GEOPHYSICS, VOL. 44, NO. 10 (OCTOBER 1979); P. 1721–1737, 4 FIGS., 8 TABLES.

The National Geothermal Exploration Technology Program

L. Ball*, J. W. Salisbury*, P. R. Kintzinger‡, A. F. Veneruso§, and S. H. Ward**

In response to the Geothermal Energy Research, Development, and Demonstration Act of 1974, a federal geothermal program has been established with the objective of stimulating the commercial development of geothermal resources. The program goal is to increase the annual rate of energy utilization from the present 0.04 quads (500 MWe) to 0.3–0.5 quads in the near term (about 1985), 4.0–9.0 quads in the mid-term (1985–2000), and 16.0–28.0 quads in the long term (by about 2020). The realization of these goals depends upon the discovery and exploitation of many new geothermal resource areas.

The Department of Energy program for geothermal exploration and assessment has been structured to address technological barriers presently hindering the economical discovery and delineation of geothermal resources. We describe the program elements—exploration technology, reservoir assessment, reservoir confirmation, and reservoir engineering—in light of the need to evaluate some 1500 new prospects in order to meet the federal midterm electric power goal of 20,000 MWe on-line by the year 2000.

We illustrate the program elements with suggested sequences for exploration, assessment, and confirmation of a 200-MWe resource in the eastern Basin and Range physiographic province. The estimated costs for these sequences are $385,000, $565,000, and $3,190,000, respectively. Deep drilling constitutes the major element in the confirmation costs.

An economical exploration strategy requires use of cost-effective techniques; thus, we have initiated a number of technology assessment studies. Pursuant to these studies, we present a summary of our initial findings and discuss the status and needs for topics such as system modeling, thermal methods, rock and fluid properties, seismic, and electrical methods.

Accurate reservoir assessment requires new developments in logging instrumentation for high-temperature, hostile environment boreholes and improved means for interpreting acquired data. The logging instrumentation program is aimed at upgrading logging systems for operation at 275°C and 48.3 MPa in the near term (1982) and 350°C and 138 MPa by 1986. Existing hardware is being upgraded, components and materials are being developed, and critically needed prototype tools for temperature, flow, and pressure measurements will be evaluated.

A program addressing log interpretation problems uses industrial expertise to analyze specific shortcomings in our ability to infer critical reservoir parameters from acquired data. The program will also establish and maintain test and calibration wells and support research logging and petrophysical studies.

INTRODUCTION

Passage of Public Law 93-410 (Geothermal Energy Research, Development, and Demonstration Act of 1974) led to the definition of a comprehensive federal geothermal energy program. We describe the national program objectives, the role of exploration technology, and a brief overview of the status of surface and borehole technologies.

Manuscript received by the Editor October 30, 1978; revised manuscript received March 12, 1979.

* U.S. Dept. of Energy, Div. of Geothermal Energy, M.S. 3122C, 20 Massachusetts Ave., N.W., Washington, D.C. 20585; L. Ball presently U.S. Dept. of Energy, Grand Junction Office, P.O. Box 2567, Grand Junction, CO 81501.
‡ Los Alamos Scientific Laboratories, P.O. Box 1663, Los Alamos, NM 87545.
§ Sandia Laboratories, Division 4736, P.O. Box 5800, Albuquerque, NM 87115.
** Dept. of Geology and Geophysics, University of Utah, 717 Mineral Sciences Building, Salt Lake City, UT 84112.

Geothermal resource types

The three major geothermal occurrences of interest to the federal program are hydrothermal, hot dry rock, and geopressured resources.

Hydrothermal resources.—These resources can themselves be subdivided into igneous-related, regional high heat flow, local high heat flow, and near-normal temperature gradient types. The highest grade hydrothermal resources, including all known dry steam systems, are igneous-related; that is, the high-grade heat is derived from near-surface magma chambers.

Regional high-heat flow, on the other hand, is likely to occur in those areas where the crust is thin, putting the earth's surface in closer touch with its hot interior. Wherever groundwater circulates at depth, it may become heated and form a hydrothermal system, although typically a lower grade than those associated with magma chambers.

Localized areas of high heat flow may occur where unusually high uranium, thorium, and potassium concentrations in otherwise cooled plutons provide radiogenic heat. The grade of this kind of heat is so low that these resources can be used only for space and process heat.

Finally, even near-normal temperature gradients in deep sedimentary basins will provide warm water, which may be recovered essentially as a by-product of oil and gas development.

Hot dry rock.—Hot dry rock occurs in all of the thermal environments listed for hydrothermal resources wherever there is an inadequate fluid supply. It is often classified as a separate resource because of the very different technology necessary for its exploitation.

Geopressured resources. Geopressured resources are another special case, occurring in the near-normal temperature gradient regime. In a deep sedimentary environment, such as is found on the Gulf Coast, aquifers may contain dissolved methane and hydraulic energy in addition to elevated temperature.

Federal objectives and goals

The objective of the federal geothermal program is to stimulate the commercial development of geothermal resources as economic, reliable, operationally safe, and environmentally acceptable alternate energy sources. The combined efforts of the federal government, state and local governments, and the private sector toward the realization of substantial geothermal energy comprise the national effort. Within the national effort, the activities of the various federal agencies constitute the federal program. The Department of Energy (DOE), designated as the lead federal agency for geothermal development, works through the Interagency Geothermal Coordinating Council (IGCC) to foster coordination within the federal program. The Council, chaired by DOE, is made up of high-level representatives from each of the agencies actively concerned with the program. The bulk of the federal research and development is now carried out by DOE's Division of Geothermal Energy (DGE) and by agencies of the Department of Interior.

The DOE/DGE and the IGCC have focused on programs to develop the nation's geothermal energy resources wherein the goal is to accelerate the actual commercial utilization of geothermal energy; that is, the production of electrical power on line and nonelectric (thermal) power in commercial quantities through a comprehensive approach to all barriers (technological, legal, institutional, etc.). National goals have been formulated through regional planning in cooperation with local entities to bring geothermal power (electric and nonelectric) on-line in a planned and rational time-phased manner. The planned pace of development is expressed in the form of resource development scenarios for each major geothermal

Table 1. Intended commercial geothermal utilization potential given successful federal program implementation.

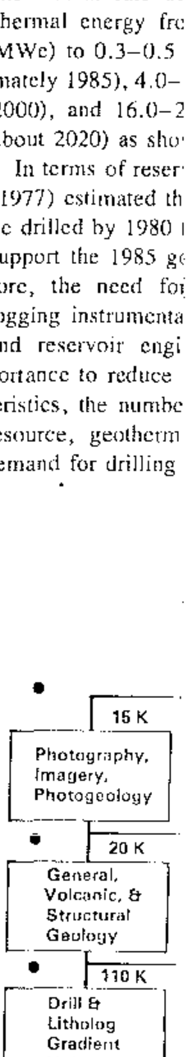
	1985	2000	2020
Electric capacity (MW)	3000–4000	20,000–40,000	70,000–140,000
Electric applications equivalent fossil fuel energy (quads/yr)	0.2–0.3	1.5–3.0	5.0–10.0
Nonelectric applications (quads/yr)	0.1–0.2	0.5–2.0	6.0–8.0
Geopressured methane (quads/yr)	0.0–0.02	2.0–4.0	5.0–10.0
Total energy (quads/yr)	0.3–0.5	4.0–9.0	16.0–28.0

---

prospect.

The intended fed
the annual rate of
thermal energy fro
MWe) to 0.3–0.5
mately 1985), 4.0–
2000), and 16.0–2
about 2020) as sho

In terms of reser
(1977) estimated th
be drilled by 1980
support the 1985 g
fore, the need fo
logging instrumenta
and reservoir engi
portance to reduce
teristics, the numbe
resource, geotherm
demand for drilling



prospect.

The intended federal program impact is to increase the annual rate of commercial utilization of geothermal energy from the present 0.04 quads (500 MWe) to 0.3–0.5 quads in the near term (approximately 1985), 4.0–9.0 quads in the mid-term (1985–2000), and 16.0–28.0 quads in the long term (by about 2020) as shown in Table 1 (DOE, 1978).

In terms of reservoir confirmation, Salisbury et al (1977) estimated that approximately 550 wells must be drilled by 1980 to provide sufficient reservoirs to support the 1985 goals for electric capacity. Therefore, the need for reliable exploration methods, logging instrumentation and interpretation methods, and reservoir engineering are of paramount importance to reduce uncertainties in resource characteristics, the number of wells necessary to define a resource, geothermal development costs, and the demand for drilling rigs.

Program organization

The DOE was formally established on October 1, 1977, and absorbed programs previously directed by the Energy Research and Development Administration (ERDA). Inasmuch as the development and commercial application of geothermal energy technology depends upon the execution of program responsibilities that are vested in several federal agencies, formation of the IGCC constituted a significant step toward realizing the national goals for geothermal energy (ERDA, 1977). The IGCC membership is composed of assistant secretary-level officials of DOE, the Department of the Interior, the Department of Agriculture, the Environmental Protection Agency, the National Science Foundation, and the Treasury Department. The Council is supported by a staff committee and three panels, each of which addresses a major aspect of interagency geothermal coordination.

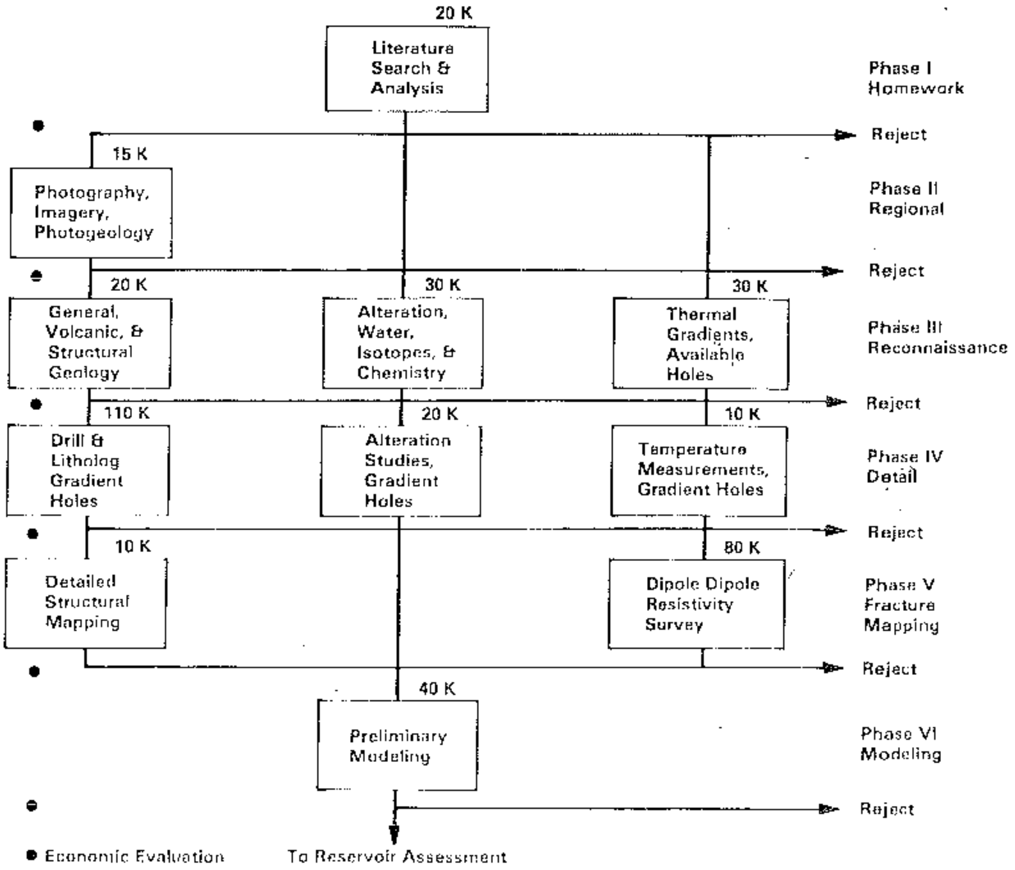


FIG. 1. Suggested geothermal exploration sequence.

Table 2. Estimated costs (1977)—suggested geothermal exploration sequence.

Phase	Description	Cost per item ($K)	Cost per phase ($K)	Cost basis (man year)
I	Literature search and analysis	20	20	0.25
II	1. Photography, imagery, photogeology	15	15	0.10 +$7K data costs
III	1. General, volcanic, and structural geology	20		0.25
	2. Alteration, water, isotopes, and chemistry	30		0.25 +$10K analytic costs
	3. Thermal gradients, available holes	30	80	0.375 (50 holes)
IV	1. Drill and litholog gradient holes	110		0.25 +$90K drilling (20 holes, cased)
	2. Alteration studies, gradient holes	20		0.25 0.125
	3. Temperature logs	10	140	
V	1. Detailed structural mapping	10		0.125
	2. Dipole-dipole resistivity surveying	80	90	60 days @800.00/day +$32K modeling and Interp.
VI	1. Preliminary conceptual Modeling	40	40	0.50
		Total exploration	385	

Of particular interest is the Research and Technology Panel, which has set forth priorities for exploration and assessment technology (ERDA, 1977). This panel has recommended that the highest priority for federal support of efforts to develop exploration technology should be given to (1) better measurements of properties of rocks and fluids at geothermal temperatures and pressures, (2) quantitative well-log interpretation, (3) improved chemical geothermometers, (4) more cost-effective geoelectrical techniques, (5) novel drilling methods, (6) improved logging devices that are reliable at high temperatures and in corrosive environments, (7) means of determining the permeability of potential reservoir rocks by surface measurements prior to drilling, (8) application of seismic reflection and seismic array methods, (9) improved understanding of heat flow data, and (10) development of techniques that will reveal hidden resources which are not associated with hot springs or geysers. Specific accomplishments and activities in these areas are discussed in IGCC's second annual report (DOE, 1978) and, for exploration technology, in more detail later in this paper.

In addition, close cooperation between the U.S. Geological Survey (U.S.G.S.) and DOE/DGE has been essential in exploiting ongoing exploration and assessment programs. Basically, the U.S.G.S. has the lead role in understanding geothermal systems, maintaining a national resource inventory, assessing the nature and energy content of each type of geothermal system, and promoting scientific research. On the other hand, DGE is responsible for stimulating commercial development of resources and technologies, confirming and evaluating individual reservoirs within geothermal systems, and conducting site-specific surveys to identify and quantify exploitable reserves. All such DGE efforts are conducted by or in cooperation with industry as well as state and local agencies.

The DGE technical development programs are typically run by field organizations, such as the national laboratories or contractors, under control and direction from headquarters. In the sections to follow, we describe recent developments in geothermal exploration technology. The topic is broadly divided into surface and logging technologies.

SURFACE EXPLORATION TECHNOLOGY

The DOE national program involves reservoir assessment, confirmation, and engineering in addition to exploration technology. Work is being done on the development of individual techniques as well as on overall exploration strategy. Selection of projects for development is based upon recommendations from workshops, technical consortia, program strategy panels, and steering committees, as well as upon specialized needs in assessment programs. New industrial programs are usually initiated through formal solicitations in support of programmatic needs. The following sections describe our fundamental concerns, suggested architectures for each phase, and the general program strategy.

Exploration technology

Exploration utilizes many techniques from the oil and mining industries that have not yet been adequately demonstrated for discovery of geothermal resources. Some techniques specific to the geothermal industry, such as isotopic and chemical prediction of subsurface temperatures from analysis of surface waters, earth noise, microearthquakes, Curie isotherm analysis of magnetic data, and heat-flow measurements, are being evaluated for their utility in exploration. Surface manifestations, such as hot springs, fumaroles, and hydrothermally altered ground, are currently being used to localize geothermal systems, making advanced exploration technology less essential in the near term than it will become when less obvious prospects must be discovered.

Cost effectiveness of various exploration sequences is of prime concern; thus, the determination of these factors is a part of the current DOE/DGE program (Ward, 1978; Goldstein et al, 1978). To illustrate a program strategy, we present in Figure 1 a modular exploration sequence which includes a carefully balanced selection of geologic, geochemical, and geophysical modules for geothermal prospecting for a high-temperature (>200°C) resource in the eastern Basin and Range physiographic province (Ward, 1977). (Different exploration sequences would apply in different geologic settings or for lower temperature resources.) Appearing early in the exploration sequence are the less expensive modules. Later, more expensive but more definitive modules are introduced. Estimated costs (1977 dollars) per module are indicated in Figure 1 and are explained in Table 2; debate on these estimates is welcomed. The

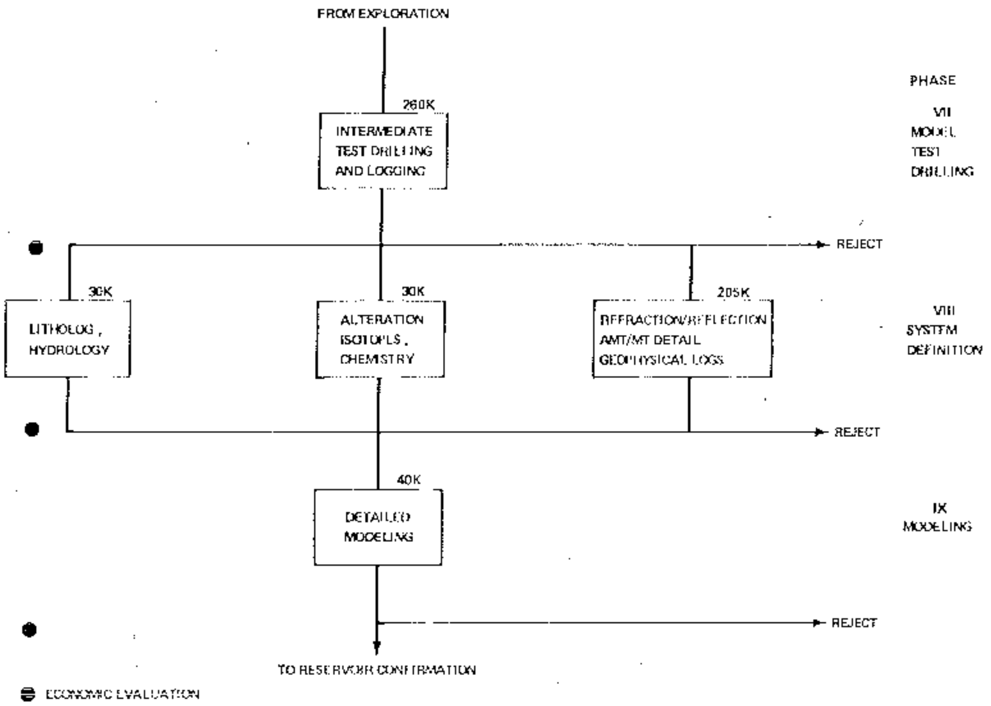


FIG. 2. Suggested geothermal reservoir assessment.

Table 3. Estimated costs (1977)—suggested geothermal reservoir assessment.

Phase	Description	Cost per item ($K)	Cost per phase ($K)	Cost basis
VII	Intermediate drilling and logging	260	260	2500 ft @ $80.00/ft plus $20K logging and 0.5 man yr.
VIII	System definition			
	1. Lithology, hydrology	30		0.25 man yr. +$10K analytic costs
	2. Alteration, isotopes, chemistry	30		0.25 man yr. +$10K analytic costs
	3. Refraction/reflection seismic	120		$80K data acquisition plus 0.5 man yr. interpretation
	AMT/MT detail	60		$40K data acquisition plus 0.25 man yr. interpretation
	Geophysical logs	25		$17K data acquisition plus 0.10 man yr. interpretation
			265	
IX	Modeling	40	40	0.5 man yr.
	Total reservoir assessment		565	

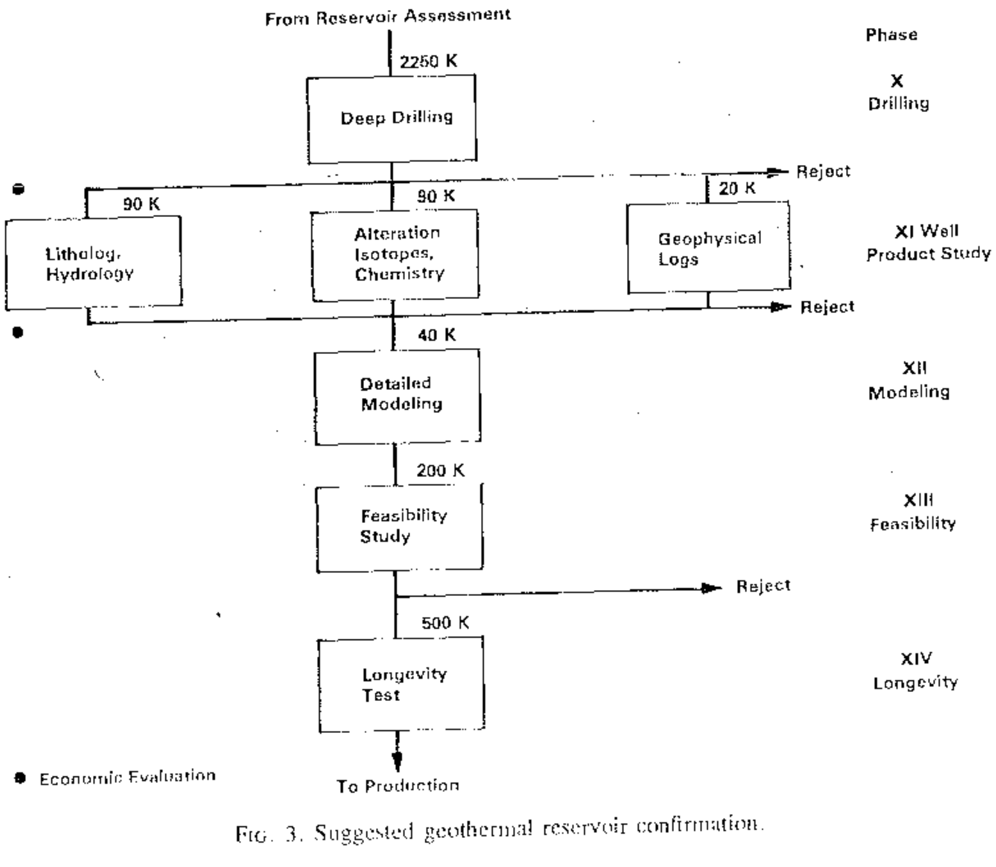


FIG. 3. Suggested geothermal reservoir confirmation.

total exploration
complete sequen

Reservoir assess

Reservoir asses
many of the same
at a more intense
test drilling. Figu
reservoir assessm
eastern Basin and
basis and summar
this approach to r
logging of a shal
expensive surface
the assessment. T
ment stage is a mo
ciently detailed tha
can be planned, i
stage.

The two compo
Program and the
current assessment
ing Program, whi
centralizing and
reservoir-related st

The State-Coupl
low- and moderate
heat applications.
both individual st
stimulates state de
for the U.S.G.S
assessment (White

Reservoir confirm

Reservoir confir
the existence of a

Tal

Phase	De
X	Deep
XI	1. Lithol
	2. Altera che
	3. Geoph
XII	Detail
XIII	Feasib
XIV	Longe

total exploration cost per prospect subjected to this complete sequence is $385,000.

Reservoir assessment

Reservoir assessment for prospect evaluation uses many of the same techniques used in exploration but at a more intense level of detail and includes some test drilling. Figure 2 shows a suggested geothermal reservoir assessment flow diagram and costs for the eastern Basin and Range, and Table 3 contains the basis and summary of costs. The basic philosophy of this approach to reservoir assessment is drilling and logging of a shallow test well plus introduction of expensive surface techniques capable of assisting in the assessment. The output of the reservoir assessment stage is a model of the geothermal system sufficiently detailed that a reservoir confirmation program can be planned, if warranted by the results of this stage.

The two components, the Reservoir Engineering Program and the State-Coupled Program, comprise current assessment efforts. The Reservoir Engineering Program, which is discussed later, is aimed at centralizing and coordinating a wide variety of reservoir-related studies.

The State-Coupled Program is designed to evaluate low- and moderate-temperature reservoirs for direct heat applications. This cooperative effort involving both individual states and the U.S.G.S. not only stimulates state development but also provides data for the U.S.G.S. national geothermal resource assessment (White and Williams, 1975).

Reservoir confirmation

Reservoir confirmation, as defined here, is proof of the existence of a volume of hot fluid that could be economically exploitable with prevailing technology and market conditions. Reservoir confirmation is essential to the establishment of reserves sufficient to support a vigorous industry and to achieve power on-line goals. Figure 3 and Table 4 contain our suggested minimal confirmation program, again related to the eastern Basin and Range. No consideration has been given herein to the considerable costs of acquiring land or providing environmental impact studies or to institutional problems, mainly because they lie outside the scope of our program analyses. This program is only suggested, and debate is welcomed on procedural and economic considerations.

This activity is composed of two main elements: the Industry-Coupled Case Study Program, and the Pre-Commercial Case Study Program. The Industry-Coupled Case Study Program consists, essentially, of sharing the cost between industry and DOE for exploration and wells. This program is designed to accelerate confirmation drilling by providing monetary incentives to industry while simultaneously distributing industry-wide the knowledge gained in cost-shared programs. This knowledge is intended to reduce uncertainty about the nature of reservoirs and the risk and cost involved in their confirmation.

The Pre-Commercial Case Study Program consists of a cooperative effort with the U.S.G.S. to confirm the existence of geothermal reservoirs, potential of which is too speculative to attract industry. Recent activities under this program include the Cascade Volcano (Mt. Hood) project, the Hawaii project, and the Snake River plain survey. As exploration activities of a progressively more vigorous geothermal industry are broadened, particularly in view of the incentives provided by the National Energy Act, these confirmation activities will be phased out.

Table 4. Estimated costs (1977)—suggested geothermal reservoir confirmation.

Phase	Description	Cost per item ($K)	Cost per phase ($K)	Cost basis
X	Deep drilling		2250	3 wells @ $750K per well to 5000 ft
XI	1. Lithology, hydrology	90		0.75 man yr. +$30K analytic cost
	2. Alteration, isotopes, chemistry	90		0.75 man yr. +$30K analytic costs
	3. Geophysical logs	20		0.25 man yr. interpretation
			200	
XII	Detailed modeling		40	0.5 man yr.
XIII	Feasibility study		200	2.5 man yr.
XIV	Longevity test		500	Gross estimate
		Total reservoir assessment	3190	

Reservoir engineering

Reservoir engineering to predict the reservoir capacity and to plan and manage reservoir production and injection is essential to attract users, such as utilities, who must make substantial investments in surface facilities. Oil field reservoir engineering techniques may not be directly transferable to geothermal problems because of the high temperature and its effect on viscosity and two-phase flow. Consequently, reservoir engineering research also is a critical path item, in part inherent in reservoir confirmation but depending almost entirely on information obtained downhole.

Recent activities have included the following: case studies conducted at sites such as Raft River, Idaho; Imperial Valley, California; and Cerro Prieto, Mexico; a continuation of applied research programs initiated under NSF; and development of improved reservoir data acquisition, analysis, and modeling methods.

Status of surface techniques

We address the ERDA/DOE and U.S.G.S. efforts to examine the status and technical needs of the many individual disciplines which comprise geothermal (surface) exploration technology. One of the first efforts to assess the needs was a workshop held early in ERDA's history (U.S.G.S., 1975). The suggested strategies were based mainly on recent experience and personal bias which was generally extrapolated from mineral and petroleum exploration. However, geothermal resources were properly reasoned to be different from either, and a sufficient base of experience did not exist from which we could adequately assess the strategy or technique effectiveness.

In 1976, while the main thrust of the ERDA program was in subsurface technology, a number of basic and applied research programs were proceeding under sponsorship of the U.S.G.S., ERDA, NSF, and the U.S. Bureau of Reclamation (U.S.B.R.). Important case histories were being developed on the east coast by Virginia Polytechnic Institute; in the Black Rock Desert, Nevada, by Colorado School of Mines; in Roosevelt Hot Springs, Utah, by the University of Utah; in Long Valley, California, by the U.S.G.S.; in northern Nevada, by Lawrence Berkeley Laboratory; and in Imperial Valley, California, by many organizations. This work afforded opportunities to assess many techniques and exploration strategies. We learned the important lesson that a cost-effective strategy will apply only to the physiographic region for which it is synthesized. The greatest controversies seemed to center first on electrical methods, then on seismic methods, some of which seemed particularly appropriate for locating geothermal resources.

Electrical and electromagnetic (EM) methods were examined in detail in a workshop (U.S.G.S., 1977), with the general conclusion that there was a need for deeply probing commercial magnetotelluric (MT) equipment and active EM systems able to operate over the frequency range of 10^{-3} to 10^{3} Hz. Other needs were seen for additional forward/inverse modeling, research in self-potential and tellurics, and continued development in both reconnaissance and detailed resistivity measuring methods. Most of these have been supported by ERDA/DOE during the past two years; however, there was no coordinated program which would give attention to all technologies. Therefore, in 1977 DOE/DGE conducted two careful assessments of technical needs (Goldstein et al, 1978; Ward, 1978), and these have formed the basis of a new coordinated program. The following is a summary of our findings in six important exploration technologies.

Reservoir modeling.—In the context of surface exploration, reservoir modeling is the inference of reservoir parameters from data acquired on the surface. This kind of modeling is of utmost importance, for it is upon these early estimates of system potential that major exploration budgets are committed. However, after more than 20 years of geothermal exploration in the United States, our conceptual models of geothermal systems are still very crude. For example, Roosevelt Hot Springs KGRA, one of the most promising high-temperature prospects, has been extensively studied (Ward et al, 1978), and still the reservoir system is poorly understood.

Ideally, geothermal modeling should provide predictions of reservoir parameters such as temperature, porosity, permeability, pressure, geometry, nature of fluids, and thermal conductivity. These parameters may be estimated from models which provide values for density, seismic velocity, electrical resistivity, total magnetization, bulk polarizability, and expected earthquake locations, size, focal mechanisms, and recurrence relations. These inversions may be improved by considering correlations between density, seismic velocity, electrical resistivity, porosity, and thermal conductivity. A considerable amount of work on inverse problems remains; thus, this is a fundamental part of the DOE/DGE program.

In the opinion of the modeling consortium (Ward,

1978), cost-effectiv
exist for geotherm
thermal infrared, s
heat flow, one- an
hydrology, convecti
seismics (both compr
electrical and EM
polarization (1-D, 2-
Because most geot
geologies, three-di
needed for representat
cal models can be em
the cost is prohibitive
empirical data whic
numerical approache
cost-effective 2-D an
several electrical and
systems, and thermal
Furthermore, it app
background is availab
of self-potential, seis
and He^3/He^4 ratios.
being studied present
programs.

A greater challenge
to the increasing ques
thermal systems. It i
and Bayesian statistic
forward and inverse
avenues for such elu
fundamental importan
straints required for re
which of the physical
surface and borehole
for prediction of reserv
productivity, longevity

Thermal methods.
in geothermal explorati
measure directly the
geothermal exploration
survey of a dozen
showed that typically
exploration budget is
exploration. Therefore,
effectiveness and the re
are of prime importan
The principal technic
proved techniques for th
interpretations and for
flow on thermal measur
to be the one which has
pretations of thermal an

1978), cost-effective forward modeling programs exist for geothermometry, gravity, magnetics, thermal infrared, surface temperature, conductive heat flow, one- and two-dimensional (1-D, 2-D) hydrology, convective heat flow (2-D), active seismics (both compressive and shear), strain ratios, electrical and EM methods (1-D, 2-D), induced polarization (1-D, 2-D), and MT (1-D, 2-D).

Because most geothermal systems are in complex geologies, three-dimensional (3-D) models are needed for representative system models. 3-D numerical models can be employed for many responses, but the cost is prohibitive, and scale models can provide empirical data which are useful to corroborate numerical approaches. Nevertheless, we still need cost-effective 2-D and 3-D forward models for MT, several electrical and EM techniques, hydrological systems, and thermally induced convection.

Furthermore, it appears that insufficient theoretical background is available to permit forward modeling of self-potential, seismic attenuation, ground noise, and He^3/He^4 ratios. Several of these problems are being studied presently under DOE and U.S.G.S programs.

A greater challenge exists for models applicable to the increasing quest for "blind" or hidden geothermal systems. It is felt that pattern recognition and Bayesian statistics along with multiple data set forward and inverse models may provide important avenues for such elusive models. Finally, it is of fundamental importance to establish the basic constraints required for reservoir modeling and identify which of the physical and chemical observables from surface and borehole studies are the most important for prediction of reservoir parameters and to estimate productivity, longevity, and size.

Thermal methods.—Thermal methods are unique in geothermal exploration in that in some sense they measure directly the major quantity of interest in geothermal exploration, i.e., heat. In fact, a recent survey of a dozen major geothermal developers showed that typically 50 percent of the geothermal exploration budget is expended for these types of exploration. Therefore, the assessment of the cost effectiveness and the research and development needs are of prime importance to the national program.

The principal technical needs are for new and improved techniques for thermal measurements and their interpretations and for studies of the effects of fluid flow on thermal measurements. This latter area seems to be the one which has caused more major misinterpretations of thermal anomalies than any other. Two prime examples are the Marysville, Montana geothermal project (Blackwell and Morgan, 1975) and the recently reported Desert Peak prospect in Nevada (Benoit, 1978). Recent studies of convective and conductive shallow hydrothermal systems (Chapman et al, 1978) illustrate the constraints of thermal gradient/heat-flow measurements. There is a need for improved highly portable instrumentation, a clear program for analyzing and predicting hydrologic effects, and increased emphasis on publishing regional and national maps of heat flow and temperature-depth profiles.

Table 5a. Rock properties pertaining to geothermal reservoir exploration, assessment, confirmation, and engineering.

Rock properties (see Table 5b)	Applications (see Table 5b)
Physical	H, E, M, G, S, L, X
Chemical	C, E, M, L, X
Mechanical	E, S, L, X
Thermal	H, L, X
Electrical	E, L
Magnetic	M, L
Seismic/acoustic	S, L
Atomic	C, L

Rock properties.—There are several important benefits to be gained from a knowledge of rock properties: (1) development costs will be reduced owing to more realistic models based on measured rock properties; (2) the lead time to commercial production can be reduced with more realistic models; and (3) environmental concerns, such as subsidence, induced seismicity, and reinjection performance, are more easily assessed with an adequate data base of rock properties. Indirectly, petrophysical data complement the interpretation of geophysical surface soundings and are useful for empirical correlations for well-log analyses. Laboratory tests on reservoir samples under in-situ conditions are vital in designing geothermal stimulation techniques and essential for predicting the magnitude of the resource.

Since the conditions of laboratory measurements must closely simulate the reservoir environment, variables which should be considered as independent in relevant experiments include overburden stress, confining pressure, pore pressure, reservoir fluid chemistry, and temperature. At present, laboratory measurements of physical properties under relevant geothermal conditions are either sparse or nonexistent.

Table 5b. Definition of terms in Table 5a.

Rock properties	
Physical	Density (grain, bulk), permeability, porosity, pore properties.
Chemical	Petrology, fluid composition and content, cation exchange capacity.
Mechanical	Elastic moduli, strength, stress-strain.
Thermal	Conductivity, diffusivity, specific heat, expansion and contraction coefficients.
Electrical	Resistivity, streaming potential, thermo-electric potential, zeta potential, cation exchange capacity.
Magnetic	Susceptibility, Curie temperature, paleomagnetism.
Seismic/acoustic	Velocities, attenuation.
Atomic	Radioactivity, neutron absorption, gamma spectroscopy.

Exploration and assessment methods

C = Geochemical
E = Electrical and electromagnetic
G = Gravity
H = Heat flow and thermal
L = Borehole logging
M = Magnetics
S = Seismics
X = Environmental concerns: subsidence, induced seismicity, reinjection

Parameters common to most data sets

Temperature
Stress
Reservoir fluid
Time
Frequency (excitation energy)
Current density (electric)
Core variability

Another shortcoming is the lack of simultaneous measurements of several physical properties on the same core. Correlations based on simultaneous measurements are essential if information on permeability, porosity, or salinity of a geothermal reservoir is to be inferred from sonic and resistivity tools, for example.

Some of the principal rock properties pertinent to various exploration methods and reservoir evaluation phases are summarized in Tables 5a and 5b. The tables are not intended to be exhaustive; rather, they serve to illustrate the kind of data which are important in understanding hydrothermal systems.

Water-rock interactions.– Studies of fluid samples (liquid and gas) and solid samples (cores and cuttings) collected from geothermal wells and from the earth's surface have an important bearing on exploration technology and reservoir evaluation. Although the presence of fluids affects interpretations of geophysical data as discussed above, they are perhaps of more importance to geochemical exploration methods.

Two types of geochemical surveys are presently used: (1) chemistry of springs, fumaroles, or shallow drill holes in which more or less altered samples of the reservoir fluid reach the surface, and (2) surveys of volatile or fugitive constituents (e.g., Hg and He) that have entered soils or rocks surrounding the reservoir. From fluid samples one can infer many aspects of the reservoir fluid, including type (hot water or steam), temperature, gas content, and subsurface fluid homogeneity. Where large numbers of vents exist, the system size, subsurface structure, and directions of fluid flow also may be indicated. Trace volatiles in soils also may indicate system size and fluid even in the absence of hot springs and fumaroles. A detailed discussion of techniques is beyond the scope of this paper; however, Truesdell (1975) presented an excellent summary of these and other geochemical exploration techniques.

These methods are critically dependent upon calibration through knowledge of subsurface conditions. Measurements of temperature and salinity variations during and after drilling, collections of aquifer fluids during production tests and with downhole samplers, and fluids extracted from core samples provide essential information to relate surface geochemical observations to the nature of reservoir fluids.

Refinement or development of new geochemical techniques that might be used to aid location of deep or blind parts of reservoirs is an important goal. This might be accomplished, for example, through documentation of trace-element zoning recorded in vein materials deposited by thermal fluids throughout the history of a geothermal system. In addition, known geochemical techniques (such as distribution of trace elements in soils) should be adapted and evaluated for specific geothermal applications. Recent studies by Bamford (1978) have indicated that such trace-element analyses may be extremely valuable to both exploration and evaluation.

Better understanding of the interactions between fluid and rock will markedly enhance the geologist's ability to interpret observations and to extrapolate into unsampled volumes of rock in three dimensions. Ultimately, the evaluation of raw prospects may include the location of reservoir and cap rocks as well as real-time drilling guidance.

Water-rock interactions affect reservoir evaluation in many ways. The economics of a geothermal development are critically dependent upon the definition of potential scaling or corrosion problems, the prediction of continued aquifer productivity, and assurance that injection wells will continue to accept effluent. These three aspects require careful determination of the solid and fluid phases in and around the reservoir.

Specific projects appropriate for national support may be categorized as (1) sample acquisition; (2) sample curation, preparation, and distribution; (3) generation of basic background data; and (4) detailed characterization of samples. Ongoing projects in each of these categories continue to enhance our growing data base in rock and fluid properties.

Seismic methods.—Both active and passive techniques have found application primarily in the exploration and assessment phases of geothermal projects. However, few if any cases exist where a prospect has been evaluated successfully on the basis of seismic data and geology alone. Although data acquisition is now reasonably straightforward (being offered commercially), the interpretations require supplemental information such as geology and tectonics, in-situ rock/fluid properties, water isotopes, alteration, and thermal gradients. Therefore, the use of seismic methods for geothermal exploration is still in a research-and-development stage.

Passive methods, typically less expensive than active methods, are used in early reconnaissance and exploration phases to define prospects and possible drilling targets. Methods include ground noise, microearthquakes, and teleseismic (*P*-wave delay) observations. Because they use natural energy sources or energy from distant shots or earthquakes, the field methods are inexpensive; however, this is somewhat offset by less certainty and resolution in interpretations, and the sometimes lengthy processing required in the laboratory. Nevertheless, passive methods have the potential for locating hydrothermal activity and for determining the location and orientation of faults and the spatial variation in Poisson's ratio. As noted by Goldstein et al (1978), research is needed in data acquisition and processing, ground-noise studies, magma chamber mapping, and fault mapping.

Although active seismic methods (reflection and refraction) have been highly developed and utilized in hydrocarbon exploration, they have not been widely used for geothermal exploration, largely because of interpretational uncertainty. These methods are potentially capable of delineating hydrothermal zones from velocity anomalies (refraction), inferring structure and Poisson's ratio (reflection), and mapping the depth of high-temperature source regions. High-resolution reflection and refraction methods have been adapted from petroleum exploration technology to geothermal exploration in recent years. The use of high-resolution methods for fault and fracture delineation, hence as a drilling locator, appears to be a most powerful means for reducing misplaced wells, thus effecting significant cost reduction in field development.

Electrical methods.—The use of electrical methods is not understood totally in geothermal areas, yet industry utilizes these methods routinely. They are of particular importance in mapping faults, fractures, and zones of alteration and are therefore fundamental in the location of wells. So many different methods exist that industry is confused over which method is best, with consequential inefficient field methods and uncertain interpretations. Since industry typically does not have the resources necessary to solve its problems in this area, it is appropriate that the national program be directed to solving specific problems using the centers of excellence existing in government, academic, or industrial laboratories.

Natural field electrical and EM methods inclu self-potential (SP), telluric (T), MT, and audio-frequency magnetotelluric (AMT). The principal advantage is elimination of the need for controlled-source instrumentation; however, one must understand the nature of the natural fields being recorded, the uncertainty of which often becomes the chief disadvantage. These passive methods have the potential for locating hydrologic circulation zones (SP), rapid reconnaissance (T, AMT), both shallow and deep-resistivity profiling (AMT, MT), and estimation of geologic structure (AMT, MT). Research is needed in all methods to understand the nature of source fields and data inversion to a model (Goldstein et al, 1978).

Controlled-source electrical and EM methods obviate the source uncertainty with the attendant expense of often very large transmitters. These methods include galvanic electrical resistivity (ER) and magnetometric resistivity (MMR), induced polarization (IP), and EM induction. In geothermal prospecting, controlled-source methods have application to reconnaissance mapping or profiling, vertical soundings, pseudosections, estimating geologic structure, and delineating reservoir boundaries and depth. Continued research and development is needed in inverse electrical resistivity modeling and both forward and inverse models for MMR and EM.

Methods to determine EM coupling effects in IP surveying are needed (Goldstein et al, 1978).

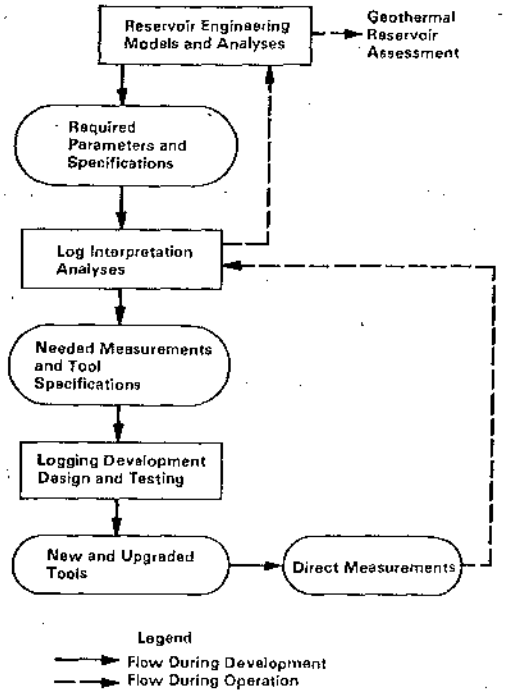


FIG. 4. Schematic diagram of geothermal logging activities.

LOGGING TECHNOLOGY

Methods for obtaining borehole measurements and making the appropriate interpretations are limited at present by technical deficiencies, in that logging tools developed for the oil and gas industry rarely encounter temperatures above 150°C (Martin and Rust, 1976). In geothermal wells, temperatures are frequently above 200°C and range up to 358°C, but most of the logging tools, cables, and seals are rated to only 180°C. Above this temperature rating is the often corrosive "hostile" environment of a geothermal well, in which logging tools and cables have significantly reduced reliability and life expectancy. Furthermore, the inference of reservoir properties from acquired data has also presented special problems in geothermal logging, since the major fluid component is hot water or steam contained in fractured igneous or metamorphic formations. It is not surprising, therefore, that the routinely used oil/gas interpretation procedures often provide misleading results.

High-temperature instrumentation

Industries that are expected to make major financial investments in geothermal power plants, space heating, or process heating are not inclined to risk large sums on construction without confidence that geothermal resources exist with temperatures, flow rates, and production longevity sufficient for long-term commercial operation. It is the purpose of the Geothermal Logging Instrumentation Development Program to help the reservoir engineers establish that confidence with information from new high-temperature instrumentation which will operate in hot, corrosive geothermal wells.

In order to satisfy critical existing needs, the near-term goal is for operation at 275°C and 48.3 MPa (7000 psi) by the end of 1982. The long-term goal is for operation up to 350°C and 138 MPa (20,000 psia) by the end of 1986. To meet these goals, existing hardware is being upgraded and new components are under development. Prototypes of critically needed tools for temperature, flow rate, and high-resolution downhole pressure will be constructed with the new components, and their performance will be evaluated under laboratory and field conditions. Our strategy involves direct cooperation with industry, where most of the development and service activities are contracted.

Table 6. Borehole parameter priorities.

1. Formation temperature
2. Formation pressure
3. Flow rate
4. Hole geometry (may be critical in log interpretation)
5. Fracture system (location, orientation, permeability, etc.)
6. Fluid compositions (pH, dissolved solids and gases)
7. Permeability
8. Porosity (interconnected and isolated)
9. Formation depth and thickness
10. Thermal conductivity
11. Electrical conductivity or resistivity
12. Heat capacity
13. Lithology and mineralogy
14. Acoustic wave velocity
15. Formation density

Too

Temperature
Pressure
Flow
Caliper

Casing collar locat
Formation resistivi
Casing and cement
Directional survey
Sonde refrigerator

Making meas
high-temperature
process that begi
ing. Figure 4 is a
A list of the para
ploration and res
6. Priorities of pa
types; however,
evaluation of mo
term are ranked
10–15 are param
may not need to b
may be reliably
physical paramet
development prio
are described in T
piled by the 1975
by the Geotherma
meeting on June

The technical
hole instrumentati
severe environme
prototype system d
ing and evaluatio
ment are direct
technical deficien
evaluating devices
able for use in geo
developments are
electronics, high-
acoustic transduce
mers, ceramics, an
have immediate
industrial capabilit
efforts are, theref
technological deve
to stimulate their
to geothermal logg

For evaluation

Table 7. Prototype geothermal logging tool goals (up to 275°C operation).

Tool	Performance goal
Temperature	1.0°C accuracy, 0.5°C resolution
Pressure	0–7000 psi, 0.1 psi accuracy, 0.01 psi resolution
Flow	0–2000 gpm in diphasic flow
Caliper	6 arm borehole geometry, 0.1 inch accuracy with fracture indication
Casing collar locator	Detect standard collars
Formation resistivity	To be determined
Casing and cementing inspection	To be determined
Directional survey	To be determined
Sonde refrigerator	50 W cooling to 125°C for at least 100 hours

Making measurements in geothermal wells with high-temperature instruments is only one step in a process that begins with needs of reservoir engineering. Figure 4 is a schematic diagram of this process. A list of the parameters desired for open borehole exploration and reservoir assessment is given in Table 6. Priorities of parameters may vary among resource types; however, certain parameters essential for evaluation of most geothermal resources in the near term are ranked as items 1–9 in Table 6. Items 10–15 are parameters which are important but which may not need to be measured in every well or which may be reliably predicted or calculated from other physical parameters. The repertoire of tools, their development priority, and performance requirements are described in Table 7. This information was compiled by the 1975 geothermal workshop and updated by the Geothermal Logging Steering Committee at a meeting on June 28, 1977 (Baker et al, 1975).

The technical development of geothermal borehole instrumentation is divided into three tasks: (1) severe environment components development, (2) prototype system development, and (3) borehole testing and evaluation. Efforts in components development are directed toward alleviating existing technical deficiencies by identifying, testing, and evaluating devices, materials, and components suitable for use in geothermal logging systems. Specific developments are underway in high-temperature electronics, high-resolution pressure transducers, acoustic transducers, and corrosion-resistant elastomers, ceramics, and metals. Results in this area will have immediate impact on improving near-term industrial capabilities for geothermal logging. Special efforts are, therefore, being made to transfer these technological developments to the logging industry to stimulate their own inventions and contributions to geothermal logging.

For evaluation of these components in complete systems, a few experimental prototype borehole instruments will be built and tested in both the laboratory and in actual geothermal boreholes.

High-temperature electronics.—The thrust of the efforts for near-term electronics, capable of operating up to 275°C, is directed toward thick-film hybrid microcircuits technology. This technology is widely used commercially for small-quantity production of special electronics, albeit for applications up to 125°C. However, this technology can be adapted for use in the required higher-temperature range, has the required ruggedness, and gives the desired level of miniaturization. Hundreds of thick-film hybrid resistor and capacitor devices have been laboratory tested for thousands of hours at 300°C. Efforts are continuing to develop thin-film dielectrics together with the necessary bonding and circuit interconnection techniques.

In the 275–300°C temperature range, the popular bipolar silicon transistors are intrinsically limited. However, a few commercially available silicon semiconductors have been found to operate satisfactorily at these high temperatures. Most of these devices are the silicon field-effect transistors (FETs) and a few silicon bipolar devices. Several types of commercially available silicon FETs have been qualified for 275°C operation through active circuit tests for 1000 hours at 300°C.

Through the above laboratory testing of active and passive electronic devices, a sufficient, though somewhat limited, line of commercial components and fabrication techniques is now available for 275°C operation to fulfill basic circuit needs for amplification, switching, and filtering (Palmer et al, 1977). For higher temperatures (300°–325°C), alloy semiconductors such as gallium arsenide FETs are being explored because they continue to exhibit semiconductor properties at temperatures where silicon

Table 8. High-temperature elastomers.

Trade name	Type	Decomposition temperature (°C)	Cost ($/lb)	Comments
Buna N	Nitrile	150	6	Good oil resistance, poor resistance to H_2S and steam.
Viton E-60-C	Fluoro elastomer	290	35	Fair resistance to steam, poor resistance to H_2S.
Viton G (peroxide cure)	Fluoro elastomer	290	40	Improved steam resistance, poor resistance to H_2S.
Kalrez	Fluoro elastomer (fully fluorinated)	400	2000	Best resistance to H_2S, fair resistance to steam.
EPR	Polyolefin	250	8	Excellent steam resistance, unknown resistance to H_2S.
Siloxane	Silicone	300	17	Poor resistance to steam and H_2S.

crystal devices cease to function and become intrinsic conductors. Above 325°C, suitable semiconductors are presently not available. Therefore, special vacuum tube-based circuits called integrated thermionic circuits (ITCs) are under development (McCormick et al, 1976). These ITCs are planar vacuum tube structures which are metal vapor deposited onto miniature sapphire substrates and packaged in a special glass ceramic container. Experimental ITCs have operated at temperatures up to 900°C. Although they are not now commercially available, they will be developed further because they offer a rather high assurance of performing satisfactorily at extremely high temperatures.

High-temperature mechanical components.—Elastomers capable of withstanding temperatures of at least 275°C and pressure of 7000 psi in the presence of geothermal brine for up to 100 hours are required for geothermal well-logging applications in seals, gaskets, connectors, cable sheathing, and wire insulation. An important aspect of these applications is the protection of sensitive electronic components from the corrosive fluids in a geothermal reservoir. Elastomers are also needed in borehole packers for geothermal well testing and completion. As shown in Table 8, testing and evaluation of available materials have identified several promising candidates for use in specific components such as seals and wire insulation. Other materials, along with specific prototype designs for cables, cableheads, and tool seals, will be tested as developments continue.

Prototype developments

To satisfy critical existing needs of geothermal reservoir engineering, prototypes of the most critically needed tools are being developed for geothermal applications. Table 7 is a list of these tools in the order of their priority. The temperature, pressure, flow, and caliper tools have the highest priority and are therefore being addressed first.

We have found that, while printed circuits are easier to fabricate than hybrid circuits, the hybrids are more rugged and reliable for high-temperature geothermal borehole instruments. Therefore, the designs generally utilize the repertoire of high-temperature thick-film hybrid circuit components already developed.

The temperature tool, which uses a platinum resistance transducer with active downhole electronics, has been successfully operated in the Los Alamos, New Mexico GT-2 test well (bottom-hole temperature about 200°C) and in a commercial well in the Jemez Mountains, New Mexico (bottom-hole temperature at least 275°C). The pressure tool uses an oven-controlled quartz crystal sensor cut for optimum operation at 275°C in conjunction with thick-film hybrid circuits and has operated successfully in laboratory test chambers.

Other prototypes being developed under industrial contracts include a borehole sonde refrigerator, a passive pressure-temperature-flow tool, and tools for measuring thermal conductivity and heat flux in situ. The last two thermal property tools were success-

---

fully tested during
well in northern C
In addition to
future efforts in
upgrading critical
hole recorders, ma
some transducers,
fabrication of high

Geothermal log i
development pro

In the early days
nized that the log
geothermal holes
not only with ins
also with the infer
the acquired data
learned that, owi
data on log respon
has been difficult
would suggest wh
holes are so often
Geothermal rese
and metamorphic
exceeding those u
exploration and d
hydrothermal reser
and Imperial Vall
water, superheate
water and steam w
Although dissolved
ppm, concentratio
been encountered.
noxious and active
Production from n
(rarely) be from
permeability but
rocks with seconda
and permeability,
in relatively im
morphic, or igne
thermal systems [s
Laboratory (LASI
Project], geotherm
artificially formed
line rocks. Thus,
from geothermal re
determining charac
of rock types and
in hydrocarbon we
Reservoir param
in Table 6. The
pendent upon rock

fully tested during 1978 in a Phillips Petroleum Co. well in northern California.

In addition to limited prototype development, future efforts in this program will concentrate on upgrading critical components such as cables, downhole recorders, magnetic transformers and wire, and some transducers, as well as contracting for industrial fabrication of high-temperature hybrid circuits.

Geothermal log interpretation development program

In the early days of ERDA's mission, it was recognized that the logging of hot, hostile environment geothermal holes presented substantial difficulties, not only with instrumentation and equipment but also with the inference of reservoir properties from the acquired data (Baker et al, 1975). We have learned that, owing to the sparseness of available data on log responses and in-situ rock properties, it has been difficult to identify specific problems which would suggest why interpreted logs in geothermal holes are so often misleading.

Geothermal reservoirs typically consist of igneous and metamorphic rocks with temperatures greatly exceeding those usually encountered in petroleum exploration and development. Naturally occurring hydrothermal reservoirs such as those at The Geysers and Imperial Valley, California, may produce hot water, superheated steam, or combinations of hot water and steam with a wide variety of composition. Although dissolved solids are typically 6000–10,000 ppm, concentrations as high as 350,000 ppm have been encountered. Fluids may also contain some noxious and active gases such as hydrogen sulfide. Production from natural geothermal reservoirs may (rarely) be from rocks with primary porosity and permeability but more often from metamorphosed rocks with secondary (solution and fracture) porosity and permeability, or from fracture systems existing in relatively impermeable sedimentary, metamorphic, or igneous rocks. For man-made geothermal systems [such as the Los Alamos Scientific Laboratory (LASL) Hot Dry Rock Geothermal Project], geothermal energy may be extracted from artificially formed fractures in impermeable crystalline rocks. Thus, interpretation of geophysical logs from geothermal reservoirs requires the capability of determining characteristics of a much larger variety of rock types and fluids than is normally encountered in hydrocarbon wells.

Reservoir parameters of primary interest are given in Table 6. These parameters are variously dependent upon rock type, temperature, permeability, porosity, pressure, pore fluid salinity, mineralogy and alteration products, and hydraulic pressure gradients. Geophysical measurements of earth properties such as electrical, seismic, sonic, gravity, magnetic, and nuclear strive to discern diagnostic responses. However, our understanding of the functional relationship of field measurements to rock properties is still developing and runs from adequate to marginal.

Some tools and interpretation techniques can be adapted directly from the existing petroleum-oriented logging industry. However, in order to evaluate geothermal reservoirs adequately, specialized interpretive techniques must be developed for boreholes where not only is the physical environment much more hostile than the typical petroleum environment, but the rock types and fluids are greatly different from the typical sedimentary sequence encountered in petroleum reservoirs.

A suite of calibrated logs, with proper interpretation, can lead to the determination of such reservoir characteristics as lithology, formation temperature, fluid composition, flow rate, porosity, permeability, mechanical properties, and formation dip. Proper interpretation has been hindered, however, by unfamiliarity with the effects on conventional logs of high temperatures, formation fluids, and lithologies radically different from those found in oil fields. For example, in sedimentary formations, porosity is commonly determined from neutron log response. Different lithologies with different compositions will yield unknown amounts of neutron moderation and hence essentially uncalibrated estimates of porosity. Therefore, other calibration approaches, such as crossplotting to establish internal calibrations, must be used. Other examples have been cited recently by West et al (1975), Kintzinger et al (1977), and Keys and Sullivan (1979).

In response to these recognized difficulties, in 1977 DOE/DGE established an initiative whereby the problems would be analyzed and logical projects to solve log interpretation problems would be conducted. Specifically, the log interpretation program seeks to aid the development of geothermal well-log interpretation technology by building on existing petroleum and mineral log interpretation techniques. The technical research and development activities to be pursued are intended to reduce the basic impediments the industry faces due to the need to develop techniques and instrumentation not normally required in servicing the petroleum industry and, therefore, for rapid developments for which insufficient incentives currently exist. With the help of a balanced and knowledgeable steering committee, the principal program elements were chosen to be the following:

1) An in-depth study of the current state of the art, which includes recommendations for log improvements, development of log interpretation techniques, and definition and categorization of significant reservoir types.
2) Establishment and support of calibration and test wells representative of the major geologic reservoir categories.
3) Special advanced well-log runs, and especially the subsequent interpretation technique developments based upon the log data enhancement afforded by the additional logging.
4) Coordination of new and existing geothermal log and core libraries.
5) Special property measurements on cores and cutting, and aid in the establishment of facilities to perform these measurements.
6) Workshops, a periodic newsletter, and finally a handbook on geothermal log interpretation.

Each of these elements is a definable project designed to answer specific problem areas. The projects and their priorities are reassessed semiannually by the steering committee to ensure that the program is necessary, responsive to needs, and conducted efficiently.

CONCLUSIONS

The National Geothermal Energy Program was mandated as one of a number of energy development programs designed to reduce our dependence on imported petroleum. We present here some aspects of the program of concern to geoscientists, namely the exploration and assessment technology activities.

Hydrothermal resources, including hot dry rock, probably comprise the major geothermal energy base, with geopressured methane expected to provide roughly half of the total energy to be commercialized as a result of geothermal developments. Exploration and assessment problems, however, are most significant for hydrothermal resources, where hydrocarbon and mineral exploration methods, while applicable, often give erroneous or misleading results.

To analyze the state of the art and technical requirements, we examined the near-, mid- and long-term geothermal energy goals and conducted many workshops to assess the technical status of surface and borehole technologies. DOE then created specific goal-oriented programs to meet technical and programmatic requirements. The common denominator for the technical programs has been to encourage industry to expand and refine their methods and to assist industry by removing technical and institutional barriers to commercial development.

Initial developments concentrated on borehole technologies because developers could not log existing hot geothermal wells owing to failures of logging tools and data interpretation methods. In assessing the problem, it was determined that most hydrothermal wells have maximum temperatures less than 275°C and that technology developments were needed to upgrade logging tools from a typical 180°C rating. For hotter holes, it was reasoned that thermal protection (e.g., dewar flasks) could be used on the 275°C-rated tools for short logging runs; however, a long-term design goal of 350°C was established to provide capabilities that will be required when the deeper or warmer resources must be developed. After two years, this program has developed prototype electronic circuits and mechanical components with which logging tools can be upgraded; however, the components are not yet commercially available (as of 1978).

Similarly, the log interpretation program has been assessing the technical needs to determine why geothermal logging data interpretations have been unreliable or inconsistent with in-situ conditions. Since a reliable data base is essential, this program will establish test and calibration facilities using both real geothermal wells in typical regimes and fabricated test holes with known targets. Analysis of data taken in the test holes using many different tools, along with petrophysical studies, should provide means of calibrating tools and making meaningful interpretations of the reservoir parameters of interest. We intend to produce a geothermal log interpretation handbook as the principal product.

Analysis of surface, predrilling exploration technology has taken several years, owing to the many facets to be considered and the priority emphasis on borehole technology initially. Nevertheless, since predrilling exploration and assessment can cost on the order of 25 percent of a program for reservoir confirmation, we reasoned that it was proper to seek cost-effective exploration architectures. Individual technologies, such as reservoir modeling, thermal methods, rock/water properties and geochemistry, seismic methods, and electrical methods, were examined as parts of the whole. Although specific technical needs and accomplishments were identified in each area, the principal common requirement was for actual detailed exploration case studies on confirmed (drilled) prospects; this is a fundamental aspect of the program plan.

These develo
expected to be
gineers and pro
dependent upon
properties and p

As a postscri
published Asses
the United State
assessment, whi
our Table 1 indi
tentions for the
exploration tech

A

We express
Mathews, Los A
contributions an
thermal Log Int
persons who ha
the past few yea

Baker, L. E., Ba
Report of the g
wells worksho
Albuquerque.
Bamford, R. W.,
from two U.S.
exploration: Un
rep. no. 77.3.2.
Blackwell, D. D.,
geophysical ex
area, Montana,
dev. and use of
902.
Benoit, W. R.,
perature gradie
western Nevada
as a model: Tra
Chapman, D. S.,
Temperatures a
flow in shallo
Res. Coun., v.
Department of En
thermal energy
tion program: [
Energy Research
First annual re
Energy, April.

These developments and the future programs are expected to be of continued value to reservoir engineers and prospect developers who are strongly dependent upon accurate measurement of resource properties and prediction of reservoir performance.

As a postscript, we draw attention to the recently published Assessment of Geothermal Resources of the United States—1978 (Muffler, 1979). The new assessment, which is not as optimistic as the data in our Table 1 indicate, nevertheless supports our contentions for the need for continued developments in exploration technology.

ACKNOWLEDGMENTS

We express sincere appreciation to Dr. Mark Mathews, Los Alamos Scientific Laboratory, for his contributions and careful management of the Geothermal Log Interpretation Program and to the many persons who have participated in these programs in the past few years.

REFERENCES

Baker, L. E., Baker, R. P. ,and Hughen, R. L., 1975, Report of the geophysical measurements in geothermal wells workshop: Sandia Lab. rep. SAND 75-0608, Albuquerque.

Bamford, R. W., 1978, Geochemistry of solid materials from two U.S. geothermal systems and its application to exploration: Univ. of Utah Res. Inst., Earth Sci. lab. rep. no. 77.3.2, July.

Blackwell, D. D., and Morgan, P., 1975, Geological and geophysical exploration of the Marysville geothermal area, Montana, USA: Proc. 2nd U.N. symp. on the dev. and use of geothermal res., San Francisco, p. 895–902.

Benoit, W. R., 1978, The use of shallow and deep temperature gradients in geothermal exploration in northwestern Nevada using the Desert Peak thermal anomaly as a model: Trans., Geoth. Res. Coun., v. 2, p. 45.

Chapman, D. S., Kilty, K. T., and Mase, C. W., 1978, Temperatures and their dependence on ground water flow in shallow geothermal systems: Trans., Geoth. Res. Coun., v. 2, p. 79–82.

Department of Energy, 1978, Second annual report, geothermal energy research, development and demonstration program: IGCC, DOE/ET-0039/1, IGCC-3, April.

Energy Research and Development Administration, 1977, First annual report: ERDA 77-9, Div. of Geothermal Energy, April.

Goldstein, N. E., Norris, R. A., and Wilt, M., 1978, Assessment of surface geophysical methods in geothermal exploration and recommendations for future research: Lawrence Berkeley lab. rep. LBL-6815.

Keys, W. S., and Sullivan, S., 1979, Role of borehole geophysics in defining the physical characteristics of the Raft River Geothermal Reservoir, Idaho: Geophysics, v. 44, p. 1116–1141.

Kintzinger, P. R., West, F. G., and Aamodt, R. L., 1977, Downhole electrical detection of hydraulic fractures in GT-2 and EE-1: Los Alamos Scientific Lab. rep. LA-6890-MS.

Martin, C. A., and Rust, D. H., 1976, Hostile environment logging: The Log Analyst, v. 12, no. 2.

McCormick, J. B., Depp, S. W., Hamilton, D. J., and Kerwin, W. T., 1976, A new electronic gain device for high temperature applications: Los Alamos Scientific Lab. rep. LA-6339-MS.

Muffler, L. J. P., Ed., 1979, Assessment of geothermal resources of the United States—1978: USGS circ. 790, U.S. Dept. of the Interior.

Palmer, D. W., Meyer, B. L., McBrayer, J. D., and White, K. R., 1977, Active devices for high temperature microcircuitry: Sandia Lab. rep. SAND 77-1145, Albuquerque.

Salisbury, J. W., Williams, D. L., and Nichols, C. R., 1977, Geothermal reservoir confirmation requirements and the need for federal initiatives: Trans., Geoth. Res. Coun., v. 1, p. 271–273.

Truesdell, A. H., 1975, Summary of section II, geochemical techniques in exploration: Proc. 2nd U.N. symp. on the dev. and use of geothermal res., San Francisco.

U.S. Geological Survey, 1975, Workshop on geophysical methods applied to detection, delineation and evaluation of geothermal resources: Univ. of Utah, USGS grant 14-08-6-191.

1977, Workshop on electrical methods in geothermal exploration, Univ. of Utah, USGS grant 14-08-0001-G-359.

Ward, S. H., 1977, Geothermal exploration architecture: Univ. of Utah tech. rep. 77-2, ERDA contract EY-76-S-07-1601.

Ed., 1978, Program review: resource evaluation, reservoir confirmation and exploration technology: Univ. of Utah report 78-1701.b.5.1, May.

Ward, S. H., Perry, W. T., Nash, W. P., Sill, W. R., Cook, K. L., Smith, R. B., Chapman, D. S., Brown, S. H., Whelan, J. A., and Bowman, J. R., 1978, A summary of the geology, geochemistry, and geophysics of the Roosevelt Hot Springs thermal area; Utah: Geophysics, v. 43, p. 1515–1542.

West, F. P., Kintzinger, P. R., and Laughlin, A. W., 1975, Geophysical logging in Los Alamos Scientific Laboratory Geothermal Test Hole No. 2: Los Alamos Scientific Lab. rep. LA-6112-MS.

White, D. F., and Williams, D. L., Ed., 1975, Assessment of geothermal resources of the United States—1975; USGS Circular 726, U.S. Dept. of the Interior.