservoir.

Task 2: Present an implementation plan for a gravity study to investigate and monitor subsidence-related formation changes.

Task 3: Identify a suitable site, or sites, where the survey plan should be implemented.

A.1.3.2 Seismological Investigations

The very high level of microearthquake activity at The Geysers field is apparently a response, at least in part, to changing stress fields induced by withdrawal and injection of steam and water. With several hundred small earthquakes occurring within the field daily, modern microearthquake recording and analysis techniques provide a means of monitoring with high precision the spatial and temporal patterns of strain energy released through faulting. Earthquake parameters such as location, fault orientation, direction of motion, rupture dimension, and stress drop can be estimated for the small events within the general field area. These parameters provide a dynamic model that can be used to investigate the mechanism of subsidence, as well as any other manifestations of the changing energy budget within the field.

Subsidence phenomena in a producing geothermal area may proceed in two stages. The first and most important is the relatively rapid collapse of large fractures, joints, and connected pores in response to pore pressure reduction. In the host rock matrix, pore pressure also decays, but at a much slower rate, resulting in a much more gradual secondary subsidence due to the closing of host rock microcracks.

Subsidence phenomena are also affected by the increase in pore pressure that accompanies reinjection of water into the geothermal reservoir. Increase in the pore pressure causes a corresponding decrease of the normal stress across the joint. Because most rock joints are subjected to a certain amount of shear stress under the lithostatic load, a decrease in normal stress may induce frictional sliding along some joints.

In a producing geothermal field, it may be difficult to differentiate between the effects of each mode of subsidence. In the laboratory, however, the various parameters can be precisely controlled and identified. It is the purpose of the proposed laboratory program to provide some basic understanding of the effect of each relevant parameter.

Scope of Work (FY 1979 and 1980)

Task 1: Complete a field-recording ASP program to be conducted in FY 1980. Emphasis has been on accelerating the fabrication and testing of Automated Seismic Processor (ASP) in order to field the 16-channel system on schedule. This acceleration required the devotion of increased manpower to system hardware, software, and fabrication.

Task 2: Collect microearthquake data at The Geysers with the ASP. A dynamic model of the stress field will be based on the results of the processed earthquake source parameters, and the investigation will then examine the implications for the subsidence process. The combined effort is directed toward better understanding of energy release through deformation, with the hope of controlling the process. The ASP system has been used at The Geysers field, and results of the study will be published in 1981.

Task 3: With calibrated high-temperature transducers in the simulated laboratory geothermal environment, investigate the deformation behavior of rock joints and their associated acoustic emissions. The deformation behavior of joints and cracks in rocks in the geothermal environment will be investigated to determine crack properties. Emphasis will be on deformation as a function of changes in pore pressure in the joint and deformation in relation to microseismic events (acoustic emissions).

Scope of Work (FY 1981 and 1982)

If the results of the surface gravity assessment and The Geysers seismic study indicate that these techniques are useful indirect indicators of reservoir compaction, the same techniques will be extended to other geothermal reservoirs.

A.2 RESERVOIR COMPACTION AND PREDICTION

A.2.1 Assessment of Compaction and Subsidence Theories

Problem Statement

A change in theoretical perspective may be needed to explore the physical processes of subsidence. The traditional interest of hydrologists and petroleum engineers has been in volume and rate of fluid flow. Because fluid movement rates are much greater than skeletal rates (rock matrix deformation), the skeletal rates have been ignored, with negligible error, for the purpose of estimating the transient distribution of fluid pressure and fluid flow. However, to predict cumulative vertical and lateral movement of the land surface, an adequate theory is needed for the neglected skeletal displacement field. Although Golder Associates stated that present deformation models are more sophisticated than the present data base, it is felt that more theoretical work is needed in order to understand the importance of fundamental physical processes to subsidence. These fundamental processes are:

1. The relationship of the lateral displacement field to the vertical displacement field.

2. The upward migration of a stress field and resulting skeletal movement (lateral and vertical) from the reservoir through the overburden to the land surface.

3. The difference between the compressional behavior of a reservoir (the directly stressed environment) and that of overburden material (the indirectly stressed environment).

4. The effect of fluid velocity on lateral skeletal displacement in a reservoir.

5. The relationship between the mechanical properties of a system at depth and its thermal and pressure properties.

6. The difference in natural response due to the compaction of unconsolidated and consolidated material; e.g., the difference between the effects of bulk fracture-compressibility and intergranular pore-compressibility on compressional properties.

7. The importance of fractures--their density, geometry, and orientation--to subsidence potential.

8. The influence of grain orientation, shape, size, and mineral content (for example, mica content) on rock compaction.

9. The variation in skeletal response due to (a) a gradual decrease in pore pressure, (b) a sudden step decrease in pore pressure, and (c) a gradual increase in total load.

10. The effect of loading (e.g., cyclic loading) on skeletal behavior.

11. The relationship between recoverable and nonrecoverable skeletal behavior.

12. The differences in the transient behavior of skeletal material from its ultimate response to the same stress.

13. The effect of pumping on the thermal (or pressure or mechanical) properties of a reservoir. Determine whether the in situ elevated temperature (or pressure) boundaries of a reservoir move vertically or laterally in response to systematic induced changes in fluid pressure.

Investigation of the physical processes of subsidence will require (1) a comprehensive review and understanding of existing theory and (2) identification of the theories most relevant to subsidence.

Research Objectives

There is a need for a constitutive theory for skeletal deformation that exhibits the following features:

1. It should be a three-dimensional theory rather than a hydrostatic theory. (This will allow consideration of horizontal and vertical displacements.)

2. It should be a nonlinear inelastic theory and should account for loading and unloading behavior. (This will allow consideration of recoverable vs. nonrecoverable local behavior and thus of recoverable vs. unrecoverable subsidence.)

3. It should allow for anisotropy of geologic media. Transverse anisotropy may be particularly important (properties normal to the bedding plane differ from those in the bedding plane). The notion of structural vs. intrinsic anisotropy will be explored. Existing effective stress laws assume isotropy and can be generalized. Experiments should investigate the degree of anisotropy.

4. Local time-dependent behavior should be included. Surface subsidence exhibits a pronounced long-term creep behavior. It is not yet clear to what extent this is related to local time-dependence as opposed to flows or stress migration in the overall formation.

Some of the foregoing analysis can be based on spherical model theory, which already exhibits nonlinearity, irreversibility, and pore pressure

effects. It also allows for consideration of a variety of loadings, slow changes in pore fluid pressure or applied pressure, cyclic changes, and sudden changes in pore fluid pressure.

Interaction between fluid flow and skeletal deformation is treated in a variety of ways, including Biot theory and theory of interacting continua (TINC). We will investigate the relationship between the two theories and the possibilities for an improved description of the phenomena.

Scope of Work (FY 1979 and 1980)

Contracts were awarded in FY 1979 to Professors M. Carroll, University of California, Berkeley, and J. Rudnicki, University of Illinois, Urbana, to undertake research as specified by the following tasks.

Task 1: Briefly review existing theories and relate them to readily available data on subsidence.

Task 2: Identify and examine the basic physical processes that influence geothermal subsidence. Work focused on two main topics: (1) deformation of a fluid-saturated porous material due to changes in pore fluid pressure or applied stress, and (2) interaction of fluid flow and skeletal deformation.

Task 3: Study constitutive theory to provide a theoretical framework for experimental, field, and numerical work and to assess the role of physical processes that are not accounted for by simple linear theories. The work concentrated on (1) determining the structure of macroscopic creep behavior by assuming the microscale mechanism of time-dependent crack growth and (2) assessing the effects of non-Darcy behavior on fluid flow: inertial and viscosity effects due to rapid flow through large fissures and deviations from local pore fluid pressure equilibrium.

Task 4: Investigate boundary-value problems using simple linear constitutive theories. The goal of these studies was to elucidate the role of coupling between the deformation of the solid matrix and thermal and fluid mass diffusion. Although linear Biot theory is probably inadequate to describe fully subsidence in geothermal systems, analytic solutions obtained using this theory will be useful as constraints on numerical solutions incorporating more sophisticated constitutive behavior and to guide the interpretations of field data.

Task 5: Identify new directions for theoretical development and experimental investigations of physical processes that influence geothermal subsidence.

A.2.2 Laboratory Studies on Cores

Problem Statement

A substantial drop in pore pressure will accompany the fluid production from a geothermal reservoir. Reinjection--or injection of other fluids, if used--will not necessarily alleviate local pore pressure reduction, since the injection zone and the production zone may not coincide. As pore pressure declines, the effective overburden load will increase and the rock will compact. It is important to predict eventual subsidence, but this will be dependent on our ability to relate rock compaction to the variables of pore pressure, pore fluid type, stresses, temperature, and time. Cores of reservoir rocks are available, and these should be tested under in situ conditions, and appropriate rock constitutive models and their parameters should be determined for input to the methodologies of subsidence prediction.

Research Projects (FY 1979 and 1980)

Over the past several years, the DOE/DGE has made a substantial effort to develop high-temperature, high-pressure, geotechnical laboratory capabilities at TerraTek, Inc., Salt Lake City, Utah. To take advantage of TerraTek's capabilities, LBL has contracted for TerraTek to analyze cores from two geothermal reservoirs: East Mesa, Imperial Valley, California; and Cerro Prieto, Baja California, Mexico. A final report will be published in February 1981.

Scope of Work (FY 1979 to 1981)

Task 1: Pre-test analysis. Prior to laboratory measurements, the TerraTek machine was modified to do long-term creep tests. Basic properties of cores, such as density, porosity, and mineralogy were established. The fluid chemistry of the fields was studied so that the fluids used during testing would match those in the geothermal environment.

Task 2: Experimental testing. The initial phase of testing established the basic short-term (noncreep) mechanical properties of the rock. Hydrostatic and triaxial testing established small-deformation elastic moduli, basic inelastic hysteretic responses to stress cycling, and the sensitivity of compaction onset to the exact choice of simulated in situ conditions of stress, pore pressure, temperature, and pore fluid type. In addition to testing production-zone cores from East Mesa and Cerro Prieto, rock from overlying shale layers at East Mesa were tested. Starting at simulated in situ conditions, pore fluid was withdrawn from samples to simulate drawdown. Several stress geometries and several rates of drawdown and cycling and were used. Ultrasonic velocities were monitored during many of the experiments to seek possible correlations with acoustic velocity logs. To determine that part of the time-dependent reservoir compaction that is an intrinsic rock property, creep tests were performed at reservoir conditions by reducing pore pressures and monitoring deformation for periods of 15-30 days. Dependence of reservoir compaction on fluid phase was investigated.

Task 3: Theoretical analysis. The compaction behavior observed experimentally will be interpreted in terms of a poro-elastic constitutive model. The creep behavior will be compared to several models, such as the spherical pore model. For constitutive modeling, a general model that incorporates time-dependence, pressure gradients, and other necessary effects will be developed for future use in computer models for subsidence prediction.

A.2.3 Subsidence Models--Assessment of Numerical Codes and Theory

Problem Statement

It is not known whether, or how well, available mathematical models estimate subsidence. Upon completion of the Golder study to evaluate subsidence models (see Section 3.2.1), additional research may be necessary to develop models to meet the geothermal program's needs. As applied to geothermal systems analysis, subsidence modeling may be treated as a two-part mathematical excercise:

1. Simulate reservoir deformation, assuming that the reservoir deforms in response to internally generated stresses resulting from the reduction of pore fluid pressures.

2. Simulate deformation of the overburden, assuming that the overburden deforms in response to a displacement at its interface with the deforming reservoir.

Although several computer codes with varying levels of sophistication exist, we must yet evaluate the merits of these codes by applying them to known field situations. Results will help us to choose the most promising approach for subsidence modeling--i.e., one that combines accuracy with economy of effort in relation to the quality of field data available. The codes will also be run for comparisons with laboratory tests on physical models.

Scope of Work (FY 1979 and 1980)

Late in FY 1978, Golder Associates of Seattle, Washington, was awarded a contract for the following general study:

1. Assess the individual attributes of available mathematical models to determine if the programs do what the developers claim and, if so, how well each performs.

2. Determine through studies of both real and hypothetical subsidence case histories the significance of the attributes of different mathematical models. For example, when can a model that does not couple flows with deformations do as well as a coupled model? When is an elastic material model inadequate?

The results of those two research efforts will be synthesized to give:

1. Detailed assessments of the available models: What types of system can they simulate and what types can they not?

2. Projected assessment of models that are still being developed.

3. Recommendations on the need for improved numerical models.

4. A general perspective on the limits of mathematical models. (It may in fact never be feasible to predict geothermal subsidence accurately.)

The study was subdivided into the following tasks:

Task 1: Decision process. Decide how to categorize the models. Contact computer-program owners and establish program availability. Categorize the available models and select a representative group for detailed evaluation.

Task 2: Proficiency assessments. Assess the proficiency of each of the selected programs in each model category.

Task 3: Case studies. Collect data on real cases. Select the two "best" cases to simulate, and define a more general hypothetical third case. Perform detailed assessments of the significance of the different model categories in each case. Review the physical processes of subsidence, and assess the theoretical importance of the model categories.

Task 4: Review and report. Review and synthesize results of Tasks 1-3.

Task 5: Prepare final report.

A.2.4 Physical Modeling, Centrifuge Tests

Problem Statement

Regarding subsidence, one class of basic tests that can be performed in the centrifuge deals with the determination of (1) the behavior of typical constituents of earth materials under increasing gravity loads, (2) the behavior of composites of these materials, and (3) the response of these materials when they make up parts of models subjected to high g loads.

Centrifuge tests provide a means of studying the effects of fractures (fracture density, orientation) if sample preparation techniques can be mastered that allow us to build into models the desired fracture pattern.

Scope of Work (FY 1979 and 1980)

In late 1978, the Colorado School of Mines, Golden, Colorado, was awarded a research contact to make centrifuge tests of geologic media.

Task 1: Perform a literature review. The available information on the geology of oil and gas reservoirs, aquifers, and geothermal reservoirs was compiled and analyzed. This information was then employed to design centrifuge test models. Thus it will be possible to incorporate into physical models local effects of alteration, brecciation, fractures, bedding, etc., which are difficult to model numerically.

Task 2: Procure rock samples. Rock samples (cores and larger size samples) were obtained from sites of active geothermal operations or experimentation in the United States. Other samples were obtained whose properties are similar to those of rocks at geothermal sites.

Task 3: Perform physical property tests. Laboratory tests on core-size specimens included the following:

A. Axial and triaxial compaction

B. Strengths

1. tensile
2. compressive
3. shear

C. Elastic parameters

D. Thin section investigations

1. composition, mineralogical
2. composition, approximate chemical
3. granular structure
4. subgranular structure
5. cementing material

E. Density

F. Porosity and permeability

Task 4: Perform centrifuge tests--small scale. Diagnostic tests in a small-diameter centrifuge were accomplished using the University of Missouri's (Rolla) 7-ft-diameter centrifuge.

Task 5: Prepare final report. A final report was scheduled for August 1980.

A.2.5 Compaction and Subsidence Modeling at the Lawrence Berkeley Laboratory

Problem Statement

During the past several years, LBL has become a major center for the development of computer codes to model the response of geothermal reservoirs to production. The current treatment of subsidence in the LBL codes assumes the one-dimensional theory of Terzaghi. Recent conceptual analysis suggests that if one could make a reasonable assumption that a geothermal reservoir is linearly elastic, then the current LBL models can be generalized to handle three-dimensional deformation of the reservoir and reservoir overburden.

Scope of Work

Task 1: Improve LBL models TERZAGI and CCC to compute lateral deformation within the reservoir.

Task 2: Update and finish the program for the dual reservoir-overburden model.

Task 3: Simulate a field problem of interest using the improved models.

A.2.6 Large-Scale Physical Modeling and Effect of Sample Size

Problem Statement

The special triaxial testing facility of the University of California, Berkeley, offers a unique opportunity to study the compressive behavior of large cores (approximately 95 cm in diameter by 183 cm in length) or physical models. Located at the Richmond Field Station, the apparatus consists of a hydraulic chamber 200 cm in diameter and 250 cm in height. Confining pressures of up to 6900 KPa (1000 psi) are possible, and a steel piston through the top of the chamber can exert up to 17.8 MN of vertical load on a specimen. The chamber may be used for both uniaxial and pseudotriaxial tests. The apparatus provides a means for studying sample-size effects, allowing for the comparison of results of tests on smaller machines.

Scope of Work (FY 1979 and 1980)

Although the research was not undertaken during the FY 1979 and 1980 period because of scheduling problems on the machine and the extremely high cost of building and testing a sample, the following tasks were identified:

Task 1: Assess how best to utilize the chamber for subsidence research, and design research program.

Task 2: Conduct sample-size effect study and analyze data.

Task 3: Construct a physical model for verification of numerical subsidence models.

A.3 IMPACT ASSESSMENT

A.3.1 Economic and Environmental Effects

Problem Statement

Information on potential environmental and economic effects of subsidence is needed in the planning process for geothermal field development. In geothermal areas with high population densities and/or intense agricultural or industrial usage, only minor subsidence might be tolerated. In contrast, many potential geothermal areas are located where subsidence is not a major concern. The evaluation of such effects prior to the authorization to build a new geothermal facility would accelerate the approval process and greatly assist the field operator during the operational phase.

Discussion of a Solution

Currently there are some published environmental or economic impact data on subsidence caused by the withdrawal of fluids (hydrocarbons, groundwater, or geothermal fluids). These data need to be compiled and used with geologic and land use data to make an environmental and economic impact study for prospective geothermal areas.

Scope of Work

This project was not pursued in FY 1979 and 1980 because it received a relatively low priority rating.

A.3.2 Preparation of a Subsidence Handbook for Regulators and Developers

Problem Statement

Regulators and developers recommended that a subsidence handbook be prepared and published as a companion volume to the EDAW-ESA report "Environmental and Economic Effects of Subsidence" (Viets et al., 1979) and distributed to regulatory and planning agencies, communities, citizen groups, etc. The topics might include:

1. The Subsidence Process: What is subsidence? What causes it? What are the surface and subsurface phenomena associated with it (e.g., vertical and horizontal movements, horizontal strains, fissures)? How fast does it happen? Where has it occurred in the world? How many geothermal areas have experienced subsidence? Can it be predicted?

2. Subsidence Damage: What types of damage can result from subsidence? Where has subsidence damage occurred? Does subsidence always cause damage? Are some areas more susceptible to damage than others? How can sensitive areas be identified in advance? Can damages be predicted? Can natural environmental systems as well as human systems be affected? Are there public safety as well as property damage risks from subsidence? How hazardous or risky is subsidence relative to other natural hazards in terms of damage potential, public safety, and dollars lost?

3. Subsidence Control and Damage Mitigation: Can subsidence be controlled? Reversed? What can be done to monitor and control reservoir development and subsidence before damage occurs? What is reinjection and how effective is it? What can be done to protect existing and new land uses and facilities in an area before subsidence damage occurs? Have these mitigation measures been used in other areas? How effective were they? How costly are they? Who pays for the mitigation measures? Who pays for damages? Can insurance be obtained to protect against subsidence damage? How can acceptable levels of damage be established? What criteria should be used?

4. Site-specific Planning: What can local, state, and federal agencies do to anticipate and avoid subsidence damages? How can reservoir developers, regulatory agencies, utility companies, and other interested parties work together to anticipate and solve problems before they occur? What step-by-step program should be followed? What sources of technical and financial aid are available for planning to minimize subsidence damage? How can subsidence and its potential damage be handled in environmental impact statements for specific projects?

5. Appendix: The appendix might include the following components: (1) a checklist of subsidence impacts and mitigation measures, (2) sources of information and aid, and (3) a generic site example to illustrate the use of materials contained in the handbook.

Scope of Work (FY 1979 and 1980)

This project was not started in FY 1979 or 1980. It was felt that insufficient information and experience were at hand.

A.3.3 Chocolate Bayou Case Study Supplement

Problem Statement

In their Chocolate Bayou Case Study, EDAW-ESA's conclusions regarding the

relationship between subsidence and geopressured gas-brine production are questionable because of weakness and/or deficiencies in the data collected. The following types of data, among others, are needed to develop a thorough case study:

1. Detailed information for each well, rather than estimates or values averaged over the entire field: fluid production, pressures, temperatures, material engineering properties, lithology, permeabilities.

2. Subsurface geology.

3. Shallow groundwater extraction.

4. Surface leveling.

5. Subsurface deformation.

In cases where these data are available, a substantial effort should be made to obtain them from oil companies and agencies.

The objective of this research is to assess the availability and applicability of additional data for improving the Chocolate Bayou Case Study and for determining the feasibility and cost of collecting such data.

Scope of Work (FY 1979 and 1980)

Task 1: Assess data needs.

A. Specify all types of additional data needed for the Chocolate Bayou Case Study so that it will:

1. contain sufficient information for mathematical modeling of subsidence,

2. be useful for developing geothermal potential maps for assessing the risk of subsidence in other Gulf Coast geopressured wells, and

3. provide sufficient information for an understanding of what is happening at the Chocolate Bayou field.

B. Provide detailed specification of the quantity and accuracy of data desired.

Task 2: Review data availability. For each type of data specified in Task 1, carry out a comprehensive search of their availability through interviews with oil company operators and researchers, local government officials, university personnel, and other data repositories such as the Texas Railroad Commission. Samples of the data will be collected for use in the final report.

Task 3: Assess impact of additional data on case study. Coordinate with other LBL contractors in assessing the sufficiency of the Chocolate Bayou data base reviewed in Task 2 for carrying out model development and validation studies. Also assess the use and importance of each type of data in verifying or disproving conclusions of the original case study.

Task 4: Presentation of results. Provide a formal presentation detailing the availability and usefulness of data for improvement of the Chocolate Bayou case study. The presentation includes:

A. The type and location of the data desired (and samples of the data, where possible).

B. How to obtain the data.

C. An explanation of the extent to which the case study could be improved with the improved data base.

D. An explanation of the extent to which mathematical modeling efforts could be improved with the added data.

E. The approximate level of effort required to improve the data base.

A.3.4 Geopressure Subsidence Research

Problem Statement

The Gulf Coast area, particularly the coastal region, is an extremely fragile environment in which a small amount of man-induced subsidence could have a significant effect on both the environment and human activities (commercial, living, agriculture, etc.). Because geopressured zones may be small, subject to rapid depletion and no/or little natural recharge, and bounded by growth that may be reactivated by injection, subsidence effects are likely to occur rapidly despite the large depth to some of the production zones.

Scope of Work (FY 1979 and 1980)

In FY 1980, a research contract was awarded to EDAW-ESA to perform the following tasks:

Task 1: Collect data from representative areas. From a survey of geopressure prospect areas in Texas and Louisiana, select two representative areas in each state on the basis of their characteristics and the availability of geotechnical, production, and environmental information.

Task 2: Assess subsidence potential and mitigation schemes. Investigate the areas in terms of proposed development schemes; compaction and subsidence potential; potential environmental, economic and social issues; and mitigation measures.

Task 3: Develop a research plan. Evaluate methods for assessing subsidence potentials and impacts; develop a research plan that may be used as the basis for initiating research specific to issues on geopressure-geothermal development.

REFERENCE

Viets, V.F., C.K. Vaughn, and R.C. Harding (EDAW/ESA), 1979. Environmental and economic impact of subsidence: University of California, Lawrence Berkeley Laboratory, LBL-8615 (GSRMP-1), 200 p.

APPENDIX B. EXECUTIVE SUMMARY OF THE ASILOMAR WORKSHOP ON GEOTHERMAL SUBSIDENCE

B.1. BACKGROUND AND INTRODUCTION

The Geothermal Subsidence Workshop was held at the Asilomar Conference Ground, Asilomar, California on October 9-13, 1978. It was organized by LBL on behalf of DOE/DGE. Approximately 50 people attended, among them geothermal developers and operators, federal and state regulators, DOE program managers, LBL contractors and consultants, and people from the academic community.

The workshop was held to review the accomplishments of the LBL Geothermal Subsidence Research Program (GSRP) and assess the possible need to revise the objectives of the GSRP. The stated purpose of the workshop was "to develop guidelines for the future of the GSRP." Recognized geothermal experts were invited to (1) review and assess current and planned future research activities, and (2) discuss and make recommendations about the relevance of the GSRP, its future emphasis, and specific future research objectives. The informal atmosphere encouraged workshop participants to share individual experiences, concerns, ideas, and insights with other participants having like interests.

Workshop presentations and discussions focused on the following research categories:

1. Case histories of subsidence areas. Review the four case studies prepared by Systems Control, Inc.

2. Field measurements methods. Review the Woodward-Clyde Monitoring Guidelines Manual.

3. Direct monitoring instrumentation. Review the Woodward-Clyde report on instrumentation.

4. Environmental and economic effects of subsidence. Review the EDAW-ESA report on subsidence impact.

5. Physical processes of subsidence and laboratory testing. Review the direction of TerraTek Laboratory studies.

6. Subsidence Modeling. Review the direction of the Golder Associates assessment of numerical models.

7. Reservoir operational control policy.

Workshop review and discussion of each research category followed the following format:

1. A brief introductory statement by a GSRP representative.

2. Contractor or GSRP management preparations, followed by plenary question and answer sessions.

3. Workshop participants regrouped into small discussion groups to review presentations in more detail.

4. Discussion group spokespersons presented group opinions in the plenary session.

Summaries of the presentations by discussion spokespersons are included in Section 2.1 of this report.

At the conclusion of the workshop, participants met to summarize what the Geothermal Subsidence Workshop had accomplished, to discuss where it could have been improved, and to identify which of the GSRP program options merit further discussion. Most of the participants believed that the workshop had produced a generally beneficial exchange of information and opinions and had met the Workshop Objectives. The workshop contributed markedly to the development of a Revised Geothermal Subsidence Research Plan.

This Executive Summary presents a brief account of the Geothermal Subsidence Workshop. It was prepared from information compiled at, and developed after, the workshop. The information consists of transcripts of tapes recorded during plenary and small group discussions, questionnaires completed by workshop participants, and recommendations subsequently made regarding the future of the GSRP.

B.2 THE GEOTHERMAL SUBSIDENCE RESEARCH PROGRAM ASSESSMENT

Since the original Subsidence Research Plan (LBL-5983) was published, two years of research have been completed and the DOE has revised the goals for research. An assessment of the GSRP Plan is needed to assess and revise the original Subsidence Research Plan. The Geothermal Subsidence Workshop was a step in performing the assessment. The workshop were designed so that the necessary information could be acquired. The agenda and format of the workshop were developed so that people from the original planning team and task force, the research contractors, selected experts involved in aspects of geothermal subsidence research, and representatives of DOE, regulatory agencies, and industry involved in geothermal site development would (1) present and assess current and planned research activities, and (2) discuss and make recommendations regarding the continued existence and thrust of the GSRP specific research and management activities.

B.2.1 Principal Recommendations

Listed here are the principal statements and recommendations from the participants of the Geothermal Subsidence Workshop.

1. The main objective of the program should be "to generate a body of knowledge and technical expertise to equip the developer to predict, monitor, and mitigate the effects of subsidence within acceptable economic and environmental limits." The same body of information could also guide regulators in setting acceptable environmental limits.

2. DOE should merge the geothermal subsidence program into an integrated geothermal environmental program.

3. The research framework should be reorganized into three major areas: (a) prediction, (b) monitoring, and (c) mitigation.

4. Within this framework two new research categories should be added: one dealing with socio-political problems and another covering field testing.

5. The thrust of the program should be refocused toward site-specific research. Immediate attention should be given to the Imperial Valley, California, and Brazoria, Texas. Other areas should also be considered.

6. The greatest emphasis (in a generic sense) should be on the physical processes of subsidence.

7. Separate from the ongoing research, which is basically long-term, develop and verify, as soon as possible, a simple yet acceptable method for estimating potential subsidence on the basis of a few computations.

8. An overview is needed to describe how environmental costs, including subsidence costs, would add to the other development costs.

9. There is a need for a better data base, located in a central repository.

B.3 PRINCIPAL ISSUES AND THE NEED FOR RESEARCH

This section contains summary statements of the principal issues and research needs discussed by the participants of the Workshop. The statements are presented in Tables B.1 to B.3, corresponding to monitoring and measurements, prediction, and impact assessment. The tables include summary statements of the research (action) recommended by LBL and the action taken by the DOE.

Table B.1. Summary of Asilomar Workshop Issues and Actions: Monitoring and Measurements

Issue Raised	Research Recommended	Action Recommended by LBL	Action Taken by DOE	Remarks
To what extent is the manual for field monitoring useful to developers and regulators; what is the best way for implementing the research results; and should the manual be refined further?	No recommendations.	Broad dissemination of results.	None	--
How to implement the monitoring techniques outlined in the manual for field monitoring?	Perform a demonstration at Valles Caldera.	Surface and shallow subsidence monitoring at Valles Caldera.	Proceed with LBL tasks to: • assess planned monitors • assess optimal contribution to existing plans.	Installation, testing, and monitoring of instruments was postponed by DOE
How best to implement the state-of-the-art assessment of direct monitoring instrumentation?	Develop reed switches, determine magnetic materials suitable for hostile environments, and enhance development of high temperature electronic components.	Proceed with lab testing and tool development regarding: • magnetic materials • electronic oscillators • electronic line drives • reed switches • induction coil and tool materials.	Rely on Sandia for lab testing of suggested components and development of high-temperature electronic components.	There are many technical questions concerning the feasibility of the tools proposed.
When instruments are made available to the geothermal community, will the community use them?	Investigate the costs and benefits of instrumentation.	Survey developers regarding implementation of specific instruments which will be available in the near future.		
What is the value of radioactive bullets in studying reservoir compaction?	Assess the value of radioactive bullets and make recommendations.	Hostile-environment lab testing and tool development should include a review of radioactive bullet feasibility.	Concur that an RFP be prepared and issued.	Measurable formation markers are desirable for measuring compaction.
Of what values are various indirect techniques, particularly gravity and seismic monitoring subsurface compaction, propagation, and resulting subsidence?	Assess various surface and subsurface indirect measuring methods and test those judged most promising.	Indirect measurement methods should be studied: • precision gravity • seismic study of reservoir dynamics.	Proceed on assessment of methods and sites and selection of most promising for tests.	Subsequent action will be based on the outcome of currently funded work.

Table B.2. Summary of Asilomar Workshop Issues and Actions: Prediction

Issue Raised	Research Recommended	Action Recommended by LBL	Action Taken by DOE	Remarks
Is the present theory of the physical processes of subsidence adequate; is inelastic behavior adequately covered?	Assess the present theory and identify inadequacies or areas of incompleteness.	Assess physical theory: • assess existing theory • document inadequacies • suggest research to remove inadequacies.	Proceed with action recommended by LBL.	
What is the most meaningful phenomenological lab testing program that could be initiated?	Determine the time-dependent response of a reservoir to production, via compaction.	Study creep phenomena and simultaneous rock properties: • core selection • conduct creep phenomena studies • conduct simultaneous rock properties study • interpret data.	Proceed with action recommended by LBL.	
How do we determine the in situ stress of a reservoir in order to do rock studies?	Develop techniques for in situ stress testing.	Hydrofracturing experiments at geothermal reservoirs are recommended.		
How useful are existing subsidence models in understanding subsurface processes?	Assess the usefulness of existing models.	Present contract with Golder Assoc. should be sufficient.		Do we want to have a working model of geothermal subsidence?
How accurate are subsidence models?	Assess or validate the accuracy of models using case histories.	Study ability of numerical models to match physical model response to actual loading.		Research could be performed by LBL.
Can we model inelastic behavior?	Assess the theory and determine the magnitude of the effects.	Assess adequacy of existing inelastic theory and study the inelastic behavior of rocks from geothermal reservoirs.	Proceed with all action recommended.	• Assessment of inelastic theory is included in the assessment of all geothermal subsidence theory. • Core studies are currently integrated in existing TerraTek contract.
How could LBL and DOE do a better job of communicating with industry and regulatory bodies?		• Publish subsidence research series. • Develop guidebook series for regulators. • Publish a regular newsletter • Conduct informational meetings, workshops, task force series.		
How can financial institutions, administrators, and regulators use the research results to support the loan guarantee and other programs?				
How does reinjection affect subsidence?	Assess the potential for reinjection designed to control subsidence.			

Table B.3. Summary of Asilomar Workshop Issues and Actions: Impact Assessment

Issue Raised	Research Recommended	Action Recommended by LBL	Action Taken by DOE	Remarks
Are additional case studies necessary and if so, what type? Would it be preferable to have statistical correlation of many cases or detailed studies of a few cases?	Case studies and subsidence potential maps are not needed as prerequisites to site development; however, additional case studies are needed to: • assist modelers • develop analytical tools • provide baseline measurements • develop guidelines for assessment.	• Statistical correlation study. • Supplemental case history for Chocolate Bayou. • Review other geopressured sites.	Proceed with a detailed case history for Chocolate Bayou.	Geopressured systems were not considered in the first funding action taken by DOE.
The extent of existing information is not known and much of the existing information is proprietary.		Contact industrial people to assess potential for developing representative case studies.	None	--
Assuming there is an economic impact, what are the appropriate methods for documenting the loss, both subsurface and surface?	• Guidelines for regulation as proposed by EDAW should be developed to facilitate data accumulation for environmental assessments.	No recommendations.	None	--
	• Document case studies of economic impact.	Subsurface financial risk assessment.	Proceed with: • assessment of engineering standards for geothermal wells. • review of documentation of well bore failure due to consolidation. • evaluate financial impact. • suggest and assess preventative control action.	• Need clarification on deliverables. • Lack of data control tends to limit credibility of results.
Which areas are likely to have the major environmental impacts? Are the impacts tolerable? What are the consequences?	Environmental impact studies need to be concentrated along the Gulf Coast, where subsidence poses the greatest environmental concern because of the extremely fragile nature of that environment.	Review geopressured sites; and monitor areas where subsidence would be costly to agriculture and man-made structures and activities.	None	Geopressured systems were not considered in the first funding taken by DOE.
Planners need to know where withdrawal of fluids could lead to eventual subsidence.	Qualitative Subsidence Potential maps need to be developed to assist state and local regulators.			The value of Potential Subsidence maps is not clear. Such maps, prepared before development begins, would certainly be crude.

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