GL01240

ROUGH DRAFT

GEOTHERMAL LOG INTERPRETATION PROGRAM

5 YEAR PLAN

Prepared for the U.S. Department of Energy, Division of Geothermal Energy,

Hydrothermal Technology Section

(Raymond J. LaSala, DGE Program Manager)

by

Mark Mathews

University of California

Los Alamos Scientific Laboratory (LASL)

Phone (505)667-2884

FTS 843-2884

ROUGH DRAFT

March, 1980

GEOTHERMAL LOG INTERPRETATION PROGRAM

5 YEAR PLAN

(FY 80 to FY 84)

Contents

ABSTRACT

This geothermal Log Interpretation Program Plan provides an outline of external and internal technical R&D activities to be performed over the next five years (FY 80-85) that will aid in the development of improved geothermal log interpretation techniques. Effective and efficient well log interpretation is necessary for the assessment of size and quality, and prediction of productive potential of a geothermal resource. A significant advancement in geothermal log interpretation capabilities should result from external industry-based research and internal laboratory research in development of improved interpretation techniques. It is estimated that the impact of the results of the research proposed will greatly improve geothermal well log interpretation technology over current practice. major accomplishments will be the development of calibration test pit facilities and publication of a geothermal log interpretation handbook. LASL has the management responsibility in the implementation of research activities in the eight major R&D areas. Redirection, review, and updating of the program plan will be accomplished through a steering committee composed of knowledgable experts in log interpretation drawn from geothermal development firms, universities, logging service companies, and the DOE National Laboratory staffs involved in the Geothermal Log Instrumentation Development, Geothermal Reservoir Engineering and the Reservoir Exploration and Assessment Technology Development programs.

I. Introduction

The development of the geothermal resources of the United States provides an energy source which can materially reduce our dependence on foreign fuel supplies and benefit the economy. With each blow dealt by world events to the international oil market, we become more aware that we may soon face a time when we shall have to place far greater dependence on domestic energy sources than is now the case. As the time approaches, it becomes important to ask whether we have available the tools and technology needed to rapidly expand our use of unconventional energy sources. Geothermal energy is relatively benign environmentally and can in many cases be brought on-line with a shorter lead time than nuclear or coal-fired power plants, making geothermal energy a good candidate for rapid development.

Development of geothermal power plants is paced by a number of factors of which the most important are, obviously, the rate of discovery of resources and the cost relative to competing energy supplies. The cost of geothermal energy is significantly affected by the risk and cost involved in drilling and developing a geothermal field. Other factors affecting development include the willingness of investors to commit capital to geothermal energy and regulatory restraints which may be necessary to protect the environment or to ensure orderly and equitable development. Many of the problems of development stem from the fact that one is dealing with subsurface conditions of which we have only limited knowledge. Similarly both the confidence of investors and the deliberations of regulatory agencies are significantly affected by the limited knowledge that we have of the long-term performance of geothermal resources. One way of encouraging the development of geothermal energy is to provide better means of obtaining data on the resources that we seek to use.

The most versatile means of obtaining data from below the earth's surface is by lowering logging instruments, which measure a variety of physical and sometimes chemical parameters, into a borehole. The data most commonly recorded on the well logs include temperature and pressure in the borehole and various physical properties of the surrounding rock. These rock properties include electrical characteristics, the velocity of sound, natural radioactivity, and the absorption and scattering of externally applied radiation such as neutrons and gamma rays. By applying a variety of relationships developed from analysis of the response of the logging tools in known or simplified theoretical borehole conditions, the unknown conditions in the logged well are inferred (Schlumberger, 1972). Because tool response can be sensitive to numerous downhole conditions, simplifying assumptions are necessary in any theoretical model of response, and a high value is placed on practical experience under known conditions. Parameters such as the depth, thickness, and permeability of reservoir rocks are sought to guide development and aid in assessing the potential of a resource.

The collection and interpretation of well log data has developed to date largely in repsonse to the needs of the oil and gas industry, with some contributions from mining and hydrology. Well logging has played a vital role in the development of the modern petroleum industry. Most of the techniques for the interpretation of logged data have been developed empirically for the formations (rock types) in which hydrocarbons have been commonly sought. The conditions, important parameters, and geology of geothermal reservoirs can be radically different from those involved in petroleum exploration, however. At present geothermal development is able to gain only very limited advantage from well logging. Oil and natural gas production is obtained, except in rare instances, from marine sedimentary formations such as sandstones or porous limestones. The petroleum fluids are trapped in place by structural conditions or stratigraphic changes that have permitted their accumulation and long-time storage. Thus the existing logging tools and interpretational techniques have been developed almost exclusively for the study of sedimentary rocks and associated oil, gas, and water found in such sedimentary rocks.

Geothermal reservoirs consist of non-marine sedimentary, igneous, and metamorphic rocks with temperatures greatly exceeding those usually encountered in petroleum reservoirs. Naturally occurring hydrothermal reservoirs such as at The Geysers and Imperial Valley, California, may produce hot water, super-heated steam or combinations of hot water and steam. Some geothermal fluids are highly saline and corrosive and may contain some noxious and active gases such as hydrogen sulfide. Production from natural geothermal reservoirs may be from rocks with intergranular porosity and permeability, from metamorphosed rocks with secondary intergranular porosity and permeability, or from fracture systems existing in relatively impermeable sedimentary, metamorphic, or igneous rocks. Thus interpretation of geophysical logs from such a wide variety of geothermal reservoir types requires capability to determine characteristics of a much larger variety of non-marine sedimentary, igneous, and metamorphic rocks, with their associated hot waters, brines, and steam, and other gases such as hydrogen sulfide and carbon dioxide.

It is planned that this program will help to establish industrial capability for the needed geothermal log interpretation, and to generate input for development of new or improved logging techniques and tools, and finally to aid in the formulation and interpretation of the reservoir models for all types of geothermal areas. The benefits expected from log interpretation are shown in Figure 1.

Crucial to reservoir evaluation is the development of techniques for the interpretation of geophysical logs run in both exploration and production drill holes. Certain parameters are essential for evaluation of a particular geothermal resource and the priority of a parameter determination varies with resource type. A list of parameters for needed development of log measurements and interpretation techniques was developed by the Geothermal Log Interpretation Steering Committee's Well Log Analysts Subgroup on Tulsa, Oklahoma on June 8, 1979. These parameters are listed in the following categories of formation evaluation and production management in Table I. These parameters must be derived from available log data by development of proper interpretation techniques.

Specifically, this program will seek to aid in the development of geothermal well log interpretation technology in the appropriate U.S. commercial sector. This will be accomplished by building on the already existing highly developed petroleum and mineral logging interpretation techniques and procedures. Research in geothermal reservoir engineering, logging tool improvement and development, and log interpretation is being pursued by the evolving geothermal industry. It is intended that the proposed DGE program supplement and aid in these commercial efforts. The technical R&D activities to be pursued are intended to reduce the basic impediments the industry faces due to the need to develop techniques and technologies not normally required in servicing the petroleum industry.

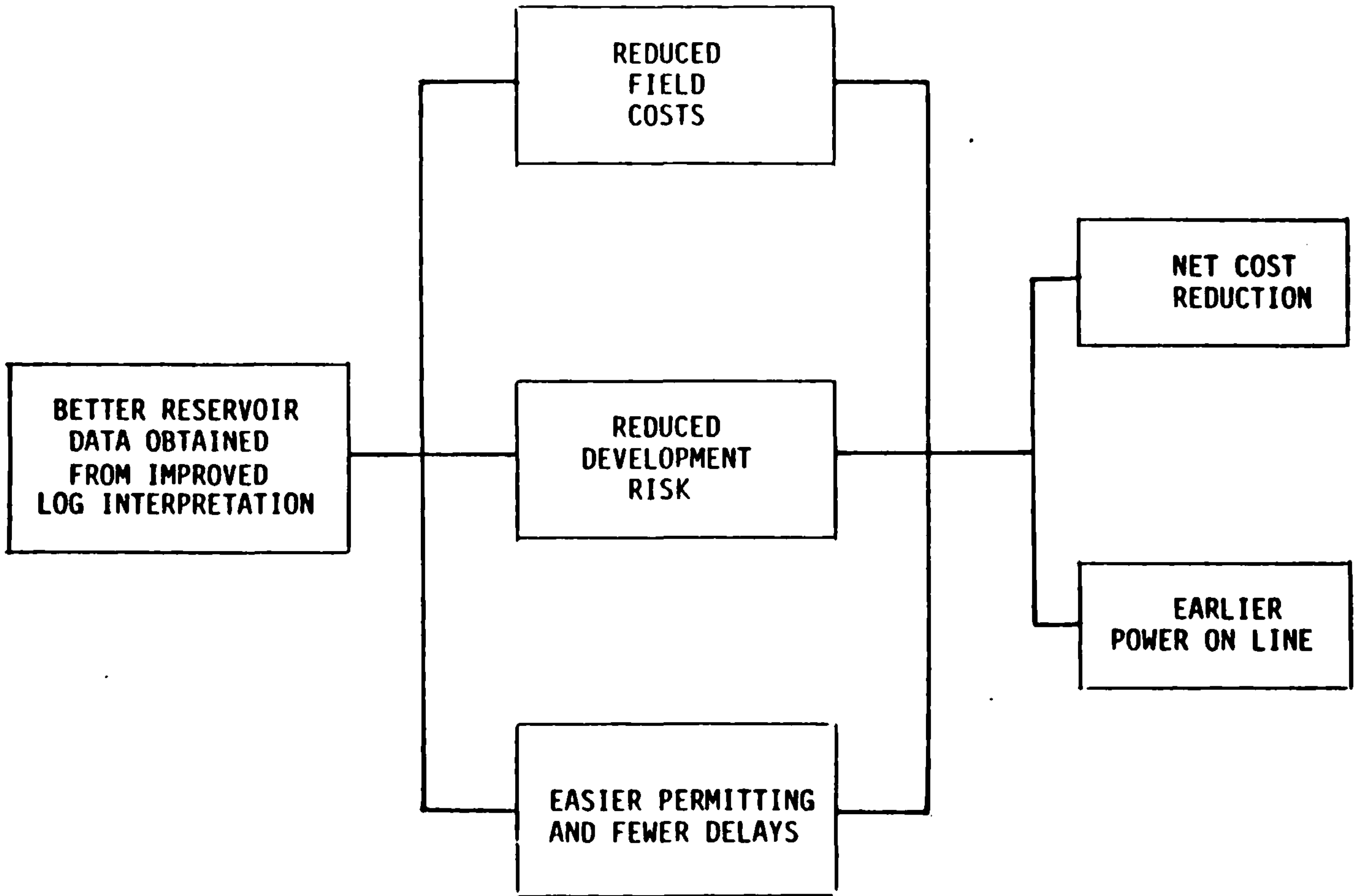


Figure 1. Nature of Benefits Expected From Improved Log Interpretation.

The areas selected for research and development were chosen from the list of priorities given in Table I, the Geothermal Well Log Interpretation State-of-the-art report, and the Benefit/Cost Analysis for Research in Geothermal Log Interpretation report to enhance the commercial geothermal log interpretation technology. They are:

- Establishment and support of calibration facilities (test pit models from which matrix and fracture responses of logging tools can be obtained) and test wells representative of the major geologic reservoir categories.
- Documentation and publication of case histories of interest and value in geothermal log interpretation.
- Special, advanced well log runs and, especially the subsequent interpretation technique developments based upon the log data enhancement afforded by these log runs.
- Establishment and support of a geothermal log library that has the capability of furnishing logs in analog and digital format and the supporting data.
- Establish property measurements on cores, well cuttings, and rock samples from many different geothermal reservoirs and fields for log interpretation applications.
- Describe and exhibit logging tool responses to fractures by analytical and/or numerical fracture modeling studies.
- Publish a quarterly newsletter, conduct a yearly steering committee meeting, and organize one or two workshops.
- Compile and publish a geothermal log interpretation handbook.

TABLE I

Formation Evaluation: Those measurements made in the borehole that are ultimately used to characterize the entire reservoir.	Production Management: Those measurements in or near the wellbore required in an engineering sense to keep the well producing over a number of years and to provide data for design and operation of surface facilities.
1. Time-lapse temperature profile measurements for true formation temperature profile	1. Flow profile including flow rate,
2. Lithology, depth, and thickness of formations	2. Pressure profile,
3. Permeability, both intergranular (matrix) and fracture	3. Fluid composition,
4. Porosity, again both intergranular (matrix) and fracture	4. Hole and/or casing mechanical conditions such as: a. scaling; b. corrosion; c. cement quality; d. mechanical properties of the borehole system itself.
5. Fracture system re-emphasized with regard to location in depth, orientation, permeability, and other characteristics	
6. Borehole geometry as an indicator of fractures and particularly with regard to size as an indication of quality and corrections for other logging data.	
7. Fluid composition	
8. Thermoconductivity and heat capacity	
9. Several elastic moduli of rock that are useful in designing well stimulation.	

To establish the goals and objectives for the Geothermal Log Interpretation Program, and to select priorities and determine budget levels, LASL has depended on seven major sources of input:

- A steering committee consisting of experts in logging interpretation and related areas, representing industry, government agencies, universities, and national laboratories.
- The Geothermal Logging Instrumentation Development Program managed by the Sandia Laboratories (SLA).
- The Geothermal Reservoir Engineering Program directed by Lawrence Berkeley Laboratory (LBL).
- The Resource Exploration and Assessment Technology Development Program centered at the University of Utah's Earth Science Laboratory (ESL) and directed by the University of Utah Research Institute (UURI).
- Feedback from workshops, newsletters, technical papers, and formal and informal contacts within the geothermal community.
- The DOE Division of Geothermal Energy.
- Two reports - Geothermal Well Log Interpretation State-of-the-Art and Benefit/Cost Analysis for Research in Geothermal Log Interpretation, have been used to assess the impacts of improvement in log interpretation in the advancement of geothermal resource evaluation and development.

II. PROGRAM SUMMARY

A. Scope

The primary aim of this plan is to continue developing and refining the capability of interpreting geophysical logs from geothermal wells through external and internal research projects and to assure industrial use of the information derived. This program is guided by a steering committee that is composed of knowledgable representatives from industry, universities, governmental agencies and the National Laboratories and managed by the Los Alamos Scientific Laboratory. By use of the reservoir parameters for log interpretation (prioritized by steering committee) listed in Table I, the methods and techniques of log interpretation will be improved to provide these needed parameters with the accuracy and reliability required. This improvement is required because the determination of the economic potential of a given geothermal well, in addition to development plans for entire geothermal fields, depends upon correct interpretation of borehole geophysical measurements. Although some tools and interpretive techniques can be modified from the petroleum, water well, and mining industries, new specialized tools and interpretive techniques must be developed for geothermal boreholes where the temperatures, pressures, and corrosive fluids are more hostile than in typical oil wells, and where rock types are significantly different from the sedimentary formations normally encountered in petroleum reservoirs. To accomplish the goals of this program, the following external and internal technical tasks are proposed:

(a) Fabrication of calibration test pits and operation of representative geothermal calibration and/or test wells for refining and verifying interpretive techniques.

(b) Support of advanced research well logging and log analysis.

(c) Establishment of a geothermal well log library.

(d) Support of case history studies.

(e) Acquisition of core property measurements and correlation of these data with geothermal well logs for in-situ measurement verification.

(f) Support for preparation of a geothermal log interpretation handbook.

(g) Provide a fracture model compendium of analytical and/or numerical investigations of geophysical well log responses to fractures.

The technical and financial management responsibilities of the research and technological aspects of the program include: project reviews; workshops; development of task schedules and priorities; initiating and terminating program elements as indicated by shifting goals and available funds; communications; and coordination with related programs.

Overall programmatic responsibility will reside with DGE's Geothermal Log Interpretation Program Manager. LASL will be responsible for active direction and implementation of the program with appropriate management and fiscal authorization from DGE.

B. Objective

The principal objective of this program, that is primarily industry-based, is to aid in the early acceleration of the commercial development of the nation's geothermal resources by providing more reliable log interpretation. This objective is in accord with the broader mission of the Division of Geothermal Energy which is to stimulate the development of geothermal energy as an economic, environmentally acceptable, and reliable source of energy. To accomplish this aim, the Division's technical effort is allocated principally to the Directorate for Resource Utilization and the Directorate for Research and Advanced Technology. The goals of these directorates are commercial development of the nation's accessible geothermal resources, and establishment of commercial feasibility of the more abundant but less tractable advanced geothermal resource types, respectively.

C. Approach

In order to achieve the objectives of this program, the log interpretation problems of the geothermal industry must be solved. These problems have been identified and reviewed in detail in the Benefit/Cost Analyses for Research in Geothermal Log Interpretation report, the Geothermal Well Log Interpretation-State-of-the-Art report, in various case history and advanced logging and interpretation reports, and by the Geothermal Log Interpretation Steering Committee. The major problems are:

1. Insufficient calibration facilities for well log response to igneous and metamorphic lithology and fracture permeability and porosity.
2. Inadequate statistical data base that is provided with only limited core analyses and log data.
3. Incomplete knowledge of well log responses to fracture porosity and permeability.
4. Inadequate ability to determine geothermal reservoir formation temperatures immediately after drilling wells.

Solutions to these problems are needed in a way that will lead to early use of the improved interpretation methods by industry. This leads to the following activities described:

1. Provide for public access and use of calibration test pits and representative geothermal calibration/test wells for refining and verifying interpretative techniques and well log responses.
2. Support case history studies, advanced logging and interpretation studies, geothermal well log library, and core property measurements to build an adequate statistical data base, define reservoir size and

quality, and determine true geothermal reservoir formation temperatures.

3. Furnish support for log response characterization by producing a fracture model compendium of geophysical well log responses to fractures in or near a well bore.
4. Support the compilation and publication of a geothermal log interpretation handbook.
5. Coordinate log interpretation activities with other appropriate DGE geothermal programs. The interrelationship of these geothermal reservoir assessment elements is shown in Figure 2. Those activities will also provide a focus for the needed industrial input. Included are meetings of the Steering Committee and a quarterly issued newsletter. The LASL project staff recognizes the need for maintaining open and effective communications with the industrial practitioners of log interpretation and the users of log interpretation. The plan provides for special attention to these matters. The industrial participation should be relatively direct since most of the R&D efforts are to be centered in the private sector through subcontracts for the accomplishment of the technical tasks.

D. Time Schedule and Budget

The technical elements of the plan are described along with a five-year budget proposal. Figures 3 and 4 indicate the technical task schedules and Table II records the projected budget through FY84. As shown in Figures 3 and 4, the major task to be accomplished is the establishment of the calibration test pits. These should be completed by October 1, 1980. The second major task is the initiation of core property measurements and the

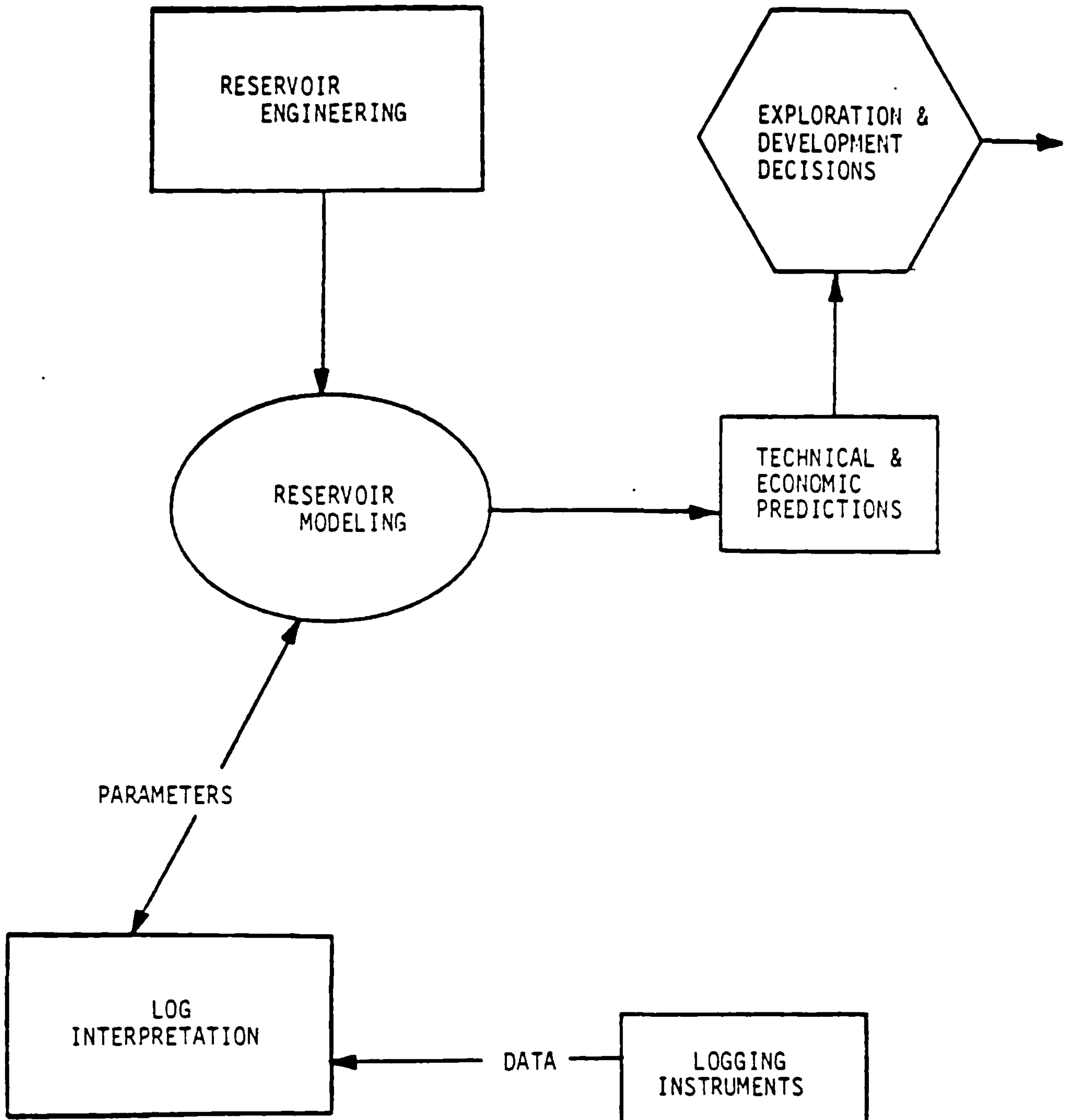


FIG. 2

INTERELATIONS AMONG RESERVOIR ASSESSMENT ELEMENTS

Fig. 3

GEOTHERMAL LOG INTERPRETATION PROGRAM

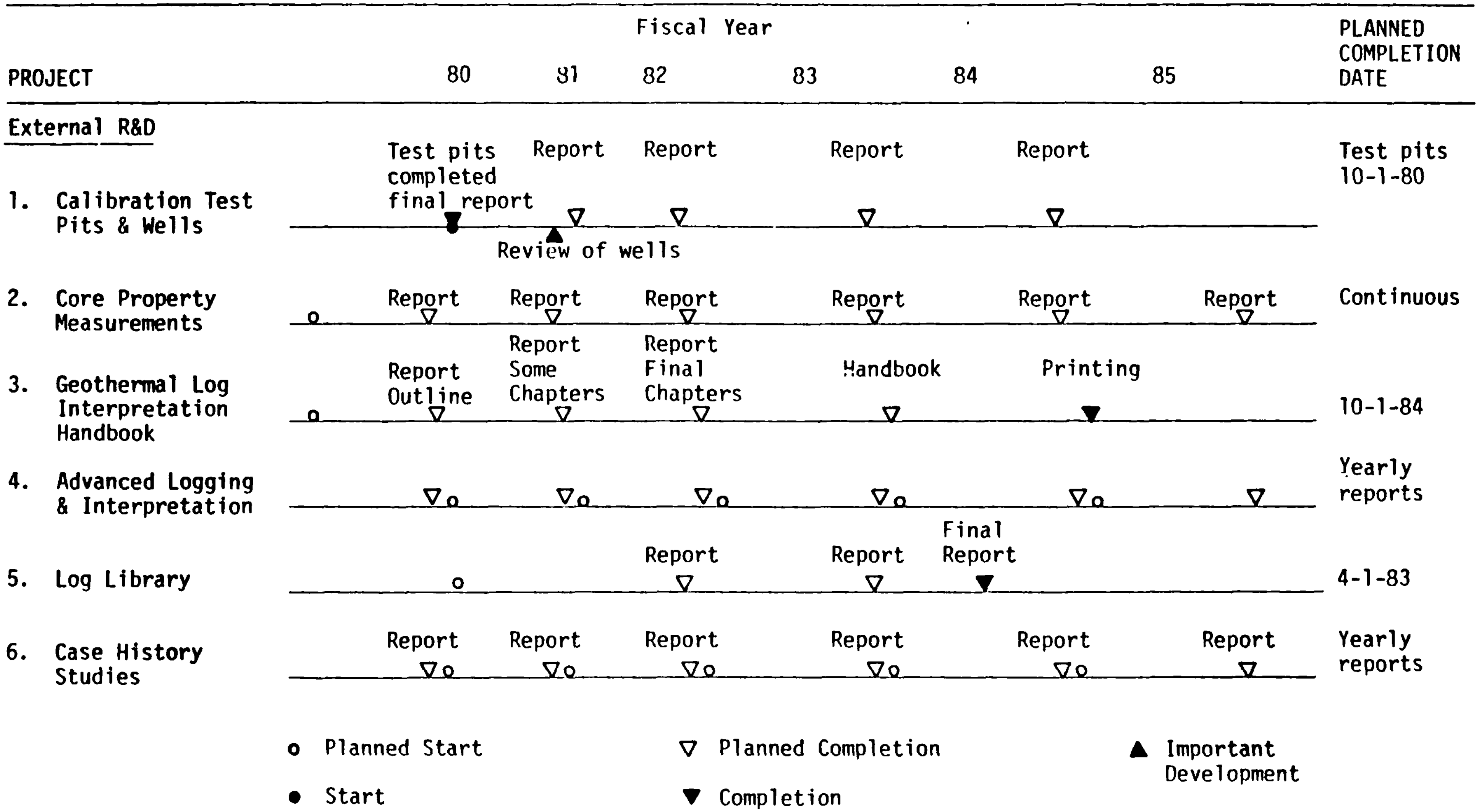


Fig. 4

GEOTHERMAL LOG INTERPRETATION PROGRAM

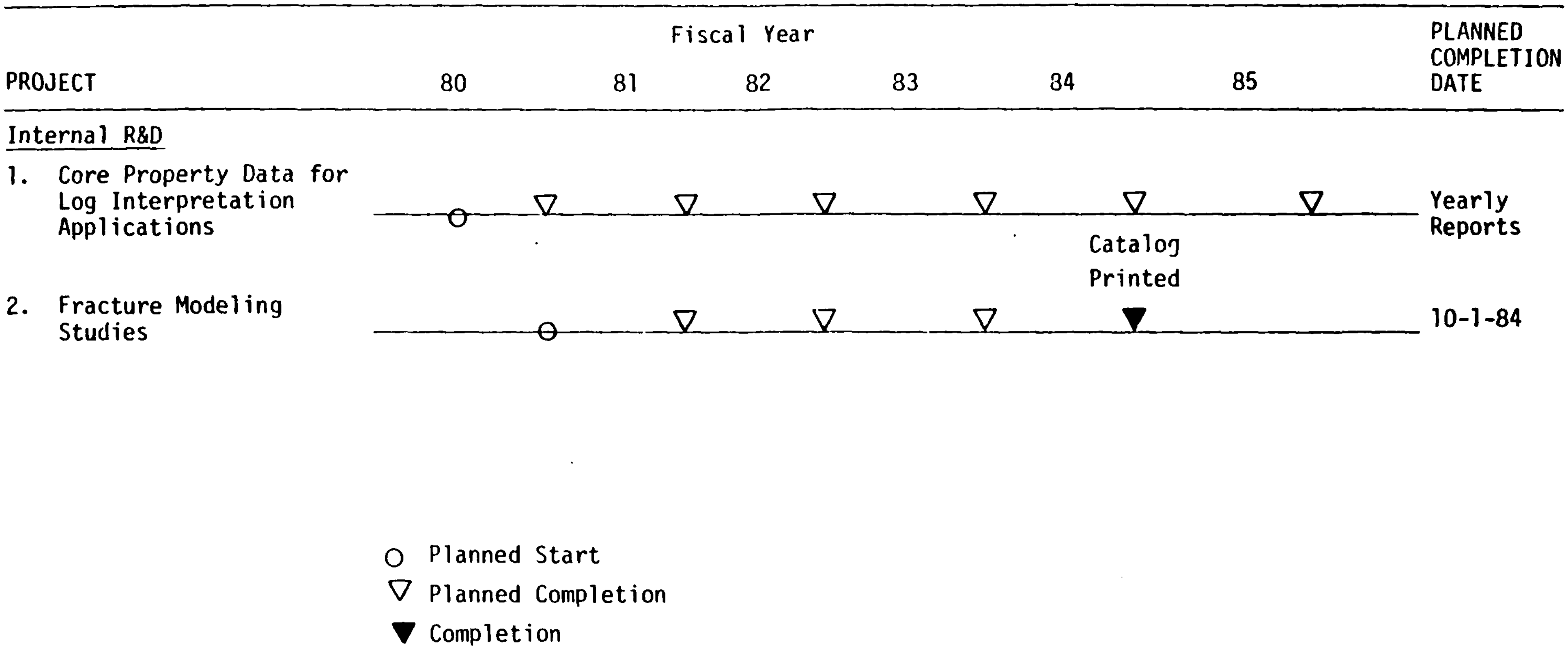


TABLE II

Proposed Budget ($1000) Geothermal Log Interpretation Project

Activity	Fiscal Year 80	81	82	83	84
External R&D					
Calibration Test Pits & Wells	480	40	40	45	45
Case History Studies	50	70	70	70	70
Advanced Logging & Interpretation	130	180	180	160	140
Log Library	-	70	80	55	-
Core Property Measurements	75	130	180	200	150
Geothermal Log Interpretation Handbook	10	50	100	50	10
Subtotal External R&D	745	540	650	580	415
Internal R&D					
Core Property Data for Log Interpretation Application		55	60	60	60
Fracture Modeling Studies	10	280	320	245	195
Subtotal Internal R&D	10	335	380	305	255
Management	200	280	310	310	310
TOTAL	955	1155	1340	1195	980

correlation of core property data with geothermal log interpretation applications. The third major task to be initiated is the fracture modeling studies. The accomplishment of these three tasks, along with completion of the fourth task, the geothermal log interpretation handbook is estimated to require a four to five year research effort to accomplish these tasks.

Support will continue for case histories and advanced logging and interpretation studies. These studies and the runs of advanced logs and/or analyses in wells or fields of opportunity will result in improved geothermal log interpretation techniques. A two to three year partial support for a commercial log library is planned to start in FY81.

E. Relationship to Other LASL, Sandia, UURI, LBL, and USGS Geothermal Development Projects

This program is closely related to the work of the LASL Geosciences Division and its geothermal groups. One of the functions of the geoscience groups of G-Division has been to develop several methods for downhole and inter-hole studies of hydraulic fractures. These include induced electric potential and seismic downhole investigative techniques. In addition, LASL G-Division and E-Division personnel have designed an induction logging tool for detection of vertical fractures that intersect the borehole. Significant contributions have been made to borehole geophysics, high temperature instrumentation sondes, cableheads, and sensors. The initial experiments have been conducted to develop the reservoir engineering techniques required to evaluate man-made reservoirs.

The above projects are directly related to the LASL Hot Dry Rock Geothermal Program whose purpose is to develop means for extraction of geothermal energy from hot impermeable rock.

The Resource Exploration and Assessment Program at the University of Utah Research Institute (UURI) also contains elements of potential interest and value in formation evaluation to the log interpretation efforts and thus close liaison will be maintained with this program.

The Logging Instrumentation Development project managed by the Sandia Laboratory and the Reservoir Engineering project of the Lawrence Berkeley Laboratory are closely related to this Log Interpretation Program. Close and continued coordination will be maintained with these two projects. Results in the interpretation program should be used as input to the Sandia Geothermal Logging Instrumentation Program to obtain improved and/or new logging techniques and instruments. The USGS geothermal logging program has been an important contributor to the understanding and development of geothermal logging and interpretation.

III. TECHNICAL PLAN

A. Goals

In accord with the broad objective of enhancing and accelerating the development of geothermal energy the goals of the Geothermal Log Interpretation program are:

- Establish calibration test pits along with test/calibration wells in typical reservoir types to provide calibration facilities for geothermal logging.
- Tabulate a variety of core property measurements and correlate these measurements with geothermal log data for geothermal reservoir in situ measurement verification parameter.
- Provide a fracture model compendium of geophysical well log responses.

- Support for a geothermal log interpretation handbook.
- Support for advanced or special log and log interpretation research projects.
- Support for case history studies and implementation of a log library.

Advances in these specific technical areas can be expected to contribute significantly to the reliability and ultimate commercial use of logs for the assessment of geothermal reservoirs. More accurate and effective means for the evaluation of reservoir size and quality will expedite the development of geothermal energy through reduction of risk for energy resource developers.

B. Strategy

The major portions of the Geothermal Log Interpretation Program will be subcontracted to industry whenever an appropriate and interested offerer can be identified. This approach is intended to build interest in and capability to perform effective analysis of geothermal logs. This capability will be directly available to the geothermal developer and reservoir engineer through the usual exercise of the free market place.

The technical and research activities identified at this juncture have been organized into six general categories or task areas. These tasks have been ordered in the next section in the sequence in which it is planned that they will be initiated.

C. Description of Tasks

(a) Calibration test pits and calibration/test wells

Geophysical well logs are generally continuous records of various measurements plotted versus depth. For these measurements to have meaning, they must be related to generally accepted standard units by a valid and specified system of comparison.

Reliable and precise measurement and recording of log data is necessary for effective well evaluation, input to reservoir engineering models, and subsurface geologic or geophysical appraisal. Proper interpretation of log data provides accurate subsurface geologic parameters. Calibration data that is auxiliary to the log data will show the degree of log accuracy and indicate the reliability of the estimated subsurface geologic parameters when the log data is reviewed with a knowledge of the calibration procedures.

The comparison systems or controlled conditions should be guided within limits of practicality by:

(A) Fixed Standards which are appropriate for the actual parameters to be measured and

(B) Fixed Standards which bracket the anticipated range of measurements.

These fixed standards are generally made of large blocks of rock. The rock is the type normally found in the subsurface geology where the wells are drilled and logged. The large size of these blocks of rock are needed so that the radius of investigation of the logging probes remains within the block of rock. Potential errors, that can be cumulative, will be introduced with each compromise one makes for practicality.

Logging equipment can be calibrated by:

(1) Primary Standards, public calibration pits such as the API test pits, the DOE Grand Junction Office test pits, and the USGS Denver Federal Center calibration pits or special laboratory environments

such as zero-conductivity achieved in air for calibrating induction probes.

The API test pits are designed for measuring the gamma-ray response in a simulated shale that has twice the average radioactive components and for measuring the porosity response for neutron probes in limestone rocks. These calibration pits and their boreholes are saturated or filled with fresh water.

The DOE Grand Junction Office test pits are doped concrete. These models are designed for measuring the gamma-ray response and the neutron fission response of uranium, thorium, and potassium simulated ore bodies in consolidated sandstone. The USGS Denver Federal Center test pits are concrete test pits designed for calibrating density, sonic, electrical, and magnetic susceptibility logging probes used in construction of buildings, dams, mining, etc.

(2) Secondary standards; usually private test pits.

(3) Portable field calibration standards, devices that have been adapted or adjusted to primary standards.

(4) Laboratory analysis of Core Samples, log response regulated by comparison of limited sample size. The radius of investigation of logging probes can vary from 6 inches to 8 ft from the borehole wall. The core is 4 to 6 inches in diameter and petrophysical measurements of this core are obtained from logging probes. Therefore, regulation of log responses with cores is limited because of these volume differences.

(5) Cross Plots, log response adjusted to local geologic conditions encountered in well. Various log responses are statistically

plotted against themselves and adjustments can be made to these responses in order to better fit the local geologic conditions. Redundacy of various log measurements greatly aids this statistical approach.

All secondary calibration standards or techniques (above items 2-5) are referenced to the primary standards (above item 1).

At the present time there are no primary standards for calibrating logging equipment in igneous and metamorphic lithology or in fracture porosity. Three test pits of the size in Figure 5 are proposed as primary standards. Each calibration pit will be constructed of large stone blocks. One pit will have Sierra White granite (fine grain) blocks, the second pit will have Rockville granite (coarse grain) blocks, and the third pit will have Wisconsin altered basalt blocks. These blocks will have a cored borehole and wire sawn simulated fractures as shown in Figure 5.

These calibration pits will be saturated with cool fresh water and the log environment obtained from these pits will be match the conditions that are routinely found in logging most sections of geothermal wells. Log responses obtained from these test pits can be compared to the log responses obtained from the two calibration/test wells that GLIP has made available and with other geothermal wells. High temperatures and hot water are anomalous conditions and these can be regulated and accounted for through the calibration/test wells, core analysis, and cross plots as outlined in Figure 6. Different water salinities can also be analyzed in this manner. The fixed primary standard calibration pit yields a base line or starting point in log response and other geologic conditions can be analyzed with reference to this starting point.

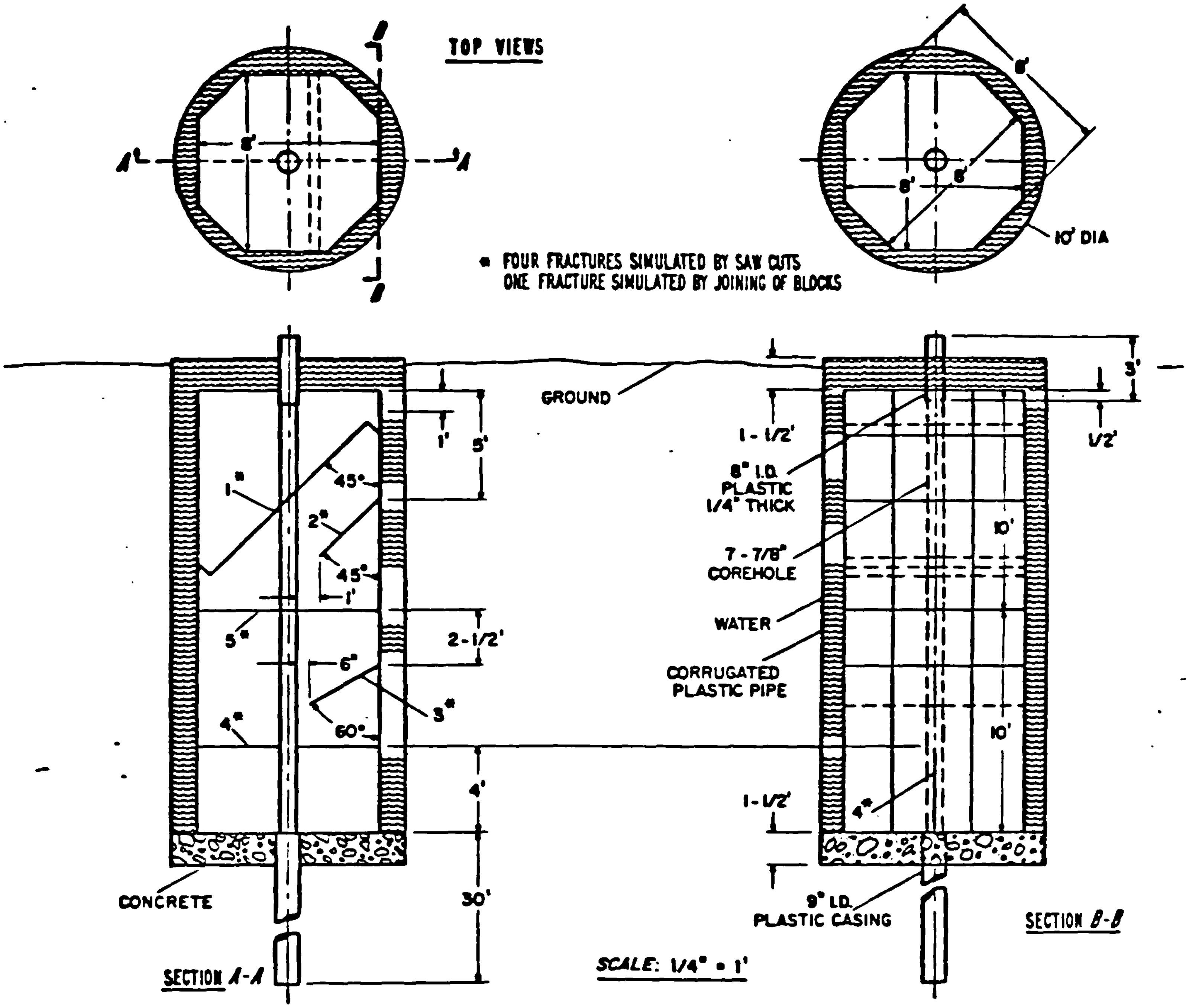


FIGURE 5 TEST PIT DESIGN

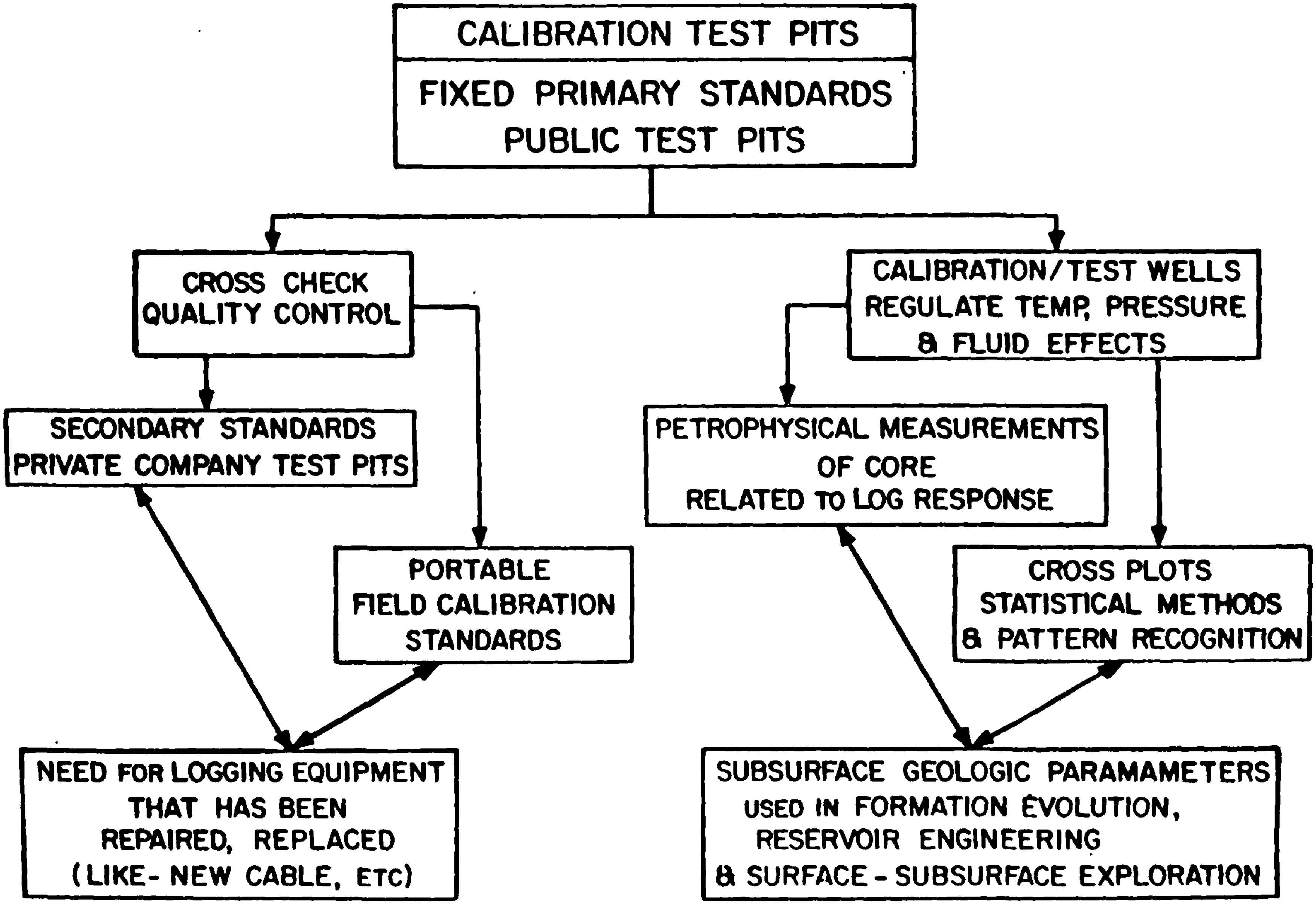


Figure 6. Calibration Rank

The cores from the cored boreholes will be analyzed in the laboratory for their petrophysical properties. These properties along with the known location and fixed geometry of the simulated fractures will provide primary standards for calibrating logging equipment in igneous and metamorphic lithology with fracture porosity. This calibration capability will greatly increase the interpretation reliability of geophysical logs obtained from geothermal wells. It will also stimulate the development of new interpretive techniques and their utilization for the development of the economic potential of geothermal prospects. These calibration pits and their standardization capability are designed to improve geophysical logging and log interpretation in geothermal development and therefore accelerate the commercialization of the nation's valuable geothermal resource potential.

(b) Correlate a variety of core property measurements with well log responses.

The economic production of geothermal fluids dictates a knowledge of the three factors that influence the potential, life, and productivity of the reservoir. These factors are: (1) the characteristics of the reservoir rock; (2) the characteristics of the subsurface fluid; and (3) the type of porosity and permeability. Core analysis and well tests, together with geophysical logs, special studies and areal correlation, give an insight into the first factor; fluid samples taken under reservoir conditions of pressure and temperature and liberated under controlled laboratory procedures give subsurface fluid characteristics; and pressure history, production history, and other field tests estimate well life and efficiency.

Core analysis is an important tool in the determination of reservoir rock characteristics, but it is only one of the many tools available for the determination of the potential of a well. The geophysical log, the well test, and core analysis, are the needed working tools for well completion design. For many reasons, any particular tool may fail to give positive results, but it is doubtful that all three will fail in the same well.

Core analysis, in addition to being an important tool in well completions and the most important tool for reservoir rock characterization, lends itself especially to specific and special tests, such as connate water, relative permeability, and acid solubility, among others, from which productivity, and well treatment can be deduced.

In order to make optimum use of cores and samples from geothermal wells in support of the log interpretation program it will be necessary to make various geophysical, petrophysical, geochemical, petrological, and structural analyses of cores and samples. This will be done to the extent possible by encouraging various specialists who have the necessary laboratory facilities to provide analytical service on a contract basis. Special core analysis will be obtained from commercial sources by subcontract. Information derived from these tests will be correlated to log responses, published, and stored (in the data file for the particular well and geothermal reservoir) in the log library to aid those needing the information in interpreting the appropriate well logs. These facilities will be supported in a manner such that industrial firms can have access to that service.

(c) Provide a compendium of geophysical well log responses to fractures.

Many geothermal lithologies and formation properties are unfamiliar or unknown. Therefore, it seems possible that calculations of theoretical log responses, by both analytical and numerical techniques, of certain discontinuities in boreholes could aid in reservoir evaluations. A tabulation of such characteristic signatures for a suite of logs would be useful in identifying and quantitatively defining the properties of such features.

The definition of a fracture system involves the location of the fractures (the subsurface depth at which the fractures occur), the width of the fracture (the aperture), and the orientation of the fracture (azimuth and dip). A single, reliable interpretation technique for detecting and evaluating fracture systems or fracture has not yet been developed. Log responses to fractures are not known in most cases.

A catalog of log responses to various fracture orientations to and location in a wellbore would be useful in identifying the nature of such fracture/faults. Obviously, the orientation of the fracture/fault, and therefore the response of certain logging tools, could prove helpful in evaluating many geothermal reservoirs.

(d) Research Logging and Log Analysis

Research logging and log analysis of wells of opportunity is a technical area in need of further support.

The wells considered may be geothermal exploration, geothermal production, or other wells of interest to the program. In wells of interest, comprehensive logging and/or sampling should be done to supplement that being done by the group financing drilling of the well. Thus, DOE funds will be used to insure acquisition of a comprehensive log suite. In exchange for this cost sharing, all data obtained from the well will be made public and placed in a well log library.

Some typical examples of studies that might be made in this task are:

- Interpretation of temperature and pressure changes with time.
- Effect of drilling mud and divalent cations on spontaneous potential logs.

- Radius of investigation of induction and other logging tools in the presence of high radial thermal gradient to the well bore.

The interpretation of a comprehensive suite of logs in an area of well-defined geology will facilitate identification of the generally applicable interpretation techniques for that area. For subsequent developmental wells in that area, only the logs critical for evaluation would be needed, thus enhancing the confidence of the resource developer and stimulating more rapid development of the geothermal industry.

(e) Geothermal Well Log Library

The objective of the proposed library is to stimulate development of geothermal resources by making copies of existing and new logs and their interpretations readily available. This log library or data bank should include all available data from existing wells. As new wells are drilled the library should be kept up to date and be made available to all on a standard fee basis. As a minimum, the following information should be included: well location; drilling information such as mud, casing, diameter, and penetration rates; core and sample data; fluid analysis; fluid temperature and pressure data; drill stem and production test data; geologic interpretation with formation tops; logs; probe identification; unprocessed probe output; calibration information and performance data on probe and logging systems.

Some of the log data will be stored on microfilm. Logs originally recorded in digital form will be stored and available in that format. The library should have the capability of digitizing microfilmed logs on a fee basis. Once digitized, the digital data would be added to the collection. Supplementary well data would be added to the collection and stored in machine-retrievable format and coordinated with the geothermal data bank (GEOTHERM) of the USGS.

Descriptions of interpretation techniques, and associated computer software for analyzing logs and data in the log library should, also, be available as developed. This material should include interpretation of case histories of wells with appropriate logs and well data, computer derived log calibration data, response curves, cross plots, and production data where available.

(f) Case History Studies

Published case histories have proved valuable and enlightened practitioners on how mineral deposits are located and developed. This development is generally through drilling wells, logging these wells, and interpreting the logs. To date, only a few published case histories exist on the interpretation of geophysical well logs obtained in geothermal wells. One of the reasons for this scarcity of published case histories on interpretation of geophysical logs in the development of geothermal fields may be the unreliable interpretations derived from these logs obtained in geothermal wells.

Published case histories often report instances where interpretation of geophysical well logs has been correct and development of mineral deposits has been successful. This may not yet be the case in the development of many geothermal fields because of the uncertainty in interpreting geophysical well logs. These unsuccessful case histories of geothermal fields should also be published to show what the uncertainties were in the interpretation of the geophysical well logs and how these uncertainties can be eliminated.

(g) Geothermal Log Interpretation Handbook

A readily usable and practical handbook to aid log interpretations in interpretating geophysical well logs acquired from geothermal wells will be constructed and written. This handbook will compile the refinement results and accomplishments in geothermal log interpretation into a format suitable so that geothermal log interpretators can readily use these results in interpreting geothermal well logs. This handbook will outline the procedures of log interpretation for formation evaluation and reservoir analysis (production and development of geothermal fields). Limitations, problems, and reliability of interpretations will also be addressed.

The proposed scheduling, priorities and funding for these tasks over the period FY80 through FY85 are indicated in Figures 1 and 2 and Table II.

IV. TECHNOLOGY UTILIZATION AND COMMERCIALIZATION

LASL will continue to conduct a vigorous technology transfer activity in conjunction with the Geothermal Log Interpretation program. Much of the research activity and technology development will be conducted by the industry; therefore, direct formal contacts with the participants will be established and maintained. Effective communication of results will be accomplished by:

- Publication of a quarterly newsletter.
- Discussions with the Steering Committee members.
- Formal presentations and publication of technical papers at appropriate professional societies and trade associations.
- Dissemination of contractor reports.
- Workshops.

- Invitations to industrial representatives to participate in the program under the G-Division Industrial Staff Member program.
- Publication of a handbook of Geothermal Log Interpretation.

The commercial use of the results during the program will be assured by the use of industrial contacts and through the Society of Professional Well Log Analyses (SPWLA) and the Geothermal Resource Council (GRC) technical societies.

V. MANAGEMENT PLAN

A. LASL Responsibilities

Proper planning and management of the program is essential to successful completion of the above described technical tasks. The planning and implementation of the technical tasks are organized under nine LASL management tasks as follows:

(i) <u>Steering Committee</u>

An important management task is to have a steering committee which will provide an interface with industry, give technological advice, review program plans and recommend future directions of the program to LASL and DGE. The steering committee consists of persons from the logging industry, geothermal development firms, universities, and federal and state agencies and is listed in Table III. The committee membership is large enough to permit flexibility of scheduling and has formed the following subgroups:

(a) Calibration and Logging

(b) Access Technology Needs and Technology Transfer

(c) Well Log Analysts

(d) Fracture Modeling

(e) Core Analysis

The steering committee along with designated people from LBL, UURI, Sandia, DOE, and LASL will meet at least once a year, for one to one and a half days to review and redirect this program.

(ii) Calibration & Calibration/Test Wells

The second management task deals with establishment and support of calibration facilities and calibration/test wells.

Two calibration/test wells have been established and a well manager has been hired. Well C/T-1 is located at East Mesa, CA and well C/T-2 is located at Roosevelt Hot Springs, Utah. WESTEC Services Inc. is the well manager for both wells.

Calibration test pits are presently being fabricated at the U.S. Geological Survey test pit site in Denver, Colorado. The U.S. Geological Survey will maintain and manage these test pits when they are completed. Use of these calibration facilities and calibration/test wells by industry will be encouraged.

(iii) Workshops

The third management task is to conduct at least two workshops on geothermal log interpretation in the next five years. The first workshop will be organized around a list of "problems-to'be-solved" generated with the aid of the steering committee. The first workshop will be convened in early fiscal 1981, after review of the comprehensive study, "Geothermal Well Log Interpretation - State-of-the-Art." Participation in the workshop will be by invitation, and participants may be reimbursed as appropriate. The workshop will be expected to produce tangible results which will be published by LASL. Prior to the workshop the results of the comprehensive study will be distributed to the participants. Also prior to the workshop

TABLE III

GEOTHERMAL LOG INTERPRETATION PROGRAM
STEERING COMMITTEE MEMBERS AS OF JANUARY 1, 1980

James K. Applegate
Geophysics Department
Colo. School of Mines
Golden, CO 80401

Myron Dorfman
Petroleum Eng. Dept.
University of Texas
Austin, TX 78712

W. Scott Keys
US Geological Survey
Denver Federal Center
Bldg. 25, Room 175
Denver, CO 80225

Walter Fertl
Dresser Industries Inc.
P.O. Box 1407
Houston, TX 77001

Dr. Dan M. Stalmach
Chevron Oil Field Research Co.
P.O. Box 446
La Habra, CA 90631

Dr. Donald G. Hill
Chevron Resources Company
P.O. Box 3722
San Francisco, CA 94119

D. Roger Wall
Aminoil USA, Inc.
1150 A Coddington Center
Santa Rosa, CA 95401

Heber Cinco
Petroleum Engineering Department
Stanford University
Stanford, CA 94305

Donald A. Campbell
Republic Geothermal Inc.
11823 East Slauson Ave., Ste. 1
Santa Fe Springs, CA 90701

J. R. (Jim) Jorden
Shell Oil Company
P.O. Box 831
Houston, TX 77001

E. Duane Percifield
Schlumberger
5700 Ralston St., Ste. 306
Ventura, CA 93003

Wallace Souder
Phillips Petroleum Company
248 FPB
Bartlesville, OK 74004

David E. Powley
Amoco Production Company
4502 East 41st St.
Tulsa, OK 74102

Robert C. Ransom
Union Oil Research Center
P.O. Box 76
Brea, CA 92621

Mel Buson
U.S. Geological Survey
345 Middlefield Road, MS 18
Menlo Park, CA 94025

Robert P. Alger
2501 Dickey Place
Houston, TX 77019

the participants will submit a priority list of interpretation needs. LASL will compile a composite list and distribute it before the workshop. The second workshop will be concerned primarily with evaluation of progress made on solutions to the problems defined in the first workshop. It will be convened in 1982 or 1983, and will follow the format of the first workshop. A third workshop may be offered, on a fee basis, to train interested personnel from industry and representatives of other organizations in the use of the geothermal interpretation technology developed in this program. This latter workshop will be coordinated with the draft of the handbook.

(iv) Advanced Research Logging and Log Analysis

A fourth management task is the planning, designing, and subcontracting with appropriate logging service companies for additional research logging of selected wells. Requests and recommendations for such logging and analyses will be solicited from other agencies, institutions, and industry through normal scientific channels and public solicitation. Initiatives for other projects may result from needs identified within the program. The selection of wells and planning for each job will be done by LASL, with consultation from the steering committee. Differences in geologic conditions, ownership, intended use of the well, and extent of existing logs may require separate specifications and contracts for each project or portion of a project. Although the logging will be done primarily to provide data for development of interpretation methods, plans will be coordinated closely with Sandia, Lawrence Berkeley Laboratories, and the University of Utah Research Institute so that the logs can be used to support the instrumentation, reservoir evaluation, or resource assessment development efforts.

(v) Well Log Library

The fifth management task is concerned with establishment of a well log library. The logs collected during the comprehensive review, case histories, and advanced logging and interpretation projects will provide a nucleus for the library. The LASL program managers will consult with potential industrial, federal and other users to determine which formats will best encourage use of the data. Design of the log storage and retrieval system will be coordinated with those of existing USGS and industry data files, to facilitate exchange of data and methods. A request for proposals to construct and operate the library will be prepared by LASL and proposals solicited from commercial firms.

(vi) Supervision of Subcontracts

The sixth management task is to provide continuing technical supervision of all subcontracts for the duration of this program. The contracts to be supervised include those for log interpretation technology, for calibration facilities and for each calibration/test well, for the well log library for additional research logging and log analysis, and for some other special work like core analysis and case history studies.

(vii) Coordination with other Programs

The seventh management task is to establish and maintain close coordination with existing and new DGE programs, with related programs of other federal and state agencies, institutions, and universities, and with industrial and commercial users and consumers of log interpretation technology. LASL quarterly newsletters will provide topical information to these related programs on LASL and other log interpretation progress. LASL will review and recommend action on unsolicited proposals received by DGE, and as requested by DGE.

(viii) Communication

The eighth management task is the preparation and distribution of reports and newsletters on all aspects of the program. This task will require LASL to publish regular progress reports with recommendations for new research as needed. LASL will also issue the progress and completion reports that result from subcontracted services. When justified, additional subcontracts may be let for detailed reports of specific advances in interpretive technique. A specific subcontract has been let for the preparation and publication of the preliminary version of the "Handbook of Methods for Geothermal Well Log Interpretation," to the Society of Professional Well Log Analysts (SPWLA).

(ix) Planning

The final management task is the initial development, preparation, and continued revision of this long term geothermal log interpretation plan.

This program plan revision will be scheduled for completion in July of each year. It will contain the results of the conclusions and recommendations of the Steering Committee reviews, and thus indicates the necessity for a Spring meeting (May or June) of the committee each year. The program schedule and milestones for the above tasks are shown in Table IV.

B. Procurement and Subcontract Management

Procurement activities will be conducted in accordance with established LASL procurement policy. This policy gives strong emphasis to competitive solicitation, with guidelines for request-for-quotations (RFQ's), and of request-for proposals (RFP's), the method of proposal evaluation, and proper source selection techniques. Where facts and circumstances indicate

TABLE IV

GEOTHERMAL LOG INTERPRETATION PROGRAM

Schedule and Milestone Chart

Task/Activity	Fiscal Year 80	81	82	83	84	85
i) Steering Committee	△	△	△	△	△	△
ii) Calibration & Calibration/Test Wells	Test △ Pits Completed	Review △ of Wells	Review △ of Wells	Review △ of Wells	Review △ of Wells	Review △ of Wells
iii) Workshops		△		△		△
iv) Advanced Logging & Research	△	△	△	△	△	△
v) Well Log Library		○	△	△	△ Final Report	
vi) Supervision of Subcontracts	○ Continuous →					
vii) Coordination with other Programs	○ "△" Continuous →	"△"	"△"	"△"	"△"	"△"
viii) Communication	* + * *	* + * *	* + * *	* + * *	* + * *	* + * *
ix) Planning	△ Program Rev.	△ Program Rev.	△ Program Rev.	△ Program Rev.	△ Program Rev.	△ Program Rev.

* Monthly Progress Report to DGE
\+ Quarterly Progress Report to DGE
** Quarterly Newsletter
△ Milestone, Meeting, Contract, or Report
○ Start
"△" Attend LBL, UURI, Sandia Steering Committee Meetings

the possible impracticability of placing a specific requirement on a competitive basis, the system provides for the possibility of noncompetitive procurement on a sole source basis.

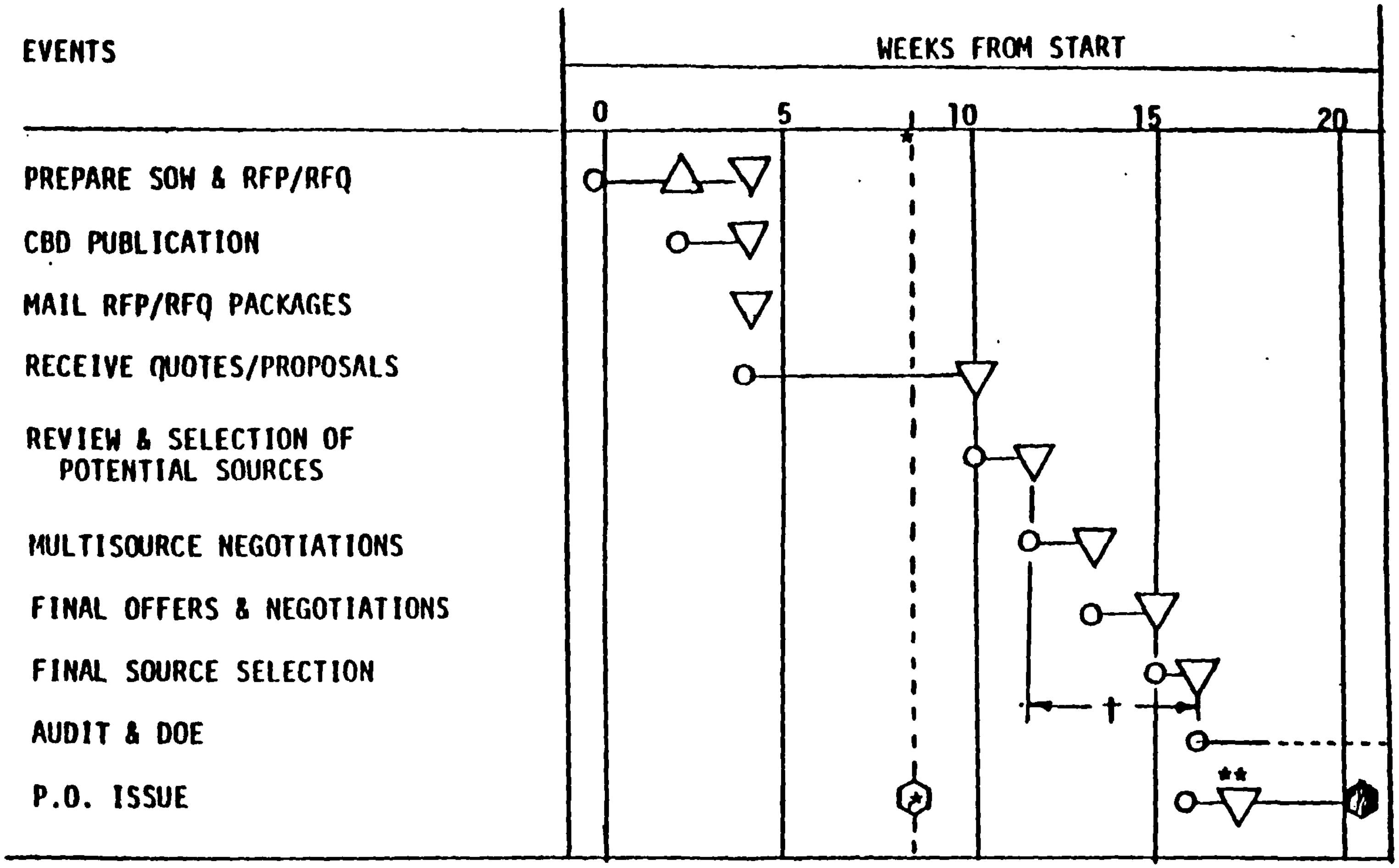
The LASL Project Manager, in coordination with the responsible DGE management, will establish the requirements of major project tasks to be contracted. Procurement and competitive solicitation will be handled by a collaboration of LASL technical and administrative personnel. Figure 7 illustrates a typical competitive procurement planning schedule. Sole source procurement can be completed on a more timely schedule. Contractor technical and fiscal activities and performance will be monitored through plant or facility visits, review of contractor reports and records, and independent analysis, experimental verification, or review of all technical results. The monitoring efforts will be conducted by the technical/procurement staff responsible for the respective contracts.

C. Project Administrative Approval Structure

In addition to the normal LASL administrative approval procedure for major contractual tasks, DGE will retain approval rights on the Statement of Work contained in RFQ's or RFP's that LASL will issue to perform the work of the program, and will have the opportunity to make additions to bidders lists. LASL will send DGE the results of any source selection process at least 10 days before negotiation with winners and will proceed with contract negotiations at the end of the 10-day period in the absence of objection by DGE.

DGE reserves the right to require publication of advance notice of intent to contract in the Commerce Business Daily.

FIG. 7. TYPICAL MAJOR MULTISOURCE COMPETITIVE PROCUREMENT PLANNING SCHEDULES FOR SUBCONTRACTS LARGER THAN $100,000



*Note: A $25,000 competitive schedule is ~ 8 weeks.

**Issue letter contract, followed by DOE review, approval and audit.

†Sole source procurement may be 4-5 weeks shorter.

D. Annual Program and Operating Plans

Prior to the beginning of each fiscal year at a time determined by DGE, LASL will submit a Program Plan which sets forth the specific objectives, activities, schedule, funding requirements, in-house level of effort, project management personnel, and any special review or reporting procedures planned for the upcoming year. Upon approval of the Program Plan, DGE will issue a Program Authorization Letter to implement the program. LASL will be responsible for a yearly revision of this Program Plan. This will be accomplished in July of each year.

E. Reporting and Review

In addition to internal LASL reviews, formal progress reviews will be conducted semiannually for evaluation by DGE management, LASL management, and other designated reviewers. The reviews will be in the form of detailed presentations on the status and problems of the several technical and management tasks. Emphasis will be placed upon items effecting goals, schedules, commercialization and costs. Evaluations of these reviews will form a portion of the material used to update and revise this Program Plan.

Informal Quarterly Reports will be issued to DGE, which will cover:

- Abstract of program
- Significant activities
- Schedule status
- Planned and actual costs and obligations
- Problems
- Interactions, contracts, and interfaces
- Technology utilization and commercialization
- Lists of contractor reports and program reviews.

A one-half page informal monthly progress letter will be prepared for DGE.

VI. SELECTED BIBLIOGRAPHY

*Reports and Papers Sponsored by the Geothermal Log Interpretation Program

Allen, L. S., Caldwell, R. L., and Mills, W. R., "Borehole Models for Nuclear Logging," Society of Petroleum Engineers Journal, pp. 109-112, June 1965.

*Applegate, J. K., Donaldson, P. R., and Moens, T. A., "Well Logging Case History of the Raft River Geothermal System, Idaho," SPWLCA 20th Annual Logging Symposium, paper YY, June 1979.

*Applegate, J. K. and Moens, T. A., "Geophysical Logging Case History of the Raft River Geothermal System, Idaho," Los Alamos Scientific Laboratory report LA-8252-MS (1980).

Baker, L. E., Baker, R. P., and Hughan, R. L., "Report of the Geophysical Measurements in Geothermal Wells Workshop," Sandia Laboratory Energy report SAND 75-0608 (December 1975).

Baker, L. E., Campbell, A. B., and Hughan, R. L., "Well-Logging Technology and Geothermal Applications," Sandia Laboratory energy report SAND 75-0275 (May 1975).

Ball, L., Dhilion, H., El-Sawy, A., and Mathews, M., "Benefit/Cost Analysis of the Department of Energy Program for Geothermal Exploration and Assessment Technology," paper GL-9 presented at the Society of Exploration Geophysicists' 48th Annual International Meeting, November 1978.

Belknap, W. B., Dewan, J. T., Kirkpatrick, C. V., Mott, W. E., Pearson, A. J., and Rabson, W. R., "API Calibration Facility for Nuclear Logs," Drilling and Production Practice, API, pp. 289-316, December 1959.

Cochrane, J. E., "Principles of Log Calibration and Their Application to Log Accuracy," Journal of Petroleum Technology, pp. 817-826, July 1966.

Curtis, M. R. and Witterholt, E. J., "Use of the Temperature Log for Determining Flow Rates in Producing Wells," Soc. Petroleum Engineers, paper SPE-4637, pp. 1-12 (preprint) (1973).

Czubek, J. A., "Comparison of Nuclear Well Logging Data With the Results of Core Analysis," Nuclear Techniques in Geochemistry and Geophysics, International Atomic Energy Agency, Vienna, pp. 93-106, 1976.

Dresser Atlas, "Calibration Fundamentals," January 1979.

*Davis, D. G. and Sanyal, S. K., "Case History Report on East Mesa and Cerro Prieto Geothermal Fields," Los Alamos Scientific Laboratory report LA-7889-MS (June 1979).

*Ershoghhi, I., Phillips, L. B., Dougherty, E. L, Handy, L. L., and Mathews, M., "Application of Oilfield Well Log Interpretation Techniques to the Cerro Prieto Geothermal Field," SPWLA 20th Annual Logging Symposium, paper PP, June 1979.

*Ershaghi, I., Phillips, L. B., Dougherty, E. L, and Handy, L. L., "Application of Oil-Field Well Log Interpretation Techniques to the Cerro Prieto Geothermal Field," Los Alamos Scientific Laboratory report LA-8130-MS (October 1979).

Glenn, W. E. and Hulen, J. B., "A Study of Well Logs from Roosevelt Hot Springs," KGRA, Utah, 20th Annual Logging Symposium, paper ZZ, June 1979.

Holt, O. R., "Log Quality Control," 16th Annual SPWLA Logging Symposium Transaction, paper BB, June 1975.

Jones, P. H. and Skibitzke, H. E., "Subsurface Geophysical Methods in Ground Water Hydrology," Advances in Geophysics, v. 3, pp. 241-300, (1956).

Keller, G. V., Murray, J. C., and Towle, G. H., "Geophysical Logs from the Kilauea Geothermal Research Drill Hole (Colorado School of Mines)," Soc. Prof. Well Log Analysts (1974).

Keys, W. S., "Borehole Geophysics in Igneous and Metamorphic Rocks," SPWLA 20th Annual Logging Symposium, paper OO, June 1979.

Kintzinger, P. R., West, F. G., and Aamodt, R. L., "Downhole Electrical Detection of Hydraulic Fractures in GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6890-MS (July 1977).

Maciula, E. A. and Cochrane, J. E., "Quantitative Use of Calibration Data to Correct Miscalibrated Well Logs," Journal of Petroleum Technology, pp. 663-670, July 1968.

Mathews, M. A., Koizumi, C. J., and Evans, H. B., "DOE-Grand Junction Logging Model Data Synopsis," Bendix Field Engineering Report No. GJBX-76(78), May 1978.

*Mathews, M, Arney, B., and Sayer, S., "Log Comparison from Geothermal Calibration/Test Well C/T-1," SPWLA 20th Annual Logging Symposium, paper RR, June 1979.

*Mathews, M., "Log Responses from the Geothermal Clibration/Test Well C/T-2," SPWLA 20th Annual Logging Symposium, paper SS, June 1979.

*Mathews, M. and Gambill, D. T., "Compilation of Cores and Cuttings from US Government-Sponsored Geothermal Wells," Los Alamos Scientific Laboratory report LA-8253-MS (1980).

Merkel, R. H., "The Generation of Thermal Conductivity and Heat-Flow Logs from Conventional Borehole Logs," (abs.), Geophys. v. 50, no. 1, p. 176 (1975).

Mills, W. R., Hoyer, W. A., Tittman, J., and Wilson, B. F., "A Proposed Calibration Facility for Pulsed Neutron Logging Tools," The Log Analyst, pp. 3-5, issue 1, 1977.

Nelson, P. H. and Glenn, W. E., "Influence of Bound Water in the Neutron Log and Mineralized Igneous Rocks," SPWLA 16th Annual Logging Symposium Transactions (1975).

*Newman, K. L., "Calibration/Test Well Management Geothermal Log Interpretation Program," Annual Topical report, 55 p., December 1979.

*Rigby, F. A. and Riardon, P., "Well Logs for Geothermal Development, Benefit Analysis," SPWLA 20th Annual Logging Symposium, paper CC, June 1979.

*Rigby, F. A. and Riardon, P., "Benefit/Cost Analysis for Research in Geothermal Log Interpretation," Los Alamos Scientific Laboraory report LA-7922-MS (July 1979).

Ritch, H. J., "An Operational Hole Logging Evaluation in Metamorphic Rock," SPWLA 16th Annual Logging Symposium Trasaction (1975).

Sanyal, S. K., Marden, J. R., and Ramey, J. J. Jr., "The Effect of Temperature on Electrical Resistiity of Porous Media," Log Analyst, v. XIV, no. 2, pp 10-24 (1973).

Sanyal, S. K. and Meidav, H. T., "Important Considerations in Geothermal Well Log Analysis," Soc. Pet. Engineers, SPE No. 6535 (1977).

*Sanyal, S. K., Wells, L. E., and Mathews, M., "Classification of Geothermal Reservoirs from the Viewpoint of Log Analysis," SPWLA 20th Annual Logging Symposium, paper HH, June 1979.

*Sanyal, S. K., Wells, L. E., and Bickham, R. E., "Geothermal Well Log Interpretation Midterm Report," Los Alamos Scientific Laboratory report LA-7693-MS (February 1979).

*Sanyal, S. K., Wells, L. E., and Bickham, R. E., "Geothermal Well Log Interpretation-State of the Art," Los Alamos Scientific Laboratory report LA-8211-MS (January 1980).

Schlumberger Limited, "Log Interpretation, Volume I-Principles," 1972 Edition.

Schlumberger Well Services, "Calibration and Quality Standards," March 1974.

*Sethi, D. K. and Fertl, W. H., "Geophysical Well Logging Operations and Log Analysis in Geothermal Well Desert Peak No. B-23-1," Los Alamos Scientific Laboratory report LA-8254-MS (1980).

Snodgrass, J. J., "Calibration Models for Geophysical Borehole Logging," Bureau of Mines Report of Investigations, RI 8148, 1976.

Waller, W. C., Cram, M. E., and Hall, J. E., "Mechanics of Log Calibration," 16th Annual SPWLA Logging Symposium Transactions, paper GG, June 1975.

Welex, "Calibration Principles and Field Calibration Procedures for Welex Logs," Bulletin A-134, January 1979.

*Wells, L. E., Sanyal, S. K., and Mathews, M., "Matrix and Response Characteristics for Sonic, Density, and Neutron," SPWLA 20th Annual Logging Symposium, paper Z, June 1979.

West, F. G., Kintzinger, P. R., and Laughlin, A. W., "Geophysical Logging in Los Alamos Scientific Laboratory Geothermal Test Hole No. 2," Los Alamos Scientific Laboratory report LA-6112-MS (November 1975).

West, F. G. and Laughlin, A. W., "Spectral Gamma Logging in Crystalline Basement Rocks," Geology (1976).