SAND75-0275
Unlimited Release
Printed May 1975

WELL-LOGGING TECHNOLOGY AND GEOTHERMAL APPLICATIONS:
A SURVEY AND ASSESSMENT WITH RECOMMENDATIONS

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ABSTRACT

This report presents the results of a study of well-logging as it applies to geothermal wells. Included is an assessment of the current state-of-the-art of well-logging in general with a detailed summary of logging tools and their characteristics. The phenomenon of geothermal energy is considered briefly, as well as the role of well-logging in the development of the geothermal resource, including problems which arise when geothermal wells are logged. It is concluded that present well-logging equipment and techniques are not adequate for geothermal well applications. Recommendations are presented for actions to foster timely development of geothermal well-logging capabilities in support of Project Independence geothermal energy goals.

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ACKNOWLEDGMENTS

We would like to acknowledge the help we received from a large number of people who are associated with oil, gas, and geothermal endeavors. These include representatives of well service companies, equipment manufacturers, major oil companies, consulting firms, universities, and government organizations and laboratories, as well as members of Sandia Laboratories.

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SUMMARY

Geothermal energy is seen as one important component of the nation's effort to achieve energy self-sufficiency. However, wells that are drilled to tap geothermal energy differ in many important respects from the much more numerous oil and gas wells. Geothermal wells are usually hotter, and are often drilled in harder rocks.

Well logging, the science of making and recording surface and borehole measurements and the art of their interpretation, provides information needed during the drilling, completion, and production phases of petroleum and geothermal wells. Broadly speaking, well logging can be divided into four general categories: electrical, radioactivity, acoustical, and specialized auxiliary logs.

Logging geothermal wells poses special problems both in the areas of data gathering and data interpretation. The problems associated with data gathering come about because of the unavailability of cables and tools which can withstand the heat and corrosion encountered in geothermal wells. The problems of data interpretation occur chiefly because geothermal wells are often drilled in unfamiliar formations, and there has not been much experience in logging in such formations, nor has there been much coring and sampling of such wells. Therefore necessary experience and log/core correlations do not exist to allow adequate geothermal well log interpretation.

The report concludes that with the present economic climate, private industry is not now developing the necessary tools and techniques for geothermal well-logging. It is therefore recommended that the government fund the development of various materials and equipment, along with the necessary data-gathering to facilitate log interpretation. The creation of a management structure is also recommended to coordinate all the organizations, public and private, that will be part of the geothermal well-logging effort.

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OBJECTIVES & STRUCTURE

Contractual Goals

The primary goals of this investigation were to

1. Determine the basic downhole measurements that must be made to evaluate geological formations and the associated environmental limits.
2. Assess the current state-of-the-art as it is currently applied in well logging.
3. Identify research that is presently being conducted in the private sector to extend the capabilities of logging instruments.
4. Suggest research areas to assure that formation evaluation tools are available as required in the development of geothermal resources.

Twelve man-months were allotted for the total effort, including publishing the report, over a total time span of four months.

Approach

Because the major portion of this effort was a survey and assessment, the main approach was that of discovering the facts concerning the current state of well-logging capabilities and current research directions for extending those capabilities for use in geothermal wells. Such facts were gathered through a literature search and discussions with representatives of organizations which have an interest in logging geothermal wells. These organizations included the well service companies, suppliers to the well service companies, operating geothermal development companies, major oil companies, university and government geoscientists, aerospace companies with interests in the geoscience and geothermal areas, consultants, and drilling contractors.

The recommendations in this report were arrived at by considering the advice of the representatives of the organizations listed above, and then making judgments as to which specific activities appeared most in need of government funding for timely development and to provide the greatest effectiveness for government R&D funds.

Form of Results Presentation

1. Two tables are presented at the end of the Well-Logging Technology section. The first table presents a concise compilation of well-logging tools and their capabilities. The second table presents well parameters that are desired and the actual measurements from which those desired parameters are inferred.

2. An extensive list of major logging tool types and characteristics is presented in some detail in Appendix A.
3. A list of conclusions concerning geothermal well-logging is presented.
4. Recommendations are included suggesting several specific tasks which the government might immediately support.

INTRODUCTION

The study presented in this report was conducted by Sandia Laboratories at the request of Dr. Louis B. Werner and Morris Skalka of the Division of Geothermal Energy, USERDA.

A concern has been expressed that with the current high level of activity in the petroleum industry, coupled with the present economic climate, the necessary activities for development of geothermal technology might not occur spontaneously. Because ERDA is charged with the development of the nation's geothermal resources, any lag in development that might delay the timely utilization of this resource is of concern. It is the basic purpose of this report to examine the probable availability of geothermal well-logging technology as it is needed to develop the geothermal resource, and to determine if the government should take any actions to insure that well-logging capabilities will be available as they are needed.

In accordance with the above goals, this report considers the following topics:

- Geothermal Energy, its characteristics and importance as a national resource.
- Well-Logging Technology, including the reasons for logging and the various categories of well-logging apparatus.
- Geothermal Well-Logging and Associated Problems.
- Conclusions concerning deficiencies in the current state of geothermal well-logging.
- Recommendations for appropriate government actions to effect timely remedies of present deficiencies in geothermal well-logging. Included is a suggested management structure for implementing the recommendations.

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GEO THERMAL ENERGY

Any very detailed or comprehensive discussion of geothermal energy is beyond the scope of this report. However, there are some general aspects of the subject which are appropriate for discussion here.

Geothermal energy refers to the heat which naturally exists in the earth's interior, and which is believed to result from radioactive decay of the elements uranium, potassium, and thorium.

The average or normal geothermal gradient, about 25°C to 30°C per kilometer of depth, is not now commercially exploitable and probably will not be in the near future. However, regions exist with gradients two or more times this average, generally associated with tectonic-plate boundaries and volcanic activity, and possibly resulting from a near surface intrusion of magma. These higher than normal gradients may occur in conjunction with an aquifer system in which case dry steam (vapor dominated system) or hot water (liquid dominated system) is produced which can be commercially extracted. Lower temperature fluid systems (<150°C/300°F)* have been used for commercial, residential, or agricultural heating purposes (e.g., Klamath Falls, Oregon; Reykjavik, Iceland). Higher temperature fluids are used to supply steam for electrical generating stations. These may have base temperatures as high as 300°C (570°F) for relatively fresh water systems (e.g., Wairakei, New Zealand) and up to 385°C (725°F) for systems with high salinity (e.g., Cerro Prieto, Mexico). Vapor dominated systems (e.g., the Geysers, California; Larderello, Italy) are characterized by initial temperatures near 240°C (465°F). A typical reservoir showing extraction, re-injection, and ground water recharging is shown in Figure 1.

Although not presently being commercially exploited, other geothermal systems may provide energy in the future. In areas with above normal geothermal gradients but no aquifer system, it has been proposed (by Los Alamos Scientific Lab and others) to use the energy in the hot dry rock by pumping water down one well and extracting steam from a second well to which a path through the rock has been intentionally fractured. Temperature of the hot rock could run to several hundred degrees Celsius. Large, highly geopressured regions exist along the U.S. Gulf Coast which contain moderately hot (175°C/350°F) waters at high pressure with high dissolved methane content presenting attractive possibilities for energy extraction. In the more distant future are plans for energy extraction using a direct magma tap. In this case, temperatures over 1000°C (1830°F) may be encountered.

* Temperature conversions are rounded to the nearest five degrees.

Figure 1

Geothermal energy is seen as one important component of the nation's effort to achieve energy self-sufficiency. The Project Independence Report predicts the generation of from 7,000 to 15,000 megawatts of electricity from geothermal sources by 1985, on the basis of their accelerated development scenario. The report from Jet Propulsion Laboratory entitled "Status Report, Geothermal Program Definition Project, April 4, 1975," establishes a tentative goal for the utilization of geothermal energy of 20,000 to 30,000 megawatts electrical by 1985, a utilization level that will save one million barrels of oil per day. Generation of electricity at this rate will require drilling an average of about 1000 wells per year over the next 10 years.

It is notable that the product sought from geothermal wells is heat itself rather than a product which can be burned to produce heat. The geothermal heat, whether in the form of steam or hot water, cannot be practically transported long distances.

Of course, geothermal heat can be used to generate electricity, which is easily transportable. Although transforming the heat energy into electrical energy does solve the transportation problem, there arises the new problem of insuring that adequate geothermal energy will be available at a site before large capital investments are made in a conversion plant, which must be near the energy source. The investors must be reasonably sure that there will be sufficient energy available at a fixed site for a sufficient time to justify the large investment required. The necessity for a large capital investment at the site of the energy source makes reservoir engineering for geothermal fields extremely important.

It is clear that the development of geothermal reservoir engineering, which requires down-hole well-logging as a source of information, is of paramount importance among the activities necessary for the efficient utilization of the geothermal energy resource.

Geothermal wells differ from oil or gas wells in many important respects. Geothermal wells are usually hotter, and often they are drilled in harder rocks. Most oil wells are drilled in sedimentary formations, whereas many geothermal wells are drilled in igneous or metamorphic formations. These harder rocks often are fractured, and many of the formations are underpressured. This combination of high temperatures and hard, fractured, and unfamiliar rock types causes a great number of problems in the drilling, logging, and completion of geothermal wells. Typical problems are crooked holes, the loss of drilling fluid in fractured or underpressured formations, and failure of drilling fluids and drilling and logging tools because of the elevated temperatures. Additionally, there are often problems of corrosion caused by naturally occurring gases such as hydrogen sulfide, as well as saline formation fluids.

As a resource geothermal energy has been slow to be exploited. There are only a few areas in the United States where geothermal energy is used at all, and only one (the Geysers in California) where significant electrical power is generated. However, at the Geysers several hundred megawatts are now being produced, with more in the planning stage. Commercial interest in geothermal energy is increasing rapidly. In recognition of this, the United States government has designated certain Known Geothermal Resource Areas (KGRA's). Within these KGRA's leases must be obtained on the basis of competitive bids. Tables which indicate recent geothermal activity, both within and outside the KGRA's, are given below in Tables 1, 2, and 3.*

Table 1
Applications for Noncompetitive Federal Geothermal Leases
(Filed in January 1974 in 11 western states)*

<u>State</u>	<u>Number of Applications</u>	<u>Approximate Area (in acres)</u>	<u>Percent of Total January Filings</u>
California	528	1,070,000	21.5
Oregon	458	1,000,000	18.6
Nevada	433	900,000	17.7
Idaho	265	580,000	10.8
New Mexico	274	630,000	11.2
Utah	207	450,000	8.5
Washington	151	340,000	6.1
Colorado	64	120,000	2.6
Montana	55	100,000	2.2
Arizona	18	40,000	0.7
Wyoming	3	6,000	0.1
TOTAL	2,456	5,236,000	100.0

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Table 2
Selected 1974 KGRA Sales*

<u>Area</u>	<u>High Bid (gross value)</u>		<u>High Bid (per acre)</u>	
	<u>Company</u>	<u>Amount</u>	<u>Company</u>	<u>Amount</u>
Geysers, Calif. ¹	Shell Oil	\$3,200,000	Natomas Oil	\$3,297.00
Mono-Long Valley, Calif. ²	Republic Geothermal	515,767	Republic Geothermal	210.00
East Mesa, Calif. ²	Republic Geothermal	432,810	Republic Geothermal	170.00
Vale, Oregon ³	Republic Geothermal	13,831	Republic Geothermal	10.25
Roosevelt, Utah ⁴	Phillips Pet.	314,200	Phillips Pet.	128.06
Brady, Nevada ⁵	Southern Union Production	15,108	Geothermal Res.Int.	10.16

1) Proven field; 2) Existing high temperature water wells; 3) Boiling springs in area; 4) Shallow steam well exists; 5) Several steam/water wells exist.

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Table 3
Geothermal Wildcats (Outside of Geysers KGRA)*

1972

<u>Area</u>	<u>Company</u>	<u>Well Name</u>
Imperial Valley, Calif.	Magma-San Diego Gas & Electric	Magmamax 1 Dearborn 1 Sharp 1 Woolsey 1 Holtz 1 Holtz 2 Magmamax 3 Magmamax 4 Mesa 1 Dunes 1 Nowlin Partnership 1
Mendocino County, Calif.	US Bureau of Reclamation	Torchio-Ferro
Lake County, Calif.	Calif. Dept. of Water Res. Chevron Oil	Kettenhofen 1 (deepen) Sullivan 1
Steamboat Springs, Nev.	Sun Oil	-
Surprise Valley, Calif.	Getty Oil E. B. Towne Gulf Oil Magma	Phipps 2

1973

Imperial Valley, Calif.	Magma	Mary Casey 1 Bonanza Farms 1 Fed-Rite Bonanza 1 KK Sharp Farms Inc. Sharp 3 Bonanza 2 Nowlin Partnership 2 Sinclair 3 Sinclair 4 Mesa 2
Lake County, Calif.	Chevron Oil Phillips Oil U.S. Bureau of Reclamation	Kettenhofen 1 (deepen) Sullivan 2
Mendocino Co., Calif.	Pacific Energy Corp. E. B. Towne	-
Sonoma County, Calif.	Sun Oil-Al Aquitaine	Bianchi 1
Surprise Valley, Calif.	Signal Oil Gulf Oil	SV - 1 ST SV - 2 ST
Honey Lake, Calif.	Gulf Oil	Honey Lake 1 Honey Lake 2
Lakeview, Ore.	Gulf Oil	Favell-Utley-1-ST
Chandler, Ariz.	Geothermal Kinetics	Power Ranches 1 Power Ranches 2
Chocolate Mtns., Calif.	QB Resources	-

Table 3 (Continued)
Geothermal Wildcats (Outside of Geysers KGRA)*

1974 (to August 31)

<u>Area</u>	<u>Company</u>	<u>Well Name</u>
Imperial Valley, Calif.	Chevron Oil	J. D. Jackson C. B. Jackson Hulse
	US Bureau of Reclamation	Mesa 5-1 Mesa 8-1 Mesa 3-1 Elmore 1
Mendocino County, Calif.	Magma	
	Sun Oil	Macii-State Torchio-Ferro 2
Plumas County, Calif.	Phillips Oil	Filippini A-1
Surprise Valley, Calif.	American Thermal Resources	ATR-1 ATR-2 ATR-3
	Magma	Phipps 2 (deepen)
Valles Caldera, NM	Atomic Energy Commission	-1 -2
	Union Oil	Baca 11 Baca 12
Brady, Nev.	Union-Magma	SP-1
	Phillips-Southern Pacific	Desert Peak 1-29
Indian Hot Springs, Ariz.	Nix Drilling Company	-
Pine Farms, Ariz.	Geothermal Kinetics-Amax	Pima Farms 1
Oreana, Ida.	Anschutz Corp. (O&G)	-
Raft River, Ida.	Griffith	-
Beowawe, Nev.	Chevron-ATR	Ginn
Brigham City, Utah	Geothermal Kinetics-Utah Power & Light	Steam Ventures Davis 1
Canby, Calif.	Geothermal Power Corp.	Kelly Hot Springs 1
Marysville, Mont.	National Science Foundation	-
San Luis Valley, Colo.	Mid-American Pipeline Company	-
Hot Lake, Ore.	Magma	-

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Well-Logging Technology

Background

When the oil industry was in its infancy, the detection of a successful oil well was often easy because drilling into a pressured oil-bearing stratum produced a gusher. However, allowing such an uncontrolled flow of oil is an inherently dangerous procedure, often leading to fires, the destruction of equipment, and the injury of personnel. Consequently, methods for controlling wells were devised, and the necessity for such well control has been widely required by law.

The key to the control of a well is the use of drilling "mud" in the borehole. This mud is usually a slurry of water or oil and various chemicals (or sometimes just water or oil alone) which provides a hydrostatic head sufficient to overcome the pressures of the subsurface zones into which the borehole penetrates, and thus to prevent the occurrence of "blowouts" (there is also a hardware blowout preventer at the wellhead). Drilling mud has two other important functions in rotary drilling: the mud cools the rotary bit, and the constant circulation of mud down the drill stem, through the bit, and back up the borehole annulus around the drill stem serves to remove the cuttings from the bottom of the hole.

The use of drilling mud has the unfortunate side-effect of making more difficult the task of determining the characteristics of the subsurface formations through which the borehole is being drilled. The mud makes this determination more difficult in two ways: first, the mud prevents the ready flow of subsurface liquids or gases into the borehole, and, second, the mud filtrate actually penetrates the formations, flushing the subsurface liquids and gases back away from the borehole. As a result of these difficulties, various methods of measurement have been devised to aid in answering the fundamental question of the nature of the formations intersected by the borehole.

Purpose

Well-logging, the science of making and recording surface and borehole measurements and the art of their interpretation, provides information to determine subsurface characteristics to facilitate addressing four related areas of resource utilization.

- To provide information for drilling, completion, and operation of individual wells.
- To provide information to aid in resource exploration and development.
- To provide information for formulation of models of reservoirs to facilitate efficient production.
- To provide information pertinent to environmental and legal aspects of the resource development.

The need for this information in the petroleum industry has stimulated the development of sophisticated devices capable of making measurements under field conditions both at the surface and in the borehole. Appendix A contains descriptions of industrial logging tools. Logging equipment, techniques for its use, and interpretation of the resulting data are usually provided by specialized service companies as requested (often on short notice).

The potential for great economic gain, the risk of large amounts of capital, and the highly competitive nature of the petroleum industry have provided the economic incentive that has resulted in the highly developed well-logging services available to the oil industry. This logging technology has made possible the reservoir modeling and resource evaluation used in petroleum exploration, evaluation, and production. It is through use of logging information and reservoir models that reserves are estimated and production is regulated in conformance with established conservation practices.

Operation and Limitations

The downhole devices used in well-logging are referred to as "tools" or "sondes." Most of these tools are operated in the hole using multiple or single conductor armored cable which serves both as a supporting cable and as a data transmission link for surface recording of measurements. The cable also provides the required borehole depth information which is used when plotting and correlating formation parameters. This depth measuring use of the cable is reflected in the cable armor design, which provides mechanical strength, abrasion resistance, and stretch resistance, and in the usual practice of logging on the uphole travel of the sonde. Figure 2 illustrates a typical logging operation.

The use of surface recording in logging as opposed to recording in the sonde itself offers the advantages of immediate access to data, visual observation of tool function, and a timely option for additional logging, perhaps at slower rates, for interesting sections. However, some tools are used which include an onboard recording or sampling capability. These tools are often attached to the drill string or the tubing, or they may be run by wire line or pumped down through the drill string.

Logging speeds range from a maximum of approximately 1000 ft/min to zero (stationary measurements, requiring up to 10 minutes). Typical logging speeds range from 10 to 50 ft/min. Thus, if a 3000-foot section is logged, the sonde and cable will be exposed to the downhole environment for times of one to five hours plus the run-in time.

Logging tools are designed for both open-hole and cased-hole operation. Those which require contact with the rock surfaces or which must not be shielded by casing are limited to open hole use (i.e., Electrical logs, Formation Samplers, Bore Calipers, and Induction Logs).

Drilling fluids, usually called "muds," are used to cool the drill bit, to flush cuttings from the drill face and from the borehole, and to provide a weighted medium to control formation pressure. The common weighted muds are of three basic types: water based, oil based, and oil emulsion based. The oil based muds offer the greatest thermal resistance but are electrically nonconductive and are expensive. Some logging tools are not suitable for use in conductive muds, while the operation of others is adversely affected by non-conductive muds. Some tools are usable only in holes filled with mud or some other liquid, whereas others can be run in dry holes.

Figure 2

When the various tools are used within their limitations, good data are obtainable which provide the following directly measurable parameters: temperature, pressure, resistivity, flow, depth, and hole size. However, many of the desired parameters must be calculated, derived, or inferred from logging measurements: no direct measurements in the borehole are available for such parameters as porosity, permeability, rock fracturing, lithology, formation dip, heat flow, fluid characteristics, formation pressure, formation mechanical properties, cement bond quality, casing condition, hole direction, or formation density.

Broadly speaking, well-logging can be divided into four general categories: electrical, radioactivity, acoustical, and specialized auxiliaries.

Electrical Well-Logging

The electrical logging tools, the first to be extensively used in the petroleum industry, were initially developed in the late 1920's in France by the Schlumberger brothers. Electrical well-logging involves the downhole measurement of electrical quantities, principally voltage and resistance. The voltage which is measured is the potential of the drilling mud column in the borehole with respect to ground potential near the drilling rig. This potential is

generated through the operation of several mechanisms which involve the fluid in the borehole and the boundaries between the subsurface strata. Measurement of this voltage is accomplished by lowering a sonde that carries one electrode down the hole and recording the difference in voltage between that sonde-borne electrode and an electrode driven into the ground at the surface. Since the potential is at least partially produced by the interface between strata, this measurement of Spontaneous Potential (SP) is useful in defining the locations of the formation boundaries and identifying the types of strata on either side of those boundaries. The resistance of the naturally occurring waters in the subsurface formations can also be determined from the SP measurement.

The resistances of the formations are measured in two general ways. One method involves placing electrodes in various configurations on a sonde in the borehole, with another ground electrode at the surface, and then exciting various of these electrodes with some sort of electrical signal while measuring the voltages between other electrodes. A variation of this method is to monitor the amount of current that is actually forced into the formation from certain of the electrodes. This method, like the SP, requires that the drilling mud be conductive, to provide electrical contact between the electrodes and the formation through the mud. The second method involves the use of induction, and thus nonconducting muds can be used. An induction log uses a transmitter in one end of a sonde to generate a magnetic field that induces eddy currents in the formation surrounding the borehole. These eddy currents in turn generate their own magnetic fields, which are sensed by a receiver in the other end of the sonde. Because the magnitude of the induced eddy currents and their associated magnetic fields is a function of the formation resistivity, the magnetic fields that are sensed by the receiver allow a determination of that resistivity. Resistivity measurements are important because they allow the determination of boundaries of beds, water saturation, and, perhaps most important, porosity.

One major consideration in measuring electrical resistance is the volume of the formation in which resistance is to be measured. In general, the farther apart the electrodes between which the current is passed, the greater the investigation region. A great deal of ingenuity has been displayed in the placement of electrodes, with some being as near each other as an inch or less, to investigate the region very close to the borehole; and others with spacings between electrodes as great as several thousand feet, to investigate very large volumes. The induction log investigates a medium-sized volume around the borehole because of the method of inducing currents with an alternating magnetic field.

With almost all electric logging, the resistance measured is that of the formation fluids. The resistance of the matrix material is usually assumed to be infinite.

A different type of electrical logging tool is the nuclear magnetism log. A strong magnetic field is used to align individual nuclear magnetic moments. When the field is removed, measurements are taken to give the magnitude of the alignment effect (or polarization) and, if desired, the time constant (or thermal relaxation time). Hydrogen is the only element that gives a significant response to this log, and, to respond, the hydrogen must be in a free fluid, i.e., not bound by surface tension, or appearing as water of hydration. Oil and water have different thermal relaxation times, which allows the nuclear magnetism log to distinguish between the two.

All electrical logs must be run in uncased holes, because the very low resistance of the metal casing between the sonde and the formation shields the formation from the electrical logging tools.

Radioactivity Logs

With the advent of the nuclear age, a new series of tools was developed based on radiation scattering or on the radioactive decay of unstable nuclei and the detection of the emitted radiation. Because certain types of radiation are very penetrating, many of the logs based on radioactivity can be used in cased holes. For the same reason, the absence or presence of borehole fluid is immaterial. These facts contribute to the versatility of the radiation logging devices.

Common to all radiation logging devices is some means of measuring radioactivity in the borehole. The radioactivity may be either natural or induced, or it can result from injection of an isotope used as a tracer.

A natural radiation log measures the gamma radiation produced by the decay of uranium, thorium, or potassium (and their daughter products). Because the energy of decay associated with each element is different, use of a spectrum discriminating detector allows determination of a particular element or elements present. A natural radiation log may also be used to detect a radioactive tracer.

A gamma density tool includes a source of gamma rays collimated into the formation at the borehole wall. A gamma detector a short distance away measures the flux of gamma rays scattered by the formation. Because Compton scattering dominates for the gamma energies used, the detected flux will be proportional to the electron density in the formation, which will be roughly proportional to the formation bulk density.

Neutrons can be injected into the formation with several effects. The standard neutron log depends on the moderation of neutron energies and the subsequent capture of the thermal neutrons. Moderation (the reduction of neutron energy through elastic collisions) is almost totally dominated by hydrogen. If a large concentration of hydrogen is present, moderation and capture will occur near the source. This results in a small signal from a detector spaced a short distance away (12 to 18 inches) and sensitive to neutrons or to gamma rays emitted upon neutron capture. As the amount of hydrogen decreases, moderation will occur progressively farther from the source and nearer the detector, with a corresponding increase in signal level. This log thus measures the hydrogen in the formation. If the hydrogen is contained in fluid (water or oil), the porosity may be inferred.

Another type of neutron log uses a pulsed source and detector time gating to measure the decay times of the thermal neutron flux from which thermal neutron capture cross section may be determined. Since chlorine has a very high relative capture cross section, this log gives information on the chlorine as well as the hydrogen present.

Other types of neutron logs include the neutron activation log and the carbon log. Most elements, upon activation by neutron bombardment, are transmuted to unstable gamma ray emitting isotopes. The neutron activation log is configured to determine the characteristic rate of decay of the gamma radiation and hence to infer the presence of a particular element. Silicon, oxygen, and aluminum have decay times (activation half lives) and

gamma energies suitable for downhole neutron activation logging. The carbon log is configured to detect the gamma rays emitted as a result of inelastic scattering of high energy neutrons by carbon atoms. In this case, the detector (a scintillation spectrometer) is enabled only during the neutron pulse.

Many of the tools discussed above can be compensated for borehole effects by including more than one detector with different spacings from the source. Ratios of readings from the detectors can be used to derive correction factors.

Acoustic Logging

The growing use of seismic surveys to locate and define subsurface structures that might contain hydrocarbon deposits, and the need for improved interpretation established the need to measure in situ sonic velocities for the overlying formations. This need and the rapid advances being made in electronics led to the development of a number of tools for borehole measurements of acoustic velocities in the formation rocks. The sonic logging tools, which include acoustic caliper, acoustic cement bond, sonic velocity, sonic amplitude, borehole compensated sonic velocity, three-dimensional sonic velocity, and sonic televiewer, have received wide use and acceptance in downhole data acquisition and interpretation.

The most sophisticated of these sonic tools, the sonic televiewer (e.g., Seisviewer), produces a shaded black and white photograph of the entire inner surface of a section of the borehole, split along a line with magnetic north at the edges. This photograph is made from a display on an oscilloscope. When the log is run in open holes, it provides information on fractures, voids, bedding orientation, and formation dip. If the measurement is made in cased holes, the photograph can show casing shoe location and support as well as locations of collars, perforations, and casing damage or corrosion.

The other sonic tools provide measurements of compression (P) and shear (S) wave velocities and signal attenuations that are used in calculations for determination of porosity, fractures, cement bond quality, and mechanical properties (bulk modulus and Young's modulus). These sonic tools all use signal generators of the magnetostrictive or piezoelectric type and transducer receivers that are appropriately located and isolated within the tool. Measurements are made of transit time through the formations or pipe walls and/or attenuation of the signal when reflected from the surface under investigation or transmitted through the formation.

The sonic velocity log is a record of the travel time for compressional waves along a path from a transmitter to a receiver. It is used to obtain a sonic porosity (which is little influenced by secondary porosity), using the known sonic velocities for the matrix and for the fluid contained in the pores.

The sonic caliper log makes use of the travel time of the compression wave between the transmitter and the borehole wall. The transmitter and receiver make use of the same transducer. The first signal received after each transmitter pulse is the signal reflected from the borehole wall and is used to calculate hole size.

The cement bond log records the amplitudes of the compressional waves as they travel along the casing wall between transmitter and receiver. Where the bond between the casing

and the cement is good, attenuations are 20 to 30 times as great as in an unbonded section.

The mechanical properties log records the transit times for the compression and shear waves through the formation as part of a variable density photographic presentation of the total wave train. This information is used to determine rock quality and deformation.

Specialized Auxiliary Logs

Most logs exhibit temperature dependence and require temperature compensations for greater accuracy. The need for knowing the temperature in order to make corrections has encouraged the development of temperature logging tools, as has their increased use in production logging. Temperature logs are of three types: those that measure absolute temperature, those that measure the equilibrium thermal gradient, and those that measure the transient changes in temperature that result when heat is added to or extracted from the formations in a well bore.

Temperatures are measured downhole with thermocouples, resistance thermometers, thermistors, and mercury thermometers. A bridge circuit is generally used for temperature measurements. This can be accomplished with only one leg of the bridge in the borehole and with all other electronics on the surface for simplified tool design. However, greater accuracy is obtained by putting the bridge within the sonde. As with radiation logs, temperature measurements can be made in cased or uncased holes. They are often used to locate flow behind casing or through unbonded cemented sections, or to locate cement tops.

A directional survey provides information on borehole slope and direction and establishes bottom hole and production zone locations with relation to the surface entry point. It is also a necessary input for all directional drilling operations.

A caliper log provides a direct measurement of borehole diameter which aids in log interpretation and serves to establish cement volumes required for cementing casing. This log also allows detection of permeable zones through location of mud cake buildup over such zones and indicates formation instability by identifying washouts and sloughing zones.

The dipmeter log, which measures the slope and direction of formation bedding, provides information needed to map subsurface strata.

Flow, pressure, and fluid density logs are principally used as production control tools in the petroleum industry. These tools and others that have had limited use, such as magnetic susceptibility and gravity, may find additional uses in the geothermal field.

Logging Summary

The logs discussed above, along with the many surface logs, such as drilling rate and mud logs, provide the information that has permitted the petroleum industry to develop into the high technology industry that it is today. Important characteristics of the major commercially available logging tools are summarized in Table 4 with more details on each tool given in Appendix A. The use of various tools for determining well parameters is indicated in Table 5. A graph showing the relative importance of the principal logs to the petroleum industry over the years is shown in Figure 3. This existing petroleum technology base must be used in the growth of geothermal exploration and development.

Table 4
Commercial Well-Logging and Sampling Equipment

<u>Type of Equipment</u>	<u>Parameters Measured</u>	<u>Parameters that may be Derived</u>	<u>Min. Tool Diameter (inches)</u>	<u>Max. Temp. Degrees °C (°F)*</u>
Cables and Connectors				250 (480)
<u>Electrical Tools</u>				
Induction	Conductivity (or resistivity) of formation fluids	Porosity, water saturation, boundaries of beds	2 3/4	260 (500)
Induction Casing Thickness Log	Relative conductivities of the casing (measured from sensing phase differences in a received magnetic signal)	Casing thickness	3 1/2	145 (285)
Microlaterolog	Resistivity of a thin section of the flushed zone	Resistivity of the flushed zone	3 5/8	175 (350)
Microlog-Microcaliper	Resistivity of a few cubic inches of formation next to the bore-hole wall	Definition of porous and permeable beds, hole diameter	3 5/8	175 (350)
Nuclear Magnetism	Magnetic polarization, relaxation time	Free fluid density, fluid identification	4 1/4	175 (350)
Resistivity, focused	Resistivity of thin segment of formation	Definition of beds and the true resistivity of undisturbed formation waters	3 3/8	175 (350)
Resistivity, non-focused	Resistivity of formation fluids	Porosity, water quality, boundaries of beds	1 1/2	260 (500)
Spontaneous Potential (SP)	Voltages in the bore-hole mud	Lithology (correlation) and formation waters resistivity	2 3/4	260 (500)
<u>Radioactivity Tools</u>				
Gamma-Gamma Density	Compton scattered gamma radiation	Formation bulk density, porosity, lithology	1 11/16	205 (400)
Gamma, Natural	Gamma intensity (spectrum)	Lithology, correlation	7/8	260 (500)
Neutron	Neutron moderation distance	Hydrogen density, porosity, lithology	1	260 (500)
Neutron Activation	Gamma from decay of neutron activated elements	Elemental density (O, Si, Al, Mg), lithology	2 3/16	175 (350)
Neutron capture cross section	Thermal neutron decay time	Chlorine density, porosity, water saturation	1 11/16	175 (350)
Neutron/carbon	Gamma from inelastic neutron scattering	Carbon density	3 5/8	175 (350)
Radioactive Tracers	Gamma	Fluid movements	1 3/8	150 (300)

Table 4 (Continued)

Commercial Well-Logging and Sampling Equipment

Type of Equipment	Parameters Measured	Parameters that may be Derived	Min. Tool Diameter (inches)	Max. Temp. Degrees °C (°F) *
<u>Acoustical Tools</u>				
Borehole Televviewer	Photograph of borehole wall	Fractures, formation dip collar location, casing shoe	3 3/8	150 (300)
Cement Bond Log	P wave attenuation	Cement bond quality	1 11/16	190 (375)
Sonic Logs	Velocity of P&S waves, amplitude of S waves	Porosity, correlation, lithology, permeability, mechanical properties	1 11/16	205 (400)
<u>Auxiliary Tools</u>				
Caliper	Hole diameters	Permeability, cement volumes	1 1/4	150 (300)
Dipmeter	Resistivity of a thin section near the borehole wall at 3-4 places	Dip of the subsurface formations	3 5/8	175 (350)
Directional Survey	Hole azimuth and direction	Bottom hole location	1 3/4	315 (600)
Flow Meter	Fluid flows	Flow rates, source, and injection or thief zones	1 11/16	315 (600)
Fluid Samplers	Borehole fluids	Water quality	3 13/16	175 (350)
Formation Samplers	Cores	Porosity, density, lithology, correlation, heat conductivity	4 3/4	270 (430)
Gradiomanometer	Pressure gradient	Multi-phase fluid flow	1 11/16	175 (350)
Gravity Meter	Gravity differential	Density, porosity, hydrocarbons behind casing	4	150 (300)
Temperature	Temperatures, absolute & gradient	Heat flow, cement tops, source and sink zones, fluid flow behind casing	7/8	315 (600)

* Temperature conversions are rounded to the nearest five degrees.

Table 5

Well Parameters and Measurements from Which They are Derived

Correlation	Resistivity, S.P., Gamma Ray, Induction, Sonic, Density, Caliper, Cuttings, Cores, Nuclear Magnetism
Permeability	S.P., Resistivity, Caliper, Microlog, Gamma Ray, Sonic, Density, Neutron
Porosity	Sonic, Density, Neutron, Resistivity, Cores, Cuttings, S.P., Gamma Ray
Lithology	Neutron, Density, Sonic, Gamma Ray, S.P., Resistivity, Cores, Cuttings
Mechanical Properties	3-D Sonic, Density
Water Quality	Resistivity, S.P., Fluid Samples
Temperature	Temperature gradient, Differential
Pressure	Bottom hole, Shut-in, Buildup, Decline
Flow Rates	Flow Meters, Tracers, Gradiomanometer
Formation Dip	Seisviewer, Dipmeter
Deviation	Borehole Surveys (Azimuth, Direction)
Borehole Properties	Caliper, Temperature, Seisviewer
Cement Bond	Sonic Amplitude, Temperature Logs
Heat Flow	Temperature Logs, Cores
Magnetic Properties	Magnetic Susceptibility Log
Natural Radioactivity	Gamma Log
Thermal Conductivity In Situ	None

Relative Usage of Various Types of Well Logs.

Figure 3*

* By permission of the University of Texas, Division of Extension, Austin, Texas.

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GEOHERMAL WELL-LOGGING AND ASSOCIATED PROBLEMS

Well-logging has developed over the past decades into a mature technology, principally in support of, and supported by, the oil industry. The existence of large economic incentives and keen competition has led to the establishment of strong programs in research and development. These have resulted in an industry that makes intensive use of advanced technology to further the state of the art in well-logging for the oil industry.

Unfortunately, there have been almost no economic incentives for the development of well-logging in support of geothermal development. The number of geothermal wells drilled (and logged) to date has been insignificant compared to the more than 25,000 wells drilled for oil and gas per year in the United States. As a result, in those areas where geothermal well-logging and oil well-logging requirements differ, the state of the art in geothermal well-logging is relatively primitive.

The problems of obtaining needed information on geothermal wells by logging may be grouped into two broad areas: data gathering and data interpretation. It is obvious that these two are somewhat interrelated. Without data there can be no interpretation, but the interpretation and analysis methods used have a bearing on the measurements required. Each of these areas presents unique problems that are discussed below.

Data Gathering

The single major obstacle to data gathering appears to be lack of sufficient high temperature capability. Equipment and techniques for working at temperatures up to 175°C (350°F) are highly developed and such operations may be described as routine when logging in familiar formations. When well temperatures exceed this limit, a number of problems are encountered. Many of the tools are not made in high temperature versions and so the variety of measurements that may be taken is limited. Logging hot wells requires special high temperature 260°C (500°F) rated cable that is more costly and not widely available. Those high temperature "hostile environment" tools that are available exist only in small quantities and may be difficult to obtain on short notice. The field engineers and technicians in general have had little experience with the high temperature equipment and procedures and so are more prone to make errors. The equipment itself is seldom, if ever, tested at its absolute temperature limit, because life at the high temperature extreme is severely limited. Hence, frequent breakdowns may be expected. As a result of equipment time/temperature limitations, logging may need to be rushed, leading to additional problems.

The preceding problems are encountered when logging holes up to 260°C. Presently no logging equipment (with the exception of a very few special purpose tools) exists which has a claimed capability for use at temperatures greater than 260°C. The method now in use for really hot holes involves cooling the hole by circulation of cooled fluid for a period of time before logging. This requires additional costly rig time and entails risks to the borehole, as well as masking important temperature relationships within the borehole.

Even with cooling, logging often involves sacrifice of some equipment, and often the results are disappointing.

Many concerned with geothermal logging have expressed the opinion that the cable limitations now present the most serious obstacle to high temperature logging. Little incentive to develop high temperature tools exists, if cables are not available on which to run them. Well temperatures slightly over 370°C (700°F) have been measured (with maximum reading mercury thermometers), which implies an eventual goal of 400°C (750°F) for equipment (perhaps higher to support hot dry rock and magma projects). For the near future, a temperature capability of about 345°C (650°F) would be adequate for most geothermal requirements and appears to be within the present state of the art for cable technology.

The major service companies are presently working to extend the temperature limits of logging tools to 260°C (500°F) to allow logging in those few hot holes encountered in oil and gas wells. There appears to be little, if any, intention to extend capability beyond this limit. Government incentives to industry will be required to assure near term development of logging tools with capability beyond 260°C. Unfortunately, those companies best able to carry out such programs are hesitant to participate in government funded development, because of lack of protection of proprietary information.

Corrosion has always been a problem in the oil and gas industry, but in addition to the normal causes of corrosion, geothermal wells also present new conditions imposed by high temperature and hot geothermal brines. The geothermal development at Cerro Prieto in Mexico has experienced extreme difficulties because of the unexpected types of corrosion caused by geothermal brines.

Data Interpretation

The general problem of data interpretation includes all those factors which are involved with the use of logs, including specifying measurements to be made, deriving well parameters from the measurements, and applying the parameters to derive useful information for resource development and utilization.

Reservoir models figure in data interpretation in two ways: first, the specification of measurements to be made is determined by requirements of the various models, and second, the results of the measurements are used as specific inputs to the models. In the petroleum industry, exploitation is guided by such models, which allow optimization of production while minimizing environmental impact. Reservoir models are particularly important for geothermal exploitation because of the large on-site capital investment required. For the petroleum industry, reservoir modeling is highly developed and the parameters needed from field measurements are well defined. Geothermal reservoir models are not so well developed. While some of the same techniques will certainly apply, geothermal reservoir models may require the determination of different parameters. Hence, modeling of the different geothermal reservoir types is needed in order to define those parameters that must be obtained through well logging for efficient resource development.

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A second problem associated with data interpretation has to do with the unfamiliar lithologies in which the wells often are drilled. These unfamiliar lithologies produce unfamiliar responses from the logging tools. This disadvantage shows up in at least two ways. First, because the responses of the tools are different from those the logging crew normally sees, there are often malfunctions in a tool that go undetected while the logging run is being made. Again, this is a problem of inexperience, because malfunctions that occur in the logging of oil or gas wells are often immediately detected when the logging crew recognizes a peculiar tool response. The second problem imposed by the unfamiliar lithologies is that interpretation of the logs after they are run is supported neither by the experience of those who are doing the interpretation nor by well-developed theoretical models of tool responses. Temperature can play a part here also in that the formation parameters themselves are sometimes a function of temperature, often affecting the interpretation model.

Because so little logging and coring has been done in geothermal wells, very little information is available to allow correlation of logs with subsurface characteristics. The development of effective log interpretation techniques will require that an extensive program of coring and logging be undertaken so that future geothermal well logs can be understood.

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CONCLUSIONS

The following are major conclusions of this study:

1. Geothermal measurement requirements are not well defined due to lack of reservoir models and to log interpretation problems in unfamiliar formations.
2. Logging problems differ with geothermal well type.
3. Attempts to log geothermal wells to date often have met with marginal success.
4. Geothermal wells usually exhibit temperatures higher than normally encountered ($\sim 175^{\circ}\text{C}/350^{\circ}\text{F}$) in oil and gas wells.
5. Maximum claimed temperature capability of well-logging equipment is presently about 260°C (500°F). Many geothermal wells are hotter than that.
6. Special corrosion problems may be encountered in geothermal wells resulting from high temperature and the varied natures of geothermal fluids.
7. Large-scale geothermal well-logging, such as is implied by Project Independence goals, should be done by private industry.
8. There is insufficient economic incentive at present for private industry to provide adequate geothermal logging capability.
9. Government support of geothermal well-logging technology will be required to meet the goals for geothermal resource development contained in the Project Independence report. This support can buy lead time for the process of eventual industrial development, as well as promote advances in near-term logging capability.

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RECOMMENDATIONS

Based on the preceding conclusions, recommendations for specific government actions are given below. These recommendations fall into three categories: geosciences, instrumentation, and field support.

Geosciences

- Survey existing geothermal reservoir modeling efforts and extend as needed.
- Develop log interpretation models and techniques for geothermal formations.
- Establish or support a data bank that will
 - a) Fund collection of data (logs and samples), and
 - b) Catalog, store, and disseminate these to interested parties.
- Select wells to be logged/sampled and define the measurement programs.
- Define priority of need for well parameter information and the measurements to determine them.

Instrumentation

- Survey existing high temperature components and materials.
- Fund development of promising new high temperature technologies.
- Develop tool insulation and/or cooling techniques.
- Develop specific high temperature tools once need is established.
- Develop technologies leading to sondes, cables and connectors usable at >345°C (650°F).
- Investigate alternative data link technologies.
- Obtain use of a laboratory test facility(s).
- Develop as necessary improved high temperature coring and sampling techniques.

Field Support

- Arrange for collection of well cores and samples.
- Contract for logging services in specific cases of interest.
- Obtain use of a field test facility(s) (e.g., a hot borehole).

Essential to completing the tasks outlined above is a management framework within which two basic functions occur: direction of individual activities, and coordination of similar activities being carried on in industry and by governmental agencies. It would be highly desirable to select a single group, reporting to ERDA, that would have overall responsibility for geothermal logging development. This would assure the most efficient utilization of resources and timely development of the required technology. Program direction could be accomplished at ERDA Headquarters if staffing permits, or could be delegated to one of the Energy Research Centers (ERC's) or some other organization.

Three major activities would be conducted under the direction of the management group and a lead laboratory for each activity should be selected. The three areas of interest are 1) geoscience studies to aid parameter selection, log interpretation and modeling; 2) development of instrumentation for data gathering; and 3) field support activities. As discussed earlier, these activities are mutually dependent. However, the disciplines required for each differ significantly and a division of activities under the direction of a geoscience lab, an instrumentation lab, and a field services group would be appropriate.

It is recognized that some of the necessary activity in each area is already underway, but the selection of a management team to coordinate these efforts and initiate tasks that are not yet being done would be most desirable. The technical activity in each area would be conducted by contracts with industry, universities, government laboratories, or through in house efforts as appropriate. The tasks that should be initiated in FY76 are summarized at the conclusion of this section.

The project management group, whether at ERDA, an ERC, or elsewhere would select the lead laboratory for each of the three major areas of activity. The primary project management tasks would be to organize and manage the total geothermal logging development program, and to coordinate the overall government effort with industrial and academic programs.

The geoscience lab would be responsible for coordinating existing reservoir modeling efforts, identifying and conducting additional studies as required, establishing priorities of tasks and contracting for additional required work. A similar function would be performed with respect to log interpretation studies.

To assist in these studies, the lab would be responsible for well information. These responsibilities would include the specification, cataloging, analysis, and storing of logs, cores and samples. The geothermal wells associated with ERDA demonstration projects should be among those utilized in such an overall plan. This lab would be in a position to identify those parameters most urgently needed for geothermal resource evaluation and the measurements required to determine the parameters. Specific assignments are as indicated above under Geosciences.

The instrumentation lab would be responsible for assessing existing logging equipment capabilities and extending these capabilities as needed by sponsoring the development of high temperature geothermal oriented instrumentation hardware and techniques. This will require identification of existing high temperature materials and components and development of new high temperature technologies as necessary. These would be applied as available in the development of high temperature equipment needed in the field. Primary tasks are those indicated above under Instrumentation.

The field support group would provide a capability to collect needed well logs and samples, and to provide field testing of new well logging and sampling equipment. Primary assignments would include the tasks listed above under Field Support.

Figure 4 presents a schematic representation of the proposed management structure.

PROPOSED ORGANIZATION STRUCTURE: GEOTHERMAL WELL-LOGGING DEVELOPMENT

Figure 4

Recommended FY76 Activities

Of the recommendations listed above, those that are most urgent and should be initiated in the coming fiscal year are discussed below.

Project Management

1. Conduct a geothermal logging workshop. The high temperature tools which are most needed should be identified and given priority. Disagreement and uncertainty have been found to exist among the various geothermal developers as to what this priority should be. A valuable first step in establishing this priority would be a workshop with participation by industry, universities, and government workers in these fields. The primary purpose of the workshop will be to foster discussion of the needed measurements program and establish a consensus on priorities for sonde development.
2. Select groups to manage the geoscience, instrumentation, and field support functions.

Geoscience

1. Organize a coordinated program of geothermal reservoir modeling. The USGS in Menlo Park currently has underway a geothermal reservoir modeling study that could serve as a nucleus for extension to various reservoir types.
2. Promote the development of geothermal log interpretation techniques. This is a major problem in geothermal logging. The USGS in Denver has an active program in geothermal log interpretation and analysis which could serve as a basis for additional studies to extend interpretation to various formation types. Such studies should include government support of coring, sampling, and lab analysis for comparison with well logs from different geothermal sites. This will require, in some cases, development of cheaper and more reliable high temperature coring and fluid sampling devices and techniques.

Instrumentation

1. Initiate procurement of high temperature, multi-conductor logging cable. A high temperature logging cable is basic to the needs of geothermal logging. There are indications that one or more companies may be in a position to produce a 315°C to 345°C (600°F to 650°F) multi-conductor logging cable. RFP's should be prepared and sent to industry. Samples of these cables should be purchased, evaluated, and the results made available to potential users.
2. Initiate development and evaluation of high temperature materials, components, and subassemblies for geothermal sondes. High temperature materials and components will be required for the development of high temperature logging tools. RFP's should be prepared and sent to the electronics industry. Promising approaches resulting from the RFP's should be funded.
3. Conduct a state-of-the-art assessment of hot hole coring and fluid sampling techniques. The acquisition of cores and in situ fluid samples is essential to the formulation of log interpretation techniques. Improved techniques should be identified by RFP's transmitted to industry. Development of selected techniques should be supported.
4. Acquire the use of a high pressure, high temperature laboratory test facility. The successful development of extended range systems and components requires environmental testing facilities that are capable of simulating the extreme environments that the equipment must survive. To our knowledge there are no facilities in existence at this time that can provide the combined range of temperature, pressure and corrosive atmosphere expected in geothermal well bores, although two that approach these conditions are in development. These two are the Reed/Terra Tek Drilling Research Lab in Salt Lake City, Utah, and Sandia Laboratories Spark Drilling Test Chamber in Albuquerque, New Mexico.

Field Support

1. Initiate a program to provide research field logging services on selected geothermal wells. The USGS, Denver, has two logging trucks that may be used for initial data gathering. In the longer term, an expanded capability will

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be required to support geothermal development. Eventually, the petroleum industry service companies will assume this role, but in the interim, an expanded capability, oriented towards the collection of research data, should be encouraged.

2. Initiate negotiations with service companies for geothermal field support. The near term (one to two year) capability to log geothermal wells will depend on the commercial service companies and the small, basically research oriented, capability of the USGS in Denver. Government funding should be used to evaluate the commercial capability and to provide experience in hot well-logging to encourage improvement in equipment and techniques.
3. Acquire the use of a high temperature field test facility. A test facility is required for realistic testing of equipment in actual formations under field conditions. Such a facility might be an already-drilled hot borehole, if sufficient cores and samples were taken during the drilling.

Appendix A
INDIVIDUAL TOOL DESCRIPTIONS

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LOGGING COST CALCULATIONS FOR THIS APPENDIX

Costs shown are intended to give relative cost information. Except as noted, costs are based on Schlumberger's September 22, 1974, California-land schedule for logging the bottom 2000 feet of a 5000-foot hole of which the first 3000 feet have already been logged. Service or mileage charges are not included. Additional costs are incurred for holes deeper than 15,000 feet, and for bottom-hole temperatures which exceed 325°F. Some typical additional charges for high temperature boreholes are shown below.

HIGH TEMPERATURE BOREHOLE CHARGES

Additional charges are applied on operations performed in wells having bottom-hole temperatures in excess of 325°F as measured or estimated by Customer prior to job. The following additional charges are applied on each trip into the well for all services except perforating, plug setting, packer setting, and customer instrument services.

<u>Depth (feet)</u>	<u>325° to 400°F</u>	<u>400° to 450°F</u>	<u>450° to 500°F</u>
0-15,000	\$ 350	\$ 600	\$ 990
15-20,000	510	750	1,210
24-25,000	1,210	1,600	2,310
29-30,000	2,170	2,700	3,690

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Electrical Logging Tools

TOOL: INDUCTION CASING-THICKNESS LOG

Parameter: Measures the differential casing thickness with respect to normal casing thickness.

Principle of Operation: This tool is a specialized variation of the induction tool. Whereas the induction tool is designed to measure the resistivity in the formations surrounding the borehole, the casing thickness tool is designed to be run in casing, and it therefore measures resistivities in the casing. This tool has a transmitting coil which generates an alternating magnetic field which induces eddy currents in the casing surrounding the tool. These eddy currents in turn generate a magnetic field which is sensed by a receiver coil. The phase difference between the current exciting the transmitter coil and the current induced in the receiver coil is a measure of the thickness of the casing.

Principle of Interpretation: Since this tool measures relative differences in casing thickness, it is the relative phase differences between the exciting current and the received current which are recorded. Relative differences in casing thickness of a few thousandths of an inch can be determined.

Logging Rate: 50 ft/min

Borehole Restrictions: The casing may be filled with any fluid, or empty. Minimum casing diameter is $4\frac{1}{2}$ inches.

Volume Investigated: A few cubic inches of the casing.

Maximum Advertised Temperature: 145°C (285°F)

Maximum Pressure: 10,000 psi

Minimum Tool Diameter: $3\frac{1}{2}$ inches

Cost: \$1,040

TOOL: INDUCTION LOG

Used With: Most logs.

Parameters: Porosity, water saturation, boundaries of beds.

Principle of Operation: A transmitter coil in one end of the sonde is driven with an alternating current so that an alternating magnetic field is set up in the rock formation surrounding the borehole. This magnetic field induces eddy currents which flow in the surrounding formation. These eddy currents in their turn set up a magnetic field which is sensed by one or more receiver coils in the end of the sonde opposite to the end with the transmitter coil. The magnitude of the eddy currents and their resulting magnetic

field depends on the resistivity of the formation, so that the resistivity can be calculated from the magnetic field which is measured by the sensing coils.

Principle of Interpretation: As with other electric logging, there are well-established equations which relate porosity and water saturation to the resistivities measured in the formations around the borehole. However, the induction log has the advantage over other electric logs that if the resistivity of the true undisturbed formation is less than the resistivity of the zone near the borehole which has been invaded by mud filtrate, then the resistivity which is measured is that of the true undisturbed formation.

The measured differences in resistivity for different kinds of rocks allow the determination of the boundaries between beds.

Logging Rate: 100 ft/min

Borehole Restrictions: Any fluid or no fluid in an uncased hole. Minimum hole diameter is four inches.

Volume Investigated: The induction log investigates a fairly deep volume, roughly equal in diameter to the distance between transmitter and receiver coils. Thus with the typical 40 inch spacing, the volume investigated will be on the order of 100 cubic feet.

Maximum Advertised Temperature: 260°C (500°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 2 3/4 inches

Cost: \$1,080 (includes short normal and SP).

Comments: This is one of the most important and commonly used logs.

TOOL: MICROLATEROLOG

Used With: Most logs

Parameters: Resistivity of the zone next to the borehole wall which has been flushed by the encroachment of mud filtrate, and definition of thin beds.

Principle of Operation: As with all microdevices, the volume investigated by this device is quite small. As with regular laterologs, the current emitted from the measuring electrode is confined by currents being emitted from focusing electrodes near the measuring electrode. In the microlaterolog, the measuring and focusing electrodes are concentric circles. The forcing of the measurement current into the formation from the electrodes which are mounted on a pad which is held against the borehole wall minimizes the effects of the mud cake.

Principle of Interpretation: Since the current flows perpendicularly across the mud cake, and since the resistivity of the formation is usually much greater than the resistivity of the mud cake, the mud cake has very little effect on the measured resistivity. For mud cakes of thickness less than 3/8 inches, no correction of the measurement is necessary. For mud cakes greater than 3/8 inches, correction charts are available. The thickness of the mud cake is found from the caliper which is part of this tool. This caliper is implemented by measuring the distance between the measurement pad and the backup pad which together expand to insure that the

measurement pad is pressed firmly against the borehole wall.

Since the current beam is so small (about 2 inches in diameter), the resolution of this device is such that very thin beds can be defined.

Logging Rate: 50 ft/min

Borehole Restrictions: Conductive muds are required, and there must not have been significant caving of the borehole wall. Minimum hole diameter is 6 1/8 inches.

Volume Investigated: Quite small, a few cubic inches

Maximum Advertised Temperature: 175 C (350 F)

Maximum Pressure: 15,000 psi

Minimum Tool Diameter: 3 5/8 inches

Cost: \$910

TOOL: MICROLOG-MICROCALIPER LOG

Used With: Most logs

Parameters: Definition of porous and permeable beds, hole diameter.

Principle of Operation: Logging devices having names which carry the prefix "micro" are intended to investigate very small volumes, and therefore their electrodes are carried on a pad which is pressed against the borehole wall, with the electrodes being mounted very closely together. To insure contact with the wall, a second pad pushes against the other side of the borehole wall. Recording of the distance between the two pads gives the caliper measurement. The microlog device is actually a "lateral" device; i.e., a device which uses two electrodes to measure the gradient of a field set up between two active electrodes. The two active electrodes set up the field between one electrode on the surface and the other carried on the pad with the two measuring electrodes. Two measurements are actually made with the microlog -- one is the lateral field gradient measurement, and the other is a "normal" measurement, which measures the potential between one of the two measuring electrodes on the pad and yet another measuring electrode on the surface.

Principle of Interpretation: Clearly, the volume of investigation is much greater for the normal measurement than the volume for the lateral measurement. The normal measurement tends to measure the resistance of the zone near the borehole which has been flushed by the mud filtrate if the formation is permeable and porous enough to allow such flushing, whereas the lateral measurement investigates a region which is so small that it measures mostly only the resistance of the mud cake on the borehole wall. Since the resistance of the flushed zone is usually greater than the resistance of the mud cake, porous and permeable zones are characterized by a higher resistance measured by the normal device than by the lateral device. Additionally, the resistivity readings are low, not more than 20 times the resistivity of the mud, and the caliper shows any mud cake buildup (with the borehole diameter being smaller than the bit size).

Logging Rate: 50 ft/min

Borehole Restrictions: Conductive muds are required, and the microlog does not work well if there has been significant caving of the borehole walls, because then the pads are not applied firmly to the borehole wall. Minimum hole diameter is 6 1/8 inches.

Volume Investigated: Very small, a few cubic inches

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 15,000 psi

Minimum Tool Diameter: 3 5/8 inches

Cost: \$910

TOOL: MICROWAVE LOG

Parameters: Unidentified

Principle of Operation: Microwaves are generated at one or more transmitters in the sonde, propagate through the formations surrounding the borehole, and are sensed at one or more receivers on the sonde.

Principle of Interpretation: The receiver signals are translated down in frequency to submicrowave signals, and their phases are compared.

Comments: This tool has been patented, but its use in the field is uncertain.

TOOL: NUCLEAR MAGNETISM LOG

Used With: Caliper log

Parameters: Effective porosity, correlation (permeability?).

Principle of Operation: Of the elements commonly encountered in logging, hydrogen is the only one which has a nuclear magnetic moment sufficient to respond to this log. With no magnetic field present, the individual magnetic moments will be randomly oriented due to thermal motion. If a strong external magnetic field (at right angles to the earth's field) is applied, these moments will tend to align with the field over a period of time characterized by the thermal relaxation time. When the field is removed, the moments will attempt to align with the earth's field, but, because of spin and gyroscopic effect, will precess. This causes a rotating polarization which can be detected with a suitably placed coil. Because only the hydrogen in a free fluid can respond, the amplitude of this signal will be proportional to the number of hydrogen atoms in free fluid in the formation. If several measurements are taken with different polarizing times, the thermal relaxation time may be calculated.

Principle of Interpretation: Because only hydrogen in free fluid (i.e., not bound by surface tension or as water of hydration) responds, porosity derived from this log will be effective porosity. Oil and water have different surface effects, and the bulk fluids have different thermal relaxation times. Therefore, this measurement may be used to distinguish oil and water.

Logging Rate: ≤20 ft/min for free fluid log. Much slower for thermal relaxation (must stop at each point logged).

Borehole Restriction: Any fluid or dry, uncased, ≥5½ inches diameter

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 4¼ inches

Comments: Cannot be used in highly magnetic formations.

TOOL: PULSED-RADAR LOG

Parameters: Salt dome/sediment interface

Principle of Operation: The salt-sediment interface provides a reflective surface for impinging microwaves.

Principle of Interpretation: As with any radar system, the reflected waves are analyzed for time delay and amplitude to define those objects which are reflecting the impinging radar signal.

Comments: This system is experimental, and has not had wide field use.

TOOL: RESISTIVITY, FOCUSED-CURRENT (LATEROLOG AND GUARD-ELECTRODE LOG)

Used With: Most logs

Parameters: Lithology (definition of beds and correlation) and the true resistivity of the undisturbed formation.

Principle of Operation: Both the laterolog and the guard-electrode devices are designed to force the measuring current to flow radially out from the borehole in a thin sheet, thus confining the measurement to a thin section of the subsurface formations, and lessening the effect of the mud column. The principle whereby the measuring current is confined is that the electrode from which that current flows is bracketed on the sonde by either two long focusing electrodes or two or six small ones. Currents are emitted from these focusing electrodes, thereby confining the current from the central measurement electrode. The difference between the laterologs and the guard-electrode is that the current from the focusing electrodes is automatically controlled in the laterologs, whereas the focusing electrodes are merely connected through a low resistivity to the measuring electrode in the guard-electrode device.

Principle of Interpretation: Because of the focusing of the measuring current, these devices excel at delineation of thin beds. There are formulas for the determination of the undisturbed resistivities which can be used when the ratio of the resistivities of the mud filtrate and the formation waters is small.

Logging Rate: 100 ft/min

Borehole Restrictions: The mud must be conductive, and the ratio of the resistivities of the mud filtrate and the formation waters should be small. Minimum hole diameter is 6 1/8 inches.

Volume Investigated: Because of the focused current, the volumes investigated are large, and extend in a disc from the borehole.

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 3 3/8 inches

Cost: \$1,080 (includes a dual-induction log)

TOOL: RESISTIVITY LOG, LATERAL

Used With: Normal resistivity log, SP, induction resistivity log, micro-resistivity, microcaliper

Parameters: Porosity, water saturation, boundaries of beds.

Principle of Operation: An electrode at the surface and an electrode on the sonde in the borehole set up an electrical field between them. A pair of fairly closely-spaced electrodes which are also carried on the sonde measures the gradient of the electrical field versus depth in the borehole. From these field gradient measurements, the resistance of the formations can be calculated.

Principle of Interpretation: There are well-established equations which relate porosity and water saturation to the various resistivities measured in the formations around the borehole.

The measured differences in resistivity for different kinds of rocks allow the determination of the boundaries between beds.

Logging Rate: 100 ft/min

Borehole Restrictions: Must be made in uncased holes containing water-base or oil-emulsion muds (conductive muds). Minimum hole diameter is three inches.

Volume Investigated: Depending on the spacing of the measuring electrodes, which varies from 4 inches to 18 feet 8 inches, from a few cubic feet to 100 cubic feet.

Maximum Advertised Temperature: 260°C (500°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 1½ inches

Cost: \$1,030 (includes a long normal, short normal, standard lateral and SP)

TOOL: RESISTIVITY LOG, NORMAL

Used With: Lateral resistivity log, SP, induction resistivity log, microresistivity, microcaliper

Parameters: Porosity, water saturation, boundaries of beds

Principle of Operation: An electrode at the surface and an electrode on the sonde in the borehole set up an electrical field between them. A third electrode (which is also carried on the sonde) measures the value of the electric field versus depth in the borehole. The voltage measured is roughly the potential of the measuring electrode referred to an infinitely distant point. From these potential measurements, the resistance of the formations can be calculated.

Principle of Interpretation: There are well-established equations which relate porosity and water saturation to the various resistivities measured in the formations around the borehole.

The measured differences in resistivity for different kinds of rock allow the determination of the boundaries between beds.

Logging Rate: 100 ft/min (except for Ultra-long Spaced Electric Logs which must be brought to rest for 60 seconds before each reading)

Borehole Restrictions: Must be made in uncased holes containing water-base or oil-emulsion muds (conductive muds). Minimum hole diameter is 6 1/8 inches.

Volume Investigated: Depending on the spacing between the down-hole active and measuring

electrodes, from 10 to 100 cubic feet for usual tools, up to several thousand cubic feet for Ultra-Long Spaced Electric Log (a Schlumberger device).

Maximum Advertised Temperature: 260°C (500°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 2 3/4 inches

Cost: \$1,030 (includes a long normal, short normal, standard lateral and SP)
\$1,080 (includes short normal, induction, and SP)

TOOL: SPONTANEOUS POTENTIAL (SP) LOG

Used With: Short normal, long normal, standard lateral, induction, microresistivity, microcaliper

Parameters: Lithology (correlation) and resistivity of the naturally-occurring formation waters.

Principle of Operation: Measures the difference in electrical potential as a function of depth between the mud pit at the surface and the mud column in the borehole.

Principle of Interpretation: The most important source of the potentials in the mud column are the electrochemical electromotive forces (emf's) which occur at the points of contact between the drilling mud (or its filtrate) and the formation waters, in the pores of the permeable beds, and across impermeable shales. Laboratory experiments have established correlations between the deflections of the SP curve and the presence of permeable zones, so those zones and their boundaries are definable from the SP curve. The theoretical static SP curve (SSP) is represented as

$$SSP = -K \log (R_{mf}/R_{we})$$

with R_{mf} being the resistivity of the mud filtrate, and R_{we} being the resistivity of the equivalent formation water.

The resistivity of the formation waters can be determined from this equation.

Logging Rate: 100 ft/min

Borehole Restrictions: Must be made in uncased holes containing water-based or oil-emulsion muds (conductive muds). Minimum hole diameter is four inches.

Volume Investigated: The volume which contains the mud and strata which generate the electrical potentials is investigated. This can be quite long, extending over many feet, and extending radially from the borehole to the mud-filtrate/water interface, and containing 10 to 100 cubic feet.

Maximum Advertised Temperature: 260°C (500°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 2 3/4 inches

Cost: \$1,020 (includes long normal, short normal, and a standard lateral)
\$1,080 (includes short normal and induction)

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Radioactivity Tools

TOOL: GAMMA-GAMMA DENSITY LOG

Used With: Gamma log, caliper log

Parameters: Density, porosity (lithology)

Principle of Operation: An isotopic gamma ray source is collimated to a beam which is Compton scattered by the formation electrons to the detector. The detected signal will be inversely proportional to the electron density in the path through the formation. Most tools use two detectors to allow compensation for borehole effects.

Principle of Interpretation: This log measures electron density. Since the ratio of charge to mass (Z/A) is about 0.5 for most elements encountered in logging, the electron density is approximately proportional to the bulk density of the matter. If matrix and fluid densities are known, porosities may be calculated, and conversely.

Logging Rate: 30 ft/min. maximum

Borehole Restriction: Any fluid, principally uncased holes, ≥ 2 inches diameter.
Needs a fairly smooth hole.

Volume Investigated: Maximum penetration is about six inches.

Maximum Advertised Temperature: 205°C (400°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 1 11/16 inches

Cost: \$1,080 (FDC)

TOOL: GAMMA LOG

Used With: Most logs

Parameters: Lithology (correlation)

Principle of Operation: Measures gamma rays from naturally occurring (U, Th, K) or artificially injected (tracers) radioactive elements. There is a limited but growing availability of spectral discrimination capability.

Principle of Interpretation: Different lithologies have different radioactivity levels (shales higher than sands). With spectrum, particular elements may be identified.

Logging Rate: ≤ 30 ft/min

Borehole Restriction: Any fluid, cased or uncased, ≥ 2 inches diameter

Volume Investigated: About a 12-inch radius sphere

Maximum Advertised Temperature: 260°C (500°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 7/8 inches

Cost: \$140 (when run with another log, no spectrum); \$680 (run alone, no spectrum)

TOOL: NEUTRON ACTIVATION LOG

Used With: Neutron capture cross section log (sometimes)

Parameters: Elemental analyses - various elements (water flow)

Principle of Operation: Most elements are transmuted to a different element or isotope when bombarded by neutrons. Such "activation products" are usually unstable and will decay, giving off radiation, at an exponential rate. Three properties, radiation intensity, decay rate, and characteristic energy, may be measured to give information on the elements activated. Usually, the logging parameters (delay between irradiation and detection, energy discrimination levels) will be chosen for detection of a particular element.

Principle of Interpretation: Oxygen is easy to detect but difficult to interpret since most formation materials contain a lot of oxygen. One use is a flow log in which oxygen in water is activated and then flows past a detector. Silicon detection is useful as a lithology indicator (distinguishes lime from sand). Aluminum detection is useful in identifying clay content. Magnesium detection is useful in identifying dolomite.

Logging Rate: Depends on tool design (spacing) and element logged, ~30 ft/min down to stationary measurements.

Borehole Restriction: Any fluid, cased or uncased, $\geq 3\frac{1}{2}$ inches diameter

Volume Investigated: ~12 inches to 24 inches penetration

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 2 3/16 inches

Cost: Varies with method and element.

Comments: Capability should improve with improved spectral discrimination capability.

TOOL: NEUTRON CAPTURE CROSS SECTION LOG

Used With: Gamma log, collar locator

Parameters: Water saturation, oil gas contact (porosity)

Principle of Operation: A detector measuring capture gammas is gated on for two intervals following a pulse of high energy neutrons. The decay time of the gamma signal, which is proportional to the decay time of the thermal neutron population, may be calculated. From this, the thermal neutron capture cross section may be derived.

Principle of Interpretation: Since chlorine has by far the largest capture cross section of elements commonly encountered in logging, this log tends to respond to formation chlorine. If water salinity is known, water saturation may be found. In a dual spaced detector version, porosity and gas may also be detected using the difference in near and far detector response.

Logging Rate: ≤ 30 ft/min

Borehole Restrictions: Any fluid, ~2 inches diameter. Because of invasion, this log is most effective in cased holes.

Volume Investigated: One to two foot penetration

Maximum Advertised Temperature: 175°C (350°F); 150°C (300°F) dual spaced

Maximum Pressure: 20,000 psi (14,000 dual spaced)

Minimum Tool Diameter: 1 11/16 inches

Cost: \$2,170 (Dual Spacing TDT)

TOOL: NEUTRON/CARBON LOG

Used With: Collar locator

Parameters: Formation carbon content

Principle of Operation: A pulsed neutron source is used to generate 14 MeV neutrons.

Gamma rays of 4.43 MeV that are produced by inelastic scattering of these neutrons by carbon are detected using a scintillation spectrometer. This detector is time gated so that it only responds during the neutron pulse to maximize the signal to noise ratio. In actual operation a carbon/oxygen ratio is determined.

Principle of Interpretation: Carbon/oxygen ratio will differ with oil content and so oil saturation can be estimated in many formations.

Logging Rate: Usually 1 to 10 minutes per point logged depending on accuracy required.

Borehole Restriction: Cased or uncased, any fluid or dry, $\geq 4\frac{1}{2}$ inches diameter

Volume Investigated: About 12 inches to 24 inches penetration

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 15,000 psi

Minimum Tool Diameter: 3 5/8 inches

TOOL: NEUTRON LOG

Used With: Caliper, gamma log

Parameters: Porosity (lithology)

Principle of Operation: Neutrons emitted by an isotopic source are moderated to thermal energies, principally by hydrogen in the surrounding media, then are captured, producing a gamma photon. If the formation is rich in hydrogen, this takes place near the source, and the detector (spaced one to two feet away) will have a low response. If the formation is low in hydrogen (low water, hydrocarbon, or shale content), the neutrons will diffuse farther before reaching thermal energies and the detector (sensitive to capture gamma, thermal, or epithermal neutrons) will have a larger response. Some tools are "compensated," i.e., use two detectors with different spacing to allow compensation for the effect of the borehole.

Principle of Interpretation: If voids are assumed filled with water or hydrocarbons, porosity may be derived from hydrogen density.

Logging Rate: ≤ 30 ft/min

Borehole Restriction: Tools available for cased or uncased holes, any fluid or dry. Tools available for 2 inch tubing.

Volume Investigated: Roughly spherical extending one to two feet into the formation.

Maximum Advertised Temperature: 260°C (500°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 1 inch

Cost: (CNL) \$1,220

Comments: Wide variety of tools all measuring hydrogen density with varying degrees of success.

TOOL: RADIOACTIVE TRACER LOGS

Used With: Alone

Parameters: Fluid movement, source and sink information

Principles of Operation: A density matched radioactive material is introduced into the well fluid where its movement can be traced by one or more gamma ray detectors mounted above or below the surface controlled ejector or "squirt gun." Capable of measuring very low fluid velocities.

Principle of Interpretation: Buildups of tracer material indicate a sink zone while thinning takes place opposite a source area. Leakage paths behind casing are indicated by space between source and sink areas. Flow profiles may be determined by measuring fluid velocities above and below investigation zone.

Logging Rate: 60 ft/min

Borehole Restriction: Cased or uncased, fluid filled, 2 inch diameter

Volume Investigated: Core hole fluids

Maximum Advertised Temperature: 150°C (300°F)

Maximum Pressure: 6,000 psi

Minimum Tool Diameter: 1 3/8 inches

Cost: \$1,700

Acoustical Tools

TOOL: BOREHOLE TELEVIEWER

Used With: Alone

Parameters: Wall discontinuities, formation dip, bore wall fracture patterns

Principles of Operation: A downhole scanner-transducer and a fluxgate magnetometer are rotated at 180 rpm about a common vertical axis. A narrow beam acoustic signal is emitted as a pulsed signal. This signal is reflected from the borehole wall before detection by the receiving transducer. The attenuation caused by irregularities in the wall varies the intensity of the output displayed on the face of recording oscilloscopes. The magnetometer generates a triggering pulse for the sweep signal to orient the oscilloscope display for recording on photographic material such that the display always starts at the same azimuth points in the borehole. This provides a direct and descriptive reproduction of the borehole wall split along a known line.

Principles of Interpretation: Fractures appear as characteristic lines, and bedding planes appear as sinusoidal curves with a single maximum and minimum point providing dip information.

Logging Rate: 10 ft/min

Borehole Restriction: Fluid filled 4 inches to 22 inches diameter, cased or uncased

Volume Investigated: Borehole surface - 360° azimuth scan

Maximum Advertised Temperature: 150°C (300°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 3 3/8 inches

Cost: \$1,600 for 500 linear feet (courtesy of Birdwell, Div. SSC)

TOOL: CEMENT BOND LOG

Used With: Sonic logs made with standard tools include bond information.

Parameters: Quality of cement bond to pipe and borehole wall

Principles of Operation: The amplitude (or signal strength) of an acoustic signal traveling along the casing is greatly reduced where the cement is well bonded to the pipe. A constant strength signal is transmitted to an acoustically isolated receiver for amplitude detection and recording.

Principles of Interpretation: An acoustic signal is attenuated more by a bonded than an unbonded pipe. Tool centering is important and is checked on the 3 3/8 inch tool by observing lapse time between triggering and signal detection which should be about three times the pipe transit time plus the travel time in the fluid across

one pipe diameter.

Logging Rate: 100 ft/min

Borehole Restrictions: Cased and cemented holes, ≥ 2 inches diameter

Volume Investigated: Cement bond line

Maximum Advertised Temperature: 190°C (375°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: $1\frac{11}{16}$

Cost: \$640 - \$840

TOOL: SEISCALIPER

Used With: Alone

Parameters: Diameter of large bore holes and solution mined cavities

Principles of Operation: The downhole motor driven rotating unit has three acoustic scanner-transducers positioned horizontally, 45° up, and 45° down, and a magnetic north sensor. A focused acoustic signal travels through the borehole fluid and strikes the cavity boundary opposite the transducer. The echo signal is used to intensity modulate a radial time sweep scope and this display is recorded on Polaroid film.

Principles of Interpretation: The photograph provides an oriented direct reading record of hole size.

Logging Rate: Stationary

Borehole Restriction: Mud, oil or water filled; 6 feet to 1000 feet in diameter; uncased

Volume Investigated: Fluid filled cavity

Maximum Advertised Temperature: 80°C (175°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 4.75 inches

Cost: \$2,400 for 50 stations (courtesy of Birdwell, Div. SSC)

TOOL: SONIC LOG

Used With: Dual induction, focused induction, caliper

Parameters: Velocity of compression and shear waves, Attenuation of shear waves and reflected compression waves. Correlation, porosity, overpressured formations.

Principles of Operation: Sonic signals are generated by magnetostrictive or piezoelectric transducers at 20 to 30 bursts per second. The first arrival energy is detected by one or two similar transducers located a short distance away. Time of travel between receiver and transmitter (Δt) is recorded as an inverse velocity. An acoustic absorber material is used between the transmitter and the receiver to insure the first arrival signal is the compression wave that has traveled through the formation. The same tool is used to measure shear wave amplitudes which, when recorded and used with photographic records of the entire wave train, are interpreted to indicate the absence or presence of fractures in the formation. By the

addition of shear wave velocity measurements, it is possible to calculate Poisson's ratios; with the addition of bulk density from a gamma density log, the determination of Young's Modulus and other elastic constants is possible. Bore compensated tools are often used to reduce the effects of borehole irregularities and tool misalignment.

Principles of Interpretation: The interval of travel time for a compression wave is dependent on formation lithology and porosity. Both the rock matrix and the liquid within the pore space must have known sonic velocities for porosity calculations to be made (Wyllie Time Average equation). A caliper log is required for accurate velocity determinations. If borehole irregularities are indicated by the caliper log, a borehole compensated velocity is recommended to minimize borehole effects.

Logging Rate: 60 ft/min

Borehole Restrictions: Fluid filled hole, cased or uncased, ≥ 2 inches diameter

Volume Investigated: Few inches around borehole

Maximum Advertised Temperature: 205°C (400°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 1 1/16 inches

Cost: \$1,080 + additional charges for amplitude logging, transit time integration, or wavetrain oscilloscope pictures

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Auxiliary Tools

TOOL: CALIPER LOGS

Used With: Most logs

Parameters: Borehole diameters

Principles of Operation: Two or more diametrically opposed pairs of arms are pushed against the bore hole walls; signals representing their diametral separation are recorded at the surface. Individual diameters, integrated values for bore hole volume, and average diameter are normally recorded. Electrical resistance measurements are sometimes included, and a sonic caliper is also available for large wash-out sections.

Principles of Interpretation: The measured diameters give an indication of hole shape, while calculated average diameters are used to find bore hole volume for use in setting packers and cementing, as well as for interpretation of other logs.

Logging Rate: 30 ft/min

Borehole Restriction: Maximum diameter 40 inches - open or cased. Any conductive mud >0.3 ohms/meter if resistance measurements are made. Open hole.

Volume Investigated: Bore hole walls and/or mud cake face

Maximum Advertised Temperature: 150°C (300°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 1½ inch

Minimum Hole Diameter: 2 inches cased or open hole

Cost: \$910

TOOL: DIPMETER LOG

Used With: Most logs

Parameters: Direction and angle of dip of subsurface strata

Principles of Operation and Interpretation: The change in resistivity between strata is measured with three or four micrologs or microlaterologs equally spaced around the circumference, and which are pressed against the bore hole wall on pads. Magnetic north is also recorded, along with the angle and direction of the bore hole, and a measurement of bore hole diameter (caliper). The correlation of significant resistivity changes measured by the micrologs with the bore hole angle, direction and diameter, and magnetic north allow the calculation of the true subsurface dip.

Logging Rate: 50 ft/min

Borehole Restriction: Electrically-conductive mud must be used, and the bore hole

must be relatively free from caving. Minimum hole diameter is 5½ inches.

Volume Investigated: Quite small

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 3 5/8 inches

Cost: \$1,370

TOOL: DIRECTIONAL SURVEY

Used With: Dipmeter

Parameters: Drift from vertical, azimuth of drift

Principles of Operation: Using a stable vertical reference (i.e., gravity or stable platform) the magnitude of the angle the bore hole makes with vertical is measured and plotted against depth together with the drift azimuth or direction of drift using magnetic north or a gyro compass as reference.

Principles of Interpretation: Provides final bottom of hole location with reference to surface location. It also provides information of possible trouble spots in running pipe, or wear problems during pumping.

Logging Rate: Continuous or station stops

Borehole Restriction: Uncased hole if magnetic referenced, ≥3 inches diameter

Maximum Advertised Temperature: 315°C (600°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 1 3/4 inches

Cost \$860

TOOL: DRILLING TIME LOGS

Used With: First log recorded on a well

Parameters: Rate of drill penetration, tripping, and other time spent with drill off bottom

Principles of Operation: Automatic recording of each foot of drill penetration on a time actuated chart. Other logs are often maintained during drilling that can provide valuable information on bore hole parameters. These often include hook load vs. time, hole size; torque vs. time; rotation speed vs. time; mud log vs. time and a record of "ditch samples," i.e., cuttings from the return circulation vs. hole depth.

Principles of Interpretation: Rates of drill penetration over short intervals are rather uniform; this permits any gross change in penetration rate to be interpreted as a formation boundary.

Logging Rate: While drilling

Borehole Restrictions: None

Volume Investigated: Formations section in the bore hole

TOOL: DRILL STEM TEST TOOLS

Used With: On the drill string

Parameters: Fluid samples, pressure, permeability

Principles of Operation: Simulates the conditions of the completed well by sealing off the test interval from the mud column above and reducing the pressure opposite the formation to atmospheric. This allows the formation fluids to enter the bore hole and be produced through the drill pipe. It amounts to a temporary completion of the well.

Principles of Interpretation: By the addition of pressure recorders, shut-in valves, thermometers, and a choke, much additional information is obtained such as bottom hole pressure, transient pressures, flow rates, bottom hole temperatures, and pressure recovery rate.

Logging Rate: Stationary

Borehole Restrictions: Suitable packer location, mud conditioning and safety precautions to prevent blow-out

Volume Investigated: Formation fluid

TOOL: FLOW METERS

Used With: Temperature, collar locator, manometer, gradiomanometer

Parameters: Flow rates and source areas or injection areas. Location of thief zones.

Principles of Operation: Flow meters can be spinner type, pitot tube, orifice type, and hot-film type, depending on flow rates. Very low rates are best determined by using radioactive tracers. Two phase flows require gradiomanometer surveys.

Principles of Interpretation: Fluid movements are indicated by pressure changes, temperature shifts, spinner rotation and dissipation, concentration, or arrival times of tracers.

Logging Rate: Stationary

Borehole Restrictions: 2 inches diameter

Volume Investigated: Borehole fluids

Minimum Tool Diameter: 1 11/16 inches

Cost: Depends on type

TOOL: FLUID SAMPLER

Used With: Alone

Parameters: In situ fluid properties, permeability and formation pressures and temperatures

Principles of Operation: A closed container is positioned at the desired depth and isolated from the bore hole fluid by packers or side wall seals. In situ pressures and temperatures are measured and container valves are opened to admit fluid; then valves are closed and the container is returned to the surface with the fluid sample.

Principles of Interpretation: Fluids are removed for laboratory analysis. In situ properties are then calculated based on measured temperatures and pressures.

Logging Rate: Stationary

Borehole Restrictions: Cased, or uncased with suitable sealing to the side wall;

4 3/4 inches diameter minimum

Volume Investigated: 4 gallons of fluid from near bore hole wall

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 3 13/16 inches

TOOL: FORMATION SAMPLERS (SIDEWALL CORING)

Used With: Alone

Parameters: Porosity, permeability, mechanical properties, heat conductivity, electrical resistivity

Principles of Operation: Hollow bullets are fired into the walls and retrieved with small formation samples (1 inch x 2½ inch) inside. The mechanical slicer cuts a 1 inch triangular section 3 feet long from the wall. Four 3 foot slices are possible per trip while as many as 60 single bullet samples may be taken each trip.

Principles of Interpretation: Samples are taken to a core laboratory for analyses. Bullet samples are not readily taken from hard formation and are usually fractured. The mechanical slicer produces less altered samples at a much slower rate but will operate in hard formations. Core samples from the hole bottom can be taken during drilling.

Logging Rate: Stationary

Borehole Restrictions: Gun (soft), 4 inches diameter

Volume Investigated: Shallow wall rock sample 1 inch to 2½ inches

Maximum Advertised Temperature: 220°C (430°F) for gun

Maximum Pressure: 20,000 psi

Minimum Tool Diameter: 4 3/4 inch gun

Cost: \$600 + \$28 per core (bullet sampler)

TOOL: GRADIOMANOMETER

Used With: Collar locator, manometer, thermometer, caliper, flow meter

Parameters: Two phase fluid flow, slippage (difference in vertical velocities of light and heavy phases) volumetric flow rate from each zone for two phase flows.

Principles of Operation: Measures the average pressure gradient over a two foot interval using two high resolution pressure sensing elements (e.g., bellows). Dynamic range of 0 to 1.6 gr/cm² per cm with a repeatability of .005 gr/cm² per cm and sensitivity accuracy of .03 gr/cm².

Principles of Interpretation: Slippage velocity must be evaluated to determine the contribution of each flow zone from pressure gradient and flow data. Slippage velocity cannot be calculated using well production and pressure gradient data; it should be based on mixture composition and density difference assuming bubble flow. Errors caused

by this assumption will be low if the flow rate is not small.

Logging Rate: 50 ft/min maximum; stationary readings desirable

Borehole Restrictions: 2 foot interval of bore hole fluid, 2 inch diameter

Maximum Advertised Temperature: 175°C (350°F)

Maximum Pressure: 15,000 psi

Minimum Tool Diameter: 1 11/16 inches

Cost: \$860

TOOL: GRAVITY METER, DOWNHOLE

Used With: Alone

Parameters: Density, porosity, presence of hydrocarbons behind casing

Principles of Operation: The difference in gravitational attraction between any two stations in a bore hole is measured using a sensitive mass balance and recording system.

Principles of Interpretation: The gravity gradient between two points below the earth's surface is a function of the free air gradient and the mass of material between the points. Gradient and distance between the points can be used to derive average bulk density.

Logging Rate: 12 to 24 hours for complete survey

Borehole Restrictions: 5½ inches diameter

Volume Investigated: Very large cylindrical volume

30 foot spacing 300 foot diameter x 30 feet

50 foot spacing 500 foot diameter x 50 feet

100 foot spacing 1000 foot diameter x 100 feet

TOOL: MAGNETIC SUSCEPTIBILITY LOG

Parameter: Lithology, correlation

Principle of Operation: The magnetic susceptibility of a magnetic flux path between a transmitter coil and one or more receiver coils is changed by the proximity of the materials in the bore hole walls. Changes in this magnetic susceptibility in the flux path change the signal at the receiver coil.

Principle of Interpretation: Rocks vary widely in magnetic susceptibility, so that a correlation of the measured downhole magnetic susceptibility with laboratory tests allows the detection of different kinds of subsurface rocks.

Borehole Restrictions: Uncased hole

Volume Investigated: Small

Comments: The difficulties in using this log are such that it is seldom used. Its use is primarily confined to mineral exploration.

TOOL: TEMPERATURE LOG

Used With: Temperature modules can be run alone or combined with other tools.

Parameters: Absolute and differential temperatures, cement top location

Principles of Operation: A temperature sensitive element such as a thermocouple, resistance wire, thermistor, or a confined fluid or metal is calibrated and used to generate signals that are recorded at the surface or downhole as temperature vs. depth.

Principles of Interpretation: A temperature anomaly from the normal gradient established uphole indicates fluid movement within the bore hole. It indicates a producing zone or an injection zone, or the flow of fluids between two zones. It provides information in injection and production profiles and may indicate a source of gas due to expansion cooling.

Logging Rate: 65 ft/min maximum

Borehole Restrictions: 2 inches diameter

Volume Investigated: Bore hole and immediately behind casing, or in the cement bond behind the casing.

Maximum Advertised Temperature: 315°C (600°F)

Maximum Pressure: 30,000 psi

Minimum Tool Diameter: Probe diameter 7/8 inch

Cost: \$780

Appendix B

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Appendix C

PERSONS CONTACTED AND THEIR AFFILIATIONS

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