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Geothermal Induced Seismicity Program Plan

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Preface

A plan for a National Geothermal Induced Seismicity Program has been prepared in consultation with a panel of experts from industry, academia, and government. The program calls for baseline seismic monitoring in regions of known future geothermal development, continued seismic monitoring and characterization of earthquakes in zones of geothermal fluid production and injection, modeling of the earthquake-inducing mechanism, in situ measurement of stresses in the geothermal development. A parallel plan is being implemented under the Geothermal Subsidence Program.

Seismic, geodetic, and gravity monitoring at The Geysers, California, by the U.S. Geological Survey has documented the occurrence of:

1. Almost continuous microearthquake activity;
2. Vertical and horizontal surface displacements of several centimeters per year, and;
3. Development of a mass deficit which implies little of any natural recharge of the field.

These phenomena are closely correlated with the regions of maximum reservoir depletion as indicated by pressure decline data. The microearthquakes appear to define the producing parts of the reservoir.

In addition, larger earthquakes (magnitudes up to 3.8) have occurred in the field, several in close proximity to injection wells. Earthquakes large enough to be felt occur on a weekly basis; some have caused temporary shutdowns of power plants.

The Geysers is the only major geothermal power development on line in the United States. Experience there suggests that earthquakes induced by fluid withdrawal and/or injection can be both of concern as a hazard (in disrupting facilities) and of use as a tool (for reservoir definition) in the future development of geothermal resources.

I. INTRODUCTION

It has long been known that an increase in the number and intensity of local seismic events can result from certain engineering activities. Such events are considered to be "induced" seismic events and are defined as statistically significant increases in local seismicity over the expected number of "natural" events. At the present time, the causal relationships involved in producing natural or induced earthquakes are not well understood; however, it is recognized that the principal causes are the alteration of the existing stress field and changes in pore pressure. More importantly, recent experiments near Rangely and Denver, Colorado, have demonstrated conclusively that seismic activity is directly related to fluid injection and withdrawal. Also, increases in local seismic events, both in number and in intensity, have been recorded in producing geothermal fields. For these reasons, the potential for the occurrence of locally damaging earthquakes must be a factor in considering exploitation of geothermal resources.

The character and extent of this seismicity has aroused interest not only because of the possible social, economic, and environmental consequences, but also because of fundamental questions raised concerning the role of fluid pressure and water in the generation of all earthquakes.

A. Program

To address these questions, the Department of Energy (DOE), through the Division of Geothermal Energy (DGE), has initiated a research effort to investigate the extent to which induced earthquakes may be associated with the development of geothermal energy facilities. The Geothermal Induced Seismicity Program (GISP) will have as its objectives the evaluation of the seismic hazard, if any, associated with geothermal resource exploitation and the devising of a technology which, when properly utilized, will control or mitigate such hazards. A well-focused study of these matters could lead toward eventual development of earthquake prediction techniques in addition to enhancement of geothermal energy production.

There is a positive aspect associated with fracture control. An expanded technology of control procedures can be an invaluable industrial tool, especially in those instances where fracture permeability plays a significant economic role. The value of selectively increasing permeability in a geothermal reservoir is self-evident.

B. Goals

The program objectives are further defined by the following four goals:

- To quantify the relationships between geothermal energy production and induced earthquake activity, and to assess the environmental hazard potential;
- To improve current technology to estimate the seismic risk for specific fields and production techniques;
- To define operating procedures for control and mitigation of induced earthquakes; and
- To disseminate the results of these studies to industry and encourage their implementation.

These goals are designed to provide practical engineering information within a reasonable time frame. Observational data will be collected on a variety of parameters and used to construct physical and empirical models of geothermal reservoirs. These models will be continuously tested and adjusted as new data are obtained. The relationship of induced earthquakes to specific reservoir production activities and the local physical perturbations they create should ultimately emerge as these models evolve.

C. Organization

Management responsibility for the Geothermal Induced Seismicity Program was assigned to the DOE Nevada Operations Office (DOE/NV) in July 1978. The NV Program Manager selected Holmes & Narver, Inc., an architect-engineering contractor, to prepare and publish a comprehensive Program Plan.

Two groups were formed to assist in preparation of this plan: a Planning Group and a Review Group. Both groups were made up of representatives from government, academia, and industry. Members of the Planning Group included:

J. T. Cherry, Systems, Science and Software, Chairman
C. B. Archambeau, University of Colorado (CIRES)
C. G. Bufe, U.S. Geological Survey, California
R. A. Crewdson, Occidental Petroleum Corporation
W. W. Hays, U.S. Geological Survey, Denver, Colorado
T. V. McEvilly, University of California, Berkeley
E. L. Majer, University of California, Lawrence Berkeley
Laboratory
C. B. Raleigh, U.S. Geological Survey, California
G. G. Sorrells, Teledyne Geotech

The Review Group consisted of:

Sidney J. Green, Terra Tek, Inc., Salt Lake City, Utah
H. M. Iyer, U.S. Geological Survey, California
David Simpson, Lamont-Doherty Geological Observatory of
Columbia University

Upon final acceptance of the plan and implementation of recommended research tasks, an Oversight Committee will be formed, whose membership will ideally be derived from the two earlier groups. The function of this committee will be to periodically review the

status of projects to ensure that the research holds to stated goals and that a cooperative flow of data between other agencies is maintained. The Oversight Committee will also provide for programmatic changes if needed to meet first-priority goals. This committee will meet periodically (not less than once a year) throughout the remainder of the program.

D. Planning Strategy

It was the consensus of the Planning Group that the GIS Program Plan be designed to function through a cooperative interface with other Federal programs investigating areas of common interest. It was further determined that in view of budget limitations, the most effective research procedure would be to focus principally on interpretation of available geophysical and reservoir production data. It is anticipated that much of the physical data required for this research will be provided by other research programs addressing related topics, and only when critical data are unavailable will laboratory and field data collection be directly funded by this program. This should reduce duplication of effort and allow a more cost-effective utilization of existing funds: it is clearly necessary to the success of this program.

Further, this effort will focus on economically proven reservoirs, and initially only on vapor-dominated and liquid-dominated hydrothermal systems. Hydrothermal resources have been used for power generation in this country and abroad for a number of years and provide a logical point to launch a research program. Numerous hydrothermal systems have been identified as having potential for exploitation, and many will be put into production in the near future.

Utilization of hot, dry rock is a new concept and the procedures needed for production and exploitation have not yet been fully demonstrated. Geopressure-geothermal is also a relatively new concept which may prove relevant as production data become available.

E. Framework

1. DGE Program Relationships

The program represents only one phase of a wide-ranging, multidisciplined research and development effort to encourage the utilization of this energy resource. Other studies include, but are not limited to, exploration and assessment technology, reservoir engineering, and subsidence. Within the DGE research framework, some program overlap is inevitable (for example, this program and the Subsidence Program), and data developed under one program may be directly applicable to another.

The GIS Program Plan is cognizant of and consistent with the activities of the Interagency Committee on Seismic Safety in Construction. That committee was created in December 1978 as a consequence of the Earthquake Hazards Reduction Act of 1977 (P.L. 95-124). Objectives of this Act are to develop standards, guidelines, and procedures to evaluate seismic hazard and risk at federally funded, assisted, and regulated construction sites. Because the DOE is a participating agency in this Federal program and is simultaneously encouraging increased utilization of geothermal energy, it is appropriate for DOE to conduct certain research programs to augment more extensive studies being conducted by other agencies (e.g., USGS) and industry.

2. Program Structure

The GIS Program research plan is an interrelated structure composed of three major elements:

-- Characterization

-- Modeling

-- Control and Mitigation

Each of these elements contains one or more research tasks which further define those areas where data are insufficient or wholly lacking. The research tasks are designed to provide or expand the data base as shown in Table 1-1. Figure 1-1 is the programmatic flow diagram showing the relationship between research tasks and the program elements leading toward stated program goals.

TABLE 1-1

<u>Element</u>	<u>Research Tasks</u>
Characterization	<ol style="list-style-type: none">1. Seismic Parameters2. In Situ Stress3. Structural Geology and Geophysics4. Reservoir Pressure, Temperature, and Rates of Change5. Rock Properties6. Mass Transfer of Fluids
Modeling	<ol style="list-style-type: none">1. Modeling
Control and Mitigation	<ol style="list-style-type: none">1. Seismic Hazard Assessment2. Operating Procedures and Guidelines3. Environmental Assessment

FIG. 1-1 FLOW DIAGRAM

II. PROGRAM DEFINITION

Data bearing on the understanding of induced earthquake activity at a producing geothermal reservoir relate to the local physical and chemical environment and include a continuous body of seismic data, both regional and local, which commences prior to production. Equally important are the regional in situ stress, mechanical and chemical properties of the reservoir, and the variation of these parameters with respect to time and reservoir exploitation.

A. Characterization

1. Seismic Parameters

Microearthquake monitoring to define the local seismicity should begin as early as possible in the development history, ideally before production commences, and should continue without interruption through the operating life of a geothermal site. These data, augmented with data from existing regional seismograph networks, will be fundamental to subsequent modeling of reservoir dynamics and the refinement of possible triggering mechanisms.

It is important that adequate instrumentation, both in terms of deployment and instrumental precision, be utilized. Initially, the microearthquake monitoring program should be relatively simple, but capable of rapid expansion if required by the level of background seismicity or when production from the reservoir starts. The sensitivity and dynamic range of the equipment should reflect current technology.

If the reservoir area is found to be seismically active in the course of preproduction monitoring, or if the area becomes active during any stage of production, the network will be expanded. Emphasis will then shift from data collection

to data analysis to provide precise hypocenters, fault plane solutions, stress drops, seismic moment, rupture dimensions, propagation effects, and frequency content of seismic waves. This network can also be used in experiments designed to detect changes in subsurface properties associated with reservoir exploitation.

2. Direct Measurement of In Situ Stress

It is important to have an independent, direct measurement of the initial stress field in a given reservoir. Hydraulic fracturing is the method which has been used for this purpose and it is now possible to measure the absolute state of stress in boreholes where temperatures reach 250°C. However, the method has operational limitations in highly fractured rock, a condition which often exists in geothermal reservoirs. The method is also expensive and therefore will be used selectively to derive the greatest value per application.

3. Structural Geology and Geophysics

Earthquakes, both natural and induced, are probably centered on zones of weakness, and rates of fluid flow depend on the amount of fracture permeability. Modeling studies for production-induced earthquake occurrence will depend heavily on the reservoir structural geology. Data on attitude, orientation, and density of preexisting faults, fractures, and joint systems, as determined from existing geological and geophysical studies, will be utilized where possible. Programs will be funded to obtain the necessary data from specific sites if data are found to be inadequate or lacking.

4. Reservoir Pressure, Temperature, and Rates of Change

To advance the understanding of induced seismicity, it is important to obtain data that reliably show changes in reservoir pressure of a few tenths of a bar and temperature changes greater than 0.1°C . Instrumentation with sensitivities of this order have been developed and are typically used in reservoir engineering studies. Data required for this program should be available from other studies. Preliminary studies will be made to determine the spatial and temporal rates necessary to adequately characterize the pressure and temperature dynamics in the producing reservoir. These studies must be site specific because spatial and temporal variations in these parameters can be expected to differ substantially from field to field.

5. Rock Properties

The effects of high temperature and pressure on the physical and elastic properties of rock are important for a complete understanding of seismic activity in geothermal reservoirs. Such data are concurrently being developed in other DGE programs. Experiments may be conducted for certain specific sites to determine the rate of temperature, strain rate, fluid content, and chemistry on rock rheology at or near failure if data are not available from other sources.

6. Mass Transfer of Fluid

The role of fluid mass transfer (e.g., withdrawal and injection) in generating earthquakes has been demonstrated for many engineering activities, partly by controlled experiments and partly by unexpected events resulting from production activities. The most prominent examples are reservoir filling, oil and water field production, and mining. In

each case, the mechanism that triggered these earthquakes appears to have been a variation in the stress field through changing fluid pressures.

Flow rates and volume data will generally not be available until field production begins in a geothermal reservoir. Also, these data will generally be developed by private industry; therefore, mutual cooperation in the flow of information is essential to this program.

In those developmental programs which are fully or partially federally funded, acquisition of data will be handled through cooperative effort between agencies. In the case of data generated by private industry, acquisition of the necessary information will be through voluntary industry cooperation or through direct purchase agreement.

B. Modeling

The primary task of this program element is to use current mechanical fluid-rock interaction models to assist in predicting rock failure at relative effective stress levels under specified fluid injection or extraction conditions. Two modeling categories are identified in this program element: reservoir models and failure process models.

Reservoir modeling will focus on simple, fundamental relations which will require knowledge of the initial state of the reservoir, including temperature, pressure, stress, effects of chemical alteration, fluid chemistry, and geological structure. Further, details of production history and resulting changes in the initial condition of the field will be required to specify time-dependent boundary conditions. Related data such as tilt, strain, compaction, and subsidence measurements will, with time, augment basic modeling capability. For failure models, rheologic and chemical behavior

of rocks as a function of stated boundary conditions must be known with reasonable certainty. To ensure model accuracy, it will be necessary to continuously study reservoir seismic activity. Final reservoir models should be capable of predicting, with a high level of confidence, the frequency, distribution, and magnitude of induced earthquakes.

C. Mitigation and Control

1. Seismic Assessment

Small-magnitude earthquakes have been known to produce damaging levels of ground motion at the surface near the earthquake epicenter. Therefore, it is not unreasonable to expect induced earthquakes also to produce such ground motion near their epicenters. Criteria exist for assessing maximum earthquake potential for an area, but they are very conservative, primarily because they relate to public health and safety considerations and may not be applicable to geothermal sites. Particularly, they do not take into account the positive applications of induced fracturing to increase reservoir permeability. Nonetheless, this kind of information would be useful in planning a new facility or expanding an existing production site. The purpose of the induced earthquake model is to provide an improved rationale for estimating maximum earthquake potential, as well as to set the parameters for the constructive use of induced seismicity, both as a factor relating to reservoir production and its impact on the local seismicity and as an effective tool when deliberately employed for planned purposes. These applications are not presently being pursued in other earthquake assessment programs.

2. Operating Procedures and Guidelines

Knowledge gained from this program will increase the understanding of seismic hazards associated with geothermal development. From this base of understanding, geothermal operators can formulate procedures for controlling and/or eliminating seismic hazards associated with construction and operation of geothermal facilities. This study could provide a potential geothermal operator with information, for instance, concerning initial siting, spacing of facilities on a site, shock mounting of structures, regulation of fluid withdrawal rate, and any other significant determinants confirmed by the study. Much of the information needed for these procedures and guidelines, such as expected seismic energy release, nature of slip, rupture depth, rupture processes, and proximity of the fault to the site, can be approximated by models. Site-specific models will be developed parallel with the ongoing development of selected geothermal fields, thereby providing operators with information for sound management decisions concerning economic, environmental, and safety considerations.

3. Environmental Assessment

Various Federal and State agencies are engaged in formulating regulations which will minimize the environmental effects of geothermal resource exploitation. In the past, wherever there has been a lack of information or uncertainty as to the degree of impact, regulations have tended to be conservative and restrictive. The geothermal industry faces just such a potential situation today. To preclude imposition of overly stringent regulations, it is imperative that information relating to short-term and long-term effects of geothermal energy production be accumulated as quickly as possible. It is the stated goal of this program to acquire and assimilate

the data necessary to remove or reduce the doubts and uncertainties associated with geothermal induced seismic activity.

Much of the data generated by this program will be used as the basis for defining the nature and extent of the problem and for developing valid prediction models which will provide insight into potential adverse environmental effects occurring during the producing lifetime of a geothermal field. Specifically, this program will assess the degree of seismic hazard, if any, that may exist at any potential site and the probable limits, in terms of ground shaking, of that risk. Realistic guidelines based on these data should produce regulations which provide an equitable balance between the demand for geothermal energy and the need to protect the environment.

III. IMPLEMENTATION

The foregoing section outlines a simple and direct program to investigate geothermal induced earthquakes. The program stresses observational studies and limits those research areas which may require long-term study. This approach was dictated by a combination of factors: the urgency to develop geothermal energy resources and to resolve the most immediate problems as quickly as possible; geothermal sites exhibit a wide and disparate variety of physical characteristics; and much of the requisite basic research on earthquake triggering is incomplete. Furthermore, budgetary constraints and controversy over the relative importance of induced earthquake hazards were a further consideration.

The research effort will be specifically tailored to each site. Those sites which are aseismic at the outset and continue to be essentially aseismic throughout production life will require only a basic seismic monitoring program maintained by the operator. In this case, simple empirical relationships between production rates and seismic activity could readily be developed and used by the operator to guide production work. At a site which exhibited a moderate or high level of seismicity, a more extensive monitoring network would be required.

In situ stress measurements usually provide essential data, particularly where rocks are highly fractured and are in high-temperature regimes--conditions which often exist in geothermal reservoir media.

Another factor which will significantly impact not only on the kind and level of research adopted, but also on whether or not a site is selected for full study, is availability of existing site data, including production and reinjection information.

It will be the strategy of this program to initially support earthquake monitoring studies at as many sites as practical. Selection of sites for additional study will depend on such factors as significant increase in seismicity with the initiation of production activities and availability of reservoir engineering and production data, as well as any other physical, technical, and fiscal factors which affect site selection.

Categories for site selection are as follows:

- Reservoirs developed under Government-funded programs (all data available).
- Reservoirs developed under cooperative programs between Government and industry (most data available).
- Reservoirs developed entirely by industrial operations (some or all data may be proprietary).
- Any of the above categories which exhibit unique physical characteristics.

Once a site has been selected, research tasks will be assigned on the basis of program needs and availability of funds.

Data acquisition will also provide a site-specific geothermal data bank for geothermal prospects. Accessible regional and local geological, geochemical, geophysical, and geothermal data can then be assigned to the prospect, and the required data base will be established for subsequent analysis.

The Planning Group has made a list of potential geothermal sites and recommends three for study. The Geysers, California, was identified as the prime target for an expanded research effort, and two other sites, East Mesa, California, and Dixie Valley, Nevada, were selected and approved for earthquake monitoring programs.

The Geysers, near Santa Rosa, California, has been studied for years and several geological and geophysical projects have been conducted or are currently in progress there. An appreciable body of accessible geophysical data exists for The Geysers field. Analysis of regional seismic data suggests that the present rate of seismic events with The Geysers field is higher than during the preproduction phase. Other seismic data show a clustering of microearthquakes around production and reinjection wells within the field.

Accessibility and range of available data from The Geysers outweigh any potential problems.

East Mesa, California, about 13 miles northeast of Calexico, was chosen because it represents a joint Federal/industry project and because of the low cost of the monitoring program.

The Dixie Valley sites are located in north-central Nevada, about 90 miles southwest of Lovelock, in an area of high natural seismic activity. There is no production in the area.

A. Program Activity

In FY 1979, the U.S. Geological Survey performed a series of tasks including seismic monitoring at The Geysers, rock mechanics studies, preliminary modeling studies, and stress drop analyses. These projects were continued into FY 1980. A microearthquake monitoring project was begun in FY 1979 at East Mesa, California, and continues under the direction of Lawrence Berkeley Laboratory. This project was temporarily expanded in FY 1980 to include an extra seismic array to record data from a hydrofracturing experiment conducted at East Mesa. An earthquake monitoring project at Dixie Valley Nevada, by the University of Nevada, Reno, was begun in FY 1979 and continued through FY 1980. In FY 1980, additional seismic monitoring projects were funded under this or related programs for Raft River, Idaho; Imperial Valley, California; Roosevelt Hot Springs, Utah; and Cerro Prieto, Mexico.

B. Program Tasks--FY 1981

Sites and tasks supported in FY 1980 will be continued into FY 1981 with the exception of the East Mesa hydrofracturing array and the monitoring effort at Dixie Valley. The latter will be suspended in 1981, to be resumed if and when geothermal production is imminent in Dixie Valley.

C. Program Tasks--FY 1982 and Beyond

The results of these investigations and availability of program funding will determine the shape of the post-FY 1981 GISP research and development effort.