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SENSOR APPLICATION SURVEY

Technical Report. Task I

Work Performed Under Contract No. EY-76-C-02-4082

Westinghouse Electric Corporation
Pittsburgh, Pennsylvania

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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1. SUMMARY

Task 1 is a survey of well logging instrumentation undertaken to determine to what extent various tools can make use of severe environment acoustic sensor technology. The major goal was to establish the most appropriate tool for Task 2 - Sensor Development and Optimization. Subject tools are borehole televiwer (BHTV), acoustic caliper, acoustic velocity logger, down hole flow meter (DHFM), and passive listening monitor. This report describes the investigation of tool capabilities, applications, operation, and limitations under present and anticipated geothermal conditions. The results of Task 1 suggest that development of a combination BHTV/Caliper tool would have the most favorable impact on improved geothermal well logging capabilities. Of nearly equal significance is DHFM. Acoustic velocity logger and passive listening devices are viewed as playing an important but lower priority role in geothermal resource characterization and development.

All Task 1 objectives have been met and it is expected that Task 2 can begin without delay.

2. INTRODUCTION

The Geothermal Well Logging Sensor program is part of a more extensive ERDA effort to insure availability of adequate well logging tools necessary for assessment and development of geothermal resources. The need for extending the hostile environment capabilities of existing well logging tools and for developing new methods where necessary is identified in a report¹ addressing geothermal measurements. In this report, of the eight parameters considered to be essential for evaluation of most geothermal resources, traditional measurement tools either require or could make use of acoustic sensors: flow rate, fracture system (televiewer), and formation depth and thickness. Of the six additional important physical parameters, severe environment acoustic sensors can aid in measuring three: lithology and minerology, P and S wave velocity, and hole size (acoustic caliper).

Westinghouse has undertaken a program to upgrade severe environment acoustic sensor performance as part of the overall effort to improve well logging instrumentation for geothermal resource development. The program consists of three tasks. Task 1 is a survey of existing logging instrumentation and existing tool needs and deficiencies to determine to what extent various tools can make appropriate use of severe environment sensor technology. The data acquired under Task 1 is to provide the technical basis for selecting the sensor type for development under Task 2. Task 2 involves experimental evaluation of materials and configurations which provide optimized performance of the selected sensor type under borehole conditions. Task 3 consists of building and demonstrating the operation of sensors in conjunction with appropriate geological modeling under simulated geothermal borehole conditions.

The primary subjects of this report are the activities and findings of Task 1, conclusions based on Task 1 findings, and suggested approach for Task 2.

¹. L.E. Baker, R.P. Baker, R.G. Huguen, "Report of the Geophysical Measurements in Geothermal Wells Workshop," Sandia Laboratories Energy Report No. SAND 75-0608 (December, 1975).

3. DESIRED PARAMETERS, MEASURABLE GEOPHYSICAL CHARACTERISTICS AND RELATION TO LOGGING INSTRUMENTS

In general, the broad range of seismic methods are among the most versatile of the geophysical techniques. They may be used in various configurations, including surface-to-surface, surface-to-borehole, borehole-to-borehole, and borehole-to-surface geometries. On a large scale, seismic methods can be used to determine spatial geologic relationships (such as structure, stratigraphy, lithology and faulting) and, on a smaller scale, can be employed to locate rock discontinuities, to detect obstacles, and to estimate the elastic parameters of rock materials.

All of the seismic techniques depend on the basic principle of seismic wave propagation, i.e., that an acoustic wave propagating in a medium will be changed (in amplitude and direction) by a change in the elastic properties of the medium. This principle is demonstrated by the simplified example shown in Figure 1. In this figure, a material with elastic properties λ , μ , and ρ^* lies near a layer of another material with slightly different elastic properties. The difference in elastic properties is manifested by a difference in wave velocity V (compressional wave in this case) between the two materials and the borehole liquid. Waves striking the interface between the materials will be altered in direction depending on the angle of incidence α . The three wave paths shown are typical and can be generalized by first considering case two, $\alpha = \alpha_2$. This is known as the critically refracted wave. The angle, α_2 , is known as the critical angle and the wave propagating along the interface is the critical refraction. At angles $\alpha < \alpha_2$, waves will be refracted into the second medium and at angles $\alpha > \alpha_2$, waves will be reflected back into the liquid medium by the interface.

In addition, another wave exists which travels parallel to the surface of the first layer. This wave is known as the direct wave (or mud wave) since it represents the minimum distance path.

* λ = Lamé's constant
 μ = Shear modulus
 ρ = density

Figure 1. Diagrammatic Representation of Seismic Travel Paths in a Borehole

The various methods of seismic or acoustic investigation employ various combinations of these waves. For instance, the refraction method is concerned only with those waves that strike the layer interfaces at the critical angle, $\alpha = \alpha_2$. Reflection surveys are concerned with those waves that are reflected from well defined interfaces. Similarly, acoustic methods are concerned with direct reflected waves, $\alpha = 0$.

Acoustic energy has proven to be very useful in characterizing the rocks in the immediate vicinity of a drill hole. A large arsenal of tools has been developed and used depending on the types of information required. Table 1 is a summary of acoustic logging both presently used and projected for near term development. The frequency range of these tools is summarized in Figure 2. Also shown on this figure is the expected average energy loss due to internal friction. Of the tools shown in Table 1, only four are of importance to rock characterization. These are the Borehole Televiewer, the Acoustic Caliper, the Velocity or Sonic Logger, and the Passive Listener. The other tool, the Flow Meter, is important from a geothermal production viewpoint. Each of these tools is discussed in Section 4.

The feasibility of specifically using acoustic techniques to locate flaws in rock materials has been demonstrated by experiments conducted at U.S. Bureau of Mines test facilities and at the Colorado School of Mines experimental mine.

Optimization of an acoustic tool begins with relating performance characteristics to basic acoustic principles. Acoustic parameter change(s) required to improve a specific aspect of tool performance can then be uniformly applied to the entire system to assess the overall impact. Often, improvement of one feature is at the expense of another. For example, better resolution of small discontinuities is generally achieved by using higher frequency (shorter wavelength) energy; but higher frequencies are attenuated more rapidly and thus provide less penetration. If both resolution and penetration are important, then compromising trade-offs must be established.

Table 1

SUMMARY OF PRESENT AND NEAR TERM ACOUSTIC LOGGING TECHNIQUES

WHAT CAN BE MEASURED?	WHAT ARE THE SPECIFIC PARAMETERS?	WHAT INFORMATION IS OBTAINED?	TOOL
ACOUSTIC PROPERTIES OF ROCKS	VELOCITIES AMPLITUDE ELASTIC MODULII	LITHOLOGY CORRELATION LITHOLOGY IDENTIFICATION POROSITY ROCK "Q" GAS/WATER SATURATION YOUNG'S, SHEAR, BULK MODULII POISSON'S RATIO	VELOCITY LOGGER
ACOUSTIC INTERFACES WITHIN ROCKS	REFLECTION/ TRANSMISSION COEFFICIENTS	ROCK BOUNDARIES LOCATION WALL ROCK FRACTURES WALL ROCK LOCATION MUD CAKE PARAMETERS	VELOCITY LOGGER BHTV SEISMIC-CAL SONIC
ACOUSTIC EMISSIONS FROM ROCKS	AMPLITUDE FREQUENCY RATE	ACTIVE FRACTURING WITHIN ROCK RESERVOIR "NOISES" MAN INDUCED FRACTURING	NEW PASSIVE LISTENING
FLOW	FLUID FLOW PAST LOGGING TOOL	RATE OF INDUCED FLOW AMOUNT OF FLUID LOSS/GAIN AREAS OF FLUID LOSS/GAIN	NEW FLOW METER
HOLE DIMENSIONS	TRANSIT TIME TO AND FROM HOLE WALL	HOLE DIAMETER HOLE ECCENTRICITY	SEISMIC-CAL
SUSPENDED SEDIMENT	AMOUNT OF SOLID MATERIAL IN LIQUID OR GAS STREAM	PERCENT SOLIDS IN STREAM SEDIMENT TRANSPORT STREAM STRATIFICATION	NEW PASSIVE LISTENING

Figure 2. Current Usage of Seismic Transducers for Remote Sensing (Logging) Operations

4. FUNCTIONAL DESCRIPTION AND ANALYSIS OF FIVE LOGGING TOOLS INCORPORATING ACOUSTIC SENSORS

The five acoustic logging tools identified during Task 1 as directly applicable to geothermal exploration, development and production are:

- Borehole Televiewer (BHTV)
- Acoustic Caliper (Seiscaliper)
- Sonic Logger (Velocity Logger)
- Passive Listener
- Down Hole Flow Meter (DHFM)

The applications of each of these tools was discussed in general terms in Section 3. This section will present a functional description of the tools and will identify required development areas and potential geothermal applications based on data acquired under Task 1.

Borehole Televiewer (Figure 3)

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 2.5 MHz acoustic signal is emitted as a pulsed signal. This signal is reflected from the borehole wall and is detected by the transducer. Scattering due to irregularities in the wall geometry varies the amplitude of the received signal. This is represented by intensity variations in the output as displayed on the face of a recording oscilloscope. 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. A typical display is shown in Figure 4.

TOOL:

Borehole Televiever

PARAMETERS:

Sonic Image of
Bore Hole Wall

STATE OF THE ART:

150 ° C
20K psi
3 3/8 Dia.

ACOUSTIC CHARACTERISTICS:

Mechanically Scanned
2.5 MHz Pulses
Power Out Unknown
Single Piezoelectric
Element
Focussed Beam
Window & Coupling Fluid Req'd.

LIMITATIONS:

Slow Logging Rate (600'/hr)
Slip Rings
Centering
Window Materials
Coupling Fluids
Internal Reverberation

DEVELOPMENT CATEGORIES:

Physical Embodiment;
Transducers; Beam Forming;
Internal Reverb Suppression;
Window; Coupling Fluid;
Possible Faster Logging Rate;
Borehole Compensation

Figure 3. Borehole Televiever

Figure 4. Borehole Televiewer Log in Fractured West Texas Precambrian Formation. Wellbore filled with drilling mud. (Reproduced from and with permission of Journal of Petroleum Technology, June 1969. Copyrighted by SPE/AIME.)

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.

Uses: The BHTV has been identified as being useful during all phases of geothermal development. It can be used to map fracture zones, bedding planes and other borehole wall manifestations of the geology. In addition, after casing, the BHTV can be used as an inspection tool to map cavitation, pitting, perforation plugging or enlargement, casing breaches and other production related parameters.

Limitations: Efforts to operate the existing BHTV at temperatures as high as 500°F have been largely unsuccessful to date. Problems with acoustic sensor components range from minor changes needed in methods for attaching wires to piezoelectric elements to major problems in acoustic window materials, possibly suggesting re-evaluating the viability of the present configuration. Other limitations of the present device relate to 1.) the use of slip rings for coupling signals to and from the rotating element, 2.) problems of apparent signal drop-out if probe is not properly centered in bore, 3.) internal coupling fluids, and 4.) internal reverberation. The relatively slow logging rate (~ 600'/hr) has also occasionally been identified as a limitation.

Development Areas: Two general approaches should be considered: 1.) investigate feasibility of hardening existing configuration and 2.) investigate new configurations. Successful hardening of the existing configuration is largely predicated on solving the acoustic window problem. A thin cylindrical shell (~ 1/16 to 1/8 inch thick) of a polyimide ("Vespel" by DuPont) has provided the highest temperature performance to date (~ 480°F). However, even when coated with protective overlays, the reliability of Vespel windows has been far from satisfactory. A combination of severe environment materials and design methods are required for providing an acoustically transparent window with mechanical durability, resistance to chemical attack, and able to contain the internal fluid. Investigation of alternate internal coupling fluids should also be considered.

Of the new configurations it is suggested that two possibilities be investigated: 1.) down-looking element (stationary) with rotating, possibly focused reflector, and 2.) multi-element array with electronic beam forming and possibly steering. While both possibilities have been successfully used in other ultrasonic instrumentation, their performance potential with regard to BHTV must be investigated. In addition, electronic beam forming/steering may require relatively complex downhole electronics. Required development areas common to any of these approaches are 1.) improved suppression of internal reverberation (e.g., high-temperature damping materials), 2.) borehole compensation (less sensitive to centering), and 3.) methods for increasing logging rate. Improved methods for bonding piezoelectric elements to various window and backing materials must also be devised.

It is suggested that a first step toward improved BHTV be a thorough evaluation of the existing device to quantitatively characterize the present acoustic performance under room temperature conditions. This data would be useful for optimization/hardening of the present device and would serve as a meaningful performance comparison (standard) for alternative designs.

Acoustic Caliper (Figure 5)

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 based on round-trip acoustic pulse travel time in the borehole fluid.

TOOL:

Acoustic Caliper

PARAMETER:

Hole Diameter

STATE OF THE ART

80 ° C (Max.)

20 K psi

4 3/4 Dia.

ACOUSTIC CHARACTERISTICS:

High Frequency Pulses

Multiple Transmit/

Receive

Transducers;

Piezoelectric;

Unknown Power;

Scanning

LIMITATIONS:

Temperature

DEVELOPMENT CATEGORIES:

Higher Temperature Transmit

Receive Sensor

2-Way Travel Path

Detection
Threshold

Figure 5. Acoustic Caliper

The acoustic caliper tool is a simplified form of the BHTV in that only the time-of-arrival of returning pulses is used in echo-ranging fashion to determine the distance from transducer to borehole wall. Actually, caliper information is usually available from the BHTV tool if the additional time-of-arrival processing is performed.

Uses: The acoustic caliper would be of particular importance in hydro-thermal deposits where wall rock erosion is significant.

Limitations: There are two basic configurations, each with different limitations. The simplest configuration is a set of non-scanning, discrete sensors which measure sensor-to-wall distances in discrete directions. Practical limitations on the number of sensors tends to limit the hole size and shape information acquired. The scanning configuration is reminiscent of the BHTV and identical limitations are apparent.

Development Areas: The non-scanning embodiment requires multiple discrete sensors in a high temperature and pressure package and incorporating design methods for minimizing internal reverberations. The scanning configuration would require development in those areas identified for the BHTV.

Velocity Logger (Figure 6)

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, two or more similar receiving transducers located various distances from the transmitter. Time of travel (Δt) between receiver and transmitter and/or between multiple receivers is recorded as an inverse velocity. Transmit and receive devices are stationary and are designed to exhibit uniform response in all radial directions and are typically protected from the

TOOL:

Velocity Logger
(Sonic Logger)

PARAMETERS:

Velocities (P, S)
Attenuation (Q^{-1})

STATE OF THE ART

205 ° C
20 K psi
1 1/16" Dia.

ACOUSTIC CHARACTERISTICS:

20-40 kHz Pulses
50-200 Watts Peak Power
Magnetostrictive or
Piezoelectric

LIMITATIONS:

Temperature
Sensitivity
Power Output
Beam Shape

DEVELOPMENT CATEGORIES

Transmit/Rec. Transducer
Window Materials
Piezoelectric Materials
Output & Sensitivity
Performance

Figure 6. Velocity Logger

borehole environment by an elastomer boot. Various acoustic and mechanical isolation features are provided between the transmitter and the receiver to insure that the first arrival signal is the compressional 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 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.

Uses: This log is useful in geothermal applications for indicating gross lithological changes and for calculation of the dynamic elastic properties of the reservoir. These latter parameters are needed for re-injection considerations.

Limitations: The primary sensor limitation of this tool is inability to withstand geothermal temperatures. Another problem common to velocity logging tools is "cycle skipping." This phenomena is usually attributed to insufficient SNR (signal-to-noise ratio) at the receiver(s) and can be traced to several sources: 1.) improper centering, 2.) inadequate transmitter output and/or receiver sensitivity, 3.) operation in conjunction with high loss (low Q) formations.

Development Areas: Velocity logging tools typically operate at frequencies of 20 kHz to 50 kHz with an acoustic source level of 50 to 250 watts. A cylindrical shell of piezoelectric material is commonly used as a receiver. Providing high temperature equivalents of these devices is not expected to be difficult. However, some attention is

needed in the area of upgrading the temperature performance of the protective covering. At these relatively low frequencies, a thin metal window may be practical. Material development programs in ceramic (and other) potting compounds may also be significant. Improved receiver SNR techniques should be considered to reduce sensitivity to centering. It is expected that higher transmitter output and increased receiver sensitivity can be achieved to serve this requirement. It appears that severe environment versions could be designed to directly replace existing sensors without major changes to the overall tool configuration.

Testing was performed on two Velocity Logging tools as part of Task 1 in order to determine acoustic characteristics. Documentation of this testing and results are contained in Appendix I.

Acoustic Flow Meter (Figure 7)

Parameters: Fluid flow, fluid loss or gain, zones of fluid loss or gain.

Principles of Operation: All three types of acoustic flow meters depicted in Figure 4-5 utilize a relatively high frequency broadcast signal. The vortex shedding flow meter transmits a CW signal across the stream. A shedding strut is placed downstream from the transducer. Vortices created by the strut amplitude-modulate the across-stream signal at some shedding frequency, f_s . f_s , which is read from an oscilloscope, can be related to the velocity of flow.

The Doppler flow meter relies on echo-type returns from acoustic scatterers (liquid, solid or gas) in the stream. The system is typically implemented by using a single send/receive transducer which emits CW signals of some frequency, f_o , in a direction not perpendicular to flow direction. These signals will reflect back from particles moving in the stream. The returning signals are shifted in frequency due to the relative motion of the particles and acoustic propagation direction. This shifted frequency, f_d , is known as the Doppler frequency and is a function of stream velocity. An important feature of this method is its inherent lack of sensitivity to particulate and moderate quantities of

TOOL:

Acoustic Flow Meter

PARAMETERS:

Fluid Flow
Net Fluid Loss/Gain
Zones of Loss/Gain

DESIRED CHARACTERISTICS:

Temp. = 275° C (Min.)
Pressure = 7 K psi
Resolution 1 part in 2000
2 Phase Flow Sensitivity
Small Size

STATE OF THE ART LIMITATIONS:

Temp.; Pressure; Accuracy;
Dynamic Range; Size;
Calibratability

DEVELOPMENT CATEGORIES:

Transducers; Packaging;
Electronics;
Calibration

EXISTING TECHNOLOGY:

Doppler; Vortex Shedding;
Travel Time

VORTEX SHEDDING FLOWMETER
Send Receive

DOPPLER FLOWMETER

TRAVEL TIME FLOWMETER

Figure 7. Acoustic Flow Meters

entrained gas. These constituents generally tend to decrease the effectiveness of other acoustic velocity measurement techniques where low attenuation in the fluid is desirable.

The travel time flow meter uses the time difference between upstream and downstream travel to calculate flow velocity. Two transducers are placed in the stream such that one is downstream from the other. The travel time for a pulse moving upstream is subtracted from the downstream pulse. This time difference, along with the speed of sound in the fluid C_o , and the upstream-downstream angle of travel, can be related to the flow velocity.

Uses: The acoustic flow meter logging tool can be used to replace the present spinner tool in severe environments. It can measure flow in open holes and in casing in order to locate thief and source zones of water and to permit mass transport calculations.

Limitations: Present device is a spinner (propeller) tool. Some of the problems with this device are 1.) substantial flow (typically 3-5 ft/min) required to overcome bearing friction, 2.) limited dynamic range ($\sim 20:1$), 3.) siezed bearings at geothermal temperatures, 4.) propellers large enough to be accurate tend to be pushed up (down) hole, and 5.) propellers small enough to stay in place tend to be inaccurate.

Development Areas: First, at least three general approaches exist, 1.) upgrade spinner type by at least improving bearings and optimizing the size vs. accuracy trade-off, 2.) investigate other non-acoustic sensor flow metering methods (e.g., hot-wire anamometer, electromagnetic, etc.), and 3.) pursue an ultrasonic flow meter.

The preferred embodiment for an ultrasonic flow meter is thought to be the Doppler type as its performance can be enhanced rather than degraded by moderate amounts of foreign substances in the geofluid. The sensor technology required for such a flow meter is very similar to that of BHTV and Caliper, all incorporating inherently high frequency devices. Window materials, piezoelectric crystal/window bonding methods, and high temperature damping materials must be incorporated into a package small enough to not appreciably alter the flow or introduce

significant pressure drops. For other less rigorous environments, ultrasonic Doppler flow meter is a relatively well developed technology, especially for biomedical purposes.

Although a suitable sensor for down-hole ultrasonic Doppler flow meter may be provided directly as a spin-off from a BHTV/Caliper development, it is suggested that an appropriate initial step toward down hole flow metering is a review of the potential and relative merits of the other approaches.

Passive Listening Device (Figure 8)

Parameters: Natural microseismic noise, induced fracturing, sediment movement.

Principles of Operation: The passive listening device is basically a single or multi axis transducer element which detects noises originating within the rock mass. The tool itself is mechanically clamped against the borehole wall and allowed to remain stationary during a fracturing or reinjection episode. By recording the axis of motion from a microseismic event, the azimuth can be determined by analysis of first arriving energy, and distance by analysis of the time of arrival differences between P and S waves.

In another application, a strut is placed in the stream of flow and a transducer mounted to the top of the strut. Then, as solid material strikes the strut, the energy of impact is detected by the transducer. By integrating or "counting" impacts, an estimate of solids in the stream can be made.

Uses: These devices are particularly useful in dry-hot rock deposits where mapping induced fractures is important. Also, in hydrothermal reinjection wells where induced seismicity is important, passive listening can be applied.

Limitations: As yet this device has not seen sufficient application for readily identifying deficiencies. Furthermore, limitations are expected to be application-sensitive.

TOOL:

Passive Listening Device

PARAMETER:

Microseismic Noise
(Natural and Induced);
Fracture Mapping

DESIRED CHARACTERISTICS:

Broad Frequency Range,
Temp. 250° C
Pressure 20 K psi
High Sensitivity
Directivity (?)
Small Size

STATE OF THE ART LIMITATIONS

Coupling
Temperature
Pressure

DEVELOPMENT CATEGORIES:

Coupling
Transducers; Packaging;
Frequency & Amplitude
Calibration

EXISTING TECHNOLOGY:

High Temp. Accelerometers

Figure 8. Passive Listening Device

Development Areas: In the few application examples listed, good high temperature performance is mandatory. Also, operating frequencies are relatively low to moderate (1 kHz to 100 kHz). Therefore, it is quite possible that commercial high-temperature accelerometers (e.g., Gulton) would suffice. It is expected that development of this class of devices would more appropriately focus on optimizing 1.) configurations (possibly arrays) of commercial sensors, 2.) coupling between formation and sondes, and 3.) frequency response in conjunction with the various applications. Improved in situ calibration techniques would also be needed under some circumstances.

5. LOGGING TOOL APPLICATION SURVEY - ACOUSTIC SENSORS

An important activity of Task 1 was investigator familiarization with acoustic sensor type logging tools, their operational characteristics and limitations. This was accomplished by visits with various organizations involved in manufacture and/or use of such. Those organizations initially visited were Simplec Co., U.S. Geological Survey - Water Resources, U.S. Bureau of Mines, Los Alamos Scientific Lab., Sandia Labs.

Discussion topics varied, ranging from sensor design and construction to desired performance characteristics of new or improved logging devices. A summary of these contacts follows:

Date: 29 October 1976

- Contacts: 1.) G. Summers, Simplec Manufacturing Co., Inc., Dallas, Texas. Manufacturer of bore-hole televiewer (BHTV), acoustic velocity logger, acoustic caliper; familiar with operational characteristics of acoustic logging tools, limitations, efforts to extend maximum operating temperatures; probes (all three) available for detailed inspection.
- 2.) J. Zemenick, Mobil Oil Research, Dallas, Texas. Co-inventor of BHTV and other acoustic logging tools; experience includes theoretical, experimental, and field-use aspects of logging instruments.

Discussion: Fracture System (Televiewer). Construction, operation, and field uses of the bore-hole televiewer (BHTV) were addressed in detail. Familiarization with transducer (sensor) characteristics, window materials, electronics, auxiliary devices (magnetometer, scanning hardware, slip-rings, cabling) was accomplished.

Problems of signal-to-noise ratio, interference sources, off-center operation, and difficulties encountered in extending operation of existing tool configuration to 480°F were discussed.

P and S Wave Velocity is conventionally measured in bore holes with the acoustic velocity logger. Principles of operation, transmit and receive sensors, and physical configuration were

discussed in detail. The present device uses a magnetostrictive transmitting device and a stacked array of cylindrical piezoceramic receiving sensors. As no information was available on transmitted sound pressure levels (SPL) and absolute sensitivity of the receivers, tentative arrangements have been made to borrow an acoustic velocity logger from USGS and measure these characteristics at the Underwater Acoustic Calibration facility ((W) Oceanic Division, Annapolis, Maryland). This data is needed for determining feasibility of extending operation of this device to include geothermal applications.

Hole Size (Acoustic Caliper). Simplec apparently has a low level in-house effort underway to produce a 4-transducer array for sampling bore-hole size in 4 azimuthal directions 90° apart. It is uncertain what the eventual maximum service temperature will be.

Date: 1 November 1976

Contacts: A. Hess, (USGS-Water Resources Div.), J. Scott, (U.S. Bureau of Mines), Denver Federal Center, Denver, Colorado. Owner/users of assorted well logging tools including BHTV, acoustic velocity logger, etc.; experienced in geothermal applications and related tool deficiencies.

Discussion: BHTV was discussed from user standpoint. Typical field results (print-out) were examined and problems of sensitivity to centering and deficiencies in elevated temperature operation were discussed. An unsuccessful attempt was described for improving the Vespel window by a thin coating of aluminum. BHTV is viewed as an extremely important tool for geothermal applications.

Flow Rate measurement requirements were discussed briefly. Presently used devices potentially suited for geothermal applications exhibit a minimum response of ~ 5 ft./min. Rotary vane or turbine types were specifically mentioned. Extension of capabilities down to 0.1 ft./min. is desirable. Additional

investigation is needed in order to further define geothermal flow meter requirements and to examine state-of-the-art of acoustic flow meter devices. The extensive experience of (W) Research Sonic Technology in acoustic flow meters will aid in further analysis of this measurement concept.

Down-Hole Passive Listening instrumentation was identified by USGS and USBM personnel as a potentially valuable addition to the list of geothermal well logging tools. Conceivably, severe-environment sensors could be used to measure acoustic signals from audio through ultrasonic frequencies to learn more about down hole natural and induced activities. While down hole experimentation would be required for determining the full range of uses, one specific potential application is already evident; such a device could be used to aid in monitoring the spawling of rock chips from fracture surfaces as geothermal extraction fluids are circulated.

Hole-to-Hole Transmit Time measuring devices were also mentioned. The exact nature of the parameters measurable by this technique are unclear as yet. It is expected that the general concept is related in part to determining formation depth and thickness.

Contact: Los Alamos Scientific Laboratory

Location: Geothermal Energy Group
Los Alamos, New Mexico

Date: 6 December 1976

Persons A. G. Blair
Contacted: L. Aamodt
B. Dennis
J. Albrecht

Purpose: Discuss experimental geothermal work.

Discussion: At the Hot Dry Rock (HDR) Geothermal Project at Fenton Hill of Valles Caldera, a hole has been successfully drilled into hard crystalline rock at a depth of ~ 3 km (10,000 ft.) where bottomhole temperatures are about 200°C. and 400 bar (5800 psi) pressures exist. This hole was cased and pressurized to produce a fracture zone and a second hole was drilled to intercept the fracture, providing for fluid communication and circulation.

Activities have concentrated on characterizing the system with an eventual goal of demonstrating operation of a top-side 10 MW (Thermal) heat exchanger in a fluid circulation system.

The primary acoustic instrumentation problem discussed was fracture mapping. Fracture mapping involves determining fracture orientation and extent. The method devised for solving this problem involves a downhole microseismic probe basically consisting of 3-geophones (velocity sensors) whose directional axes are mutually orthogonal. The probe is accurately located in the bore hole in the vicinity of the fracture and microseismic signals emitted by the fracture process are monitored during fracture growth.

Distance (range) of the microseismic event is determined by relative arrival times of P- and S-wave components. Direction (bearing) information is determined according to vectors inferred by the output amplitudes and polarities (phases) of the three mutually orthogonal sensors. Microseismic signals have been observed up through ~ 4 kHz with a general maximum level at ~ 600 Hz. It was not clear if this is an intrinsic spectral characteristic of the fracture process or is the result of the various electrical and mechanical transfer functions of the sensor system.

In addition to the basic concept, means for coupling the probe to the bore hole wall were discussed. The present probe uses a cantilever arm which is motor driven against the bore hole wall thereby pressing the probe against the opposite side. A significant problem mentioned was lack of testing to determine

the effective coupling transfer function between the formation and the 3 orthogonal sensors within the probe when using this contact method. Lacking this data, it may be difficult to accurately correlate sensor output with absolute formation motion thus introducing uncertainties in the three components comprising the vector for the displacement event.

Another problem discussed was the temperature limitation ($\sim 200^{\circ}\text{C}$) of the present geophone sensors. For higher temperatures, high temperature accelerometers are being considered. This appears to be a good solution although it probably requires redesign of downhole electronics.

Usefulness of the bore hole televiewer (BHTV) was again underscored by Los Alamos investigators and again problems of reliability at 200°C were mentioned.

Various sonic echo ranging and through-transmission (pitch-catch) methods were also identified as important for surveying surrounding geological features and to aid in fracture mapping. Ideally, fracture mapping should be performed from one bore hole as this information would be used in part to direct drilling of other fracture-intercepting holes.

A report¹ is available describing the Los Alamos HDR project in detail.

¹A.G. Blair, J.W. Tester, J.J. Mortensen, "LASL Hot Dry Rock Geothermal Project," Los Alamos Scientific Lab Progress Report #LA-6525-PR, (October, 1976).

Contact: Sandia Laboratories
Location: Albuquerque, New Mexico
Date: 7 December 1976
Persons: L.E. Baker
Contacted: C.R. Hickam
Purpose: Discuss geothermal instrumentation under development there.

Discussion: The need for downhole flow meters was discussed. Such flow meters are needed for mapping source and thief zones in the well for example. Ideally, a device sensitive to variations of a few cfm out of a total flow of ~ 7000 cfm (6-8 inch diameter hole) is desired. Devices presently under consideration are 1.) vortex shedding types, 2.) rotary vane (propeller, turbine) types, and 3.) methods involving injection of tagging substances into the flow.

The possible existence of 2-phase flow downhole was also suggested. This potential problem has an effect on practically any downhole acoustic instrument which interacts with the fluid or relies on the fluid for coupling to the formation. The existence of gas bubbles in a liquid causes excessive acoustic losses and reverberation due to scattering. Generally, this problem is more pronounced at higher sonic frequencies such as those typically used for BHTV and acoustic caliper. However, even for low frequency instruments, design methods must be provided to prevent an accumulation of gas on critical acoustic surfaces, thereby degrading performance. Dissolved gas is not expected to be so great a problem.

A Quartz Resonator Pressure Transducer (QPT) was also discussed as it relates to acoustic sensors to some degree. The stress dependent effect on the resonant frequency of piezoelectric quartz crystals is well known and a particularly useful pressure-sensing embodiment is described in the literature.² A commercial

2. H.E. Karrer, J. Leach, "A Quartz Resonator Pressure Transducer," IEEE Transactions on Industrial Electronics and Control Instr., Vol. IECI-16, No. 1, (July, 1969).

well bore pressure gage is available (Hewlett-Packard Model 2811B) based on this configuration. Geothermal investigators at Sandia wish to use this device under geothermal well conditions and are concerned with performance of the quartz resonator and crystal electrodes at temperature.

The operating temperature range specified by the manufacturer is 0 to 150°C. Some questions were raised regarding use of higher temperature piezoelectric materials as resonators. A review of the operating principles of the device reveals that it contains two such quartz resonators, one exposed to temperature and pressure and the other just to temperature. They are jointly used in a differential configuration which should produce an output strictly related to pressure.

In principle then, this sensor should operate up to temperatures approaching the Curie Point for quartz, above which the piezoelectric effect ceases. The Curie temperature for quartz is 576°C corresponding to the α - β transition point. Unless the static strain sensitive characteristics are lost at geothermal operating temperatures ($\sim 275^\circ\text{C}$) it is expected that quartz is an acceptable sensor material and that only problems of electrode diffusion into quartz need be addressed.

Toward the end of Task 1, the survey began to focus on hydrothermal activities in accord with priorities established by ERDA. Five organizations engaged in hydrothermal projects were contacted and visited: Idaho National Engineering Labs, Lawrence Livermore Labs, Chevron Oil Co., Union Oil Co., U.S. Bureau of Reclamation (East Mesa Test Site). The primary objective of these visits was to determine how severe environment versions of the five identified acoustic sensor tools relate to present and anticipated future logging problems of hydrothermal investigators.

Framework for discussion was provided by a hand-out describing operating principles and characteristics of the five subject tool types. Following this discussion, those present were asked to associate their logging problems with these tools. Priorities were established by asking which tool would solve their most critical problem(s). A summary of the results is shown below:

<u>ORGANIZATION</u>	<u>PRIORITY</u>	
	<u>1st</u>	<u>2nd</u>
Idaho National Engineering Lab.	BHTV/Caliper	Downhole Flow Meter
Lawrence Livermore Lab.	2-phase surface or single phase downhole flow meter	BHTV
Chevron Oil Co.	BHTV/Caliper	Downhole Flow Meter
Union Oil Co.	BHTV/Caliper	Downhole Flow Meter
East Mesa Site	Downhole Flow Meter	BHTV

The following pages contain a summary of the information acquired at each organization.

ORGANIZATION: Idaho National Engineering Labs.
550 Second Street
Idaho Falls, Idaho 83401
(208)-522-6640

DATE: 24 February 1977

CONTACTS: L. Miller - x 1781 (talked to by phone only)
S. Prestwich - x 1877
R.C. Stoker - x 1877

MAJOR ACTIVITY AREA(S):

Hydrothermal resource exploration and characterization at Raft River Project, et al.

DOWN HOLE ENVIRONMENT:

Temperature 80°F-350°F; 2500 psi @ 5000-6000' Depth; 2K ppm dissolved solids; liquid dominated system; hole sizes: 6" Dia. (Min.), 8", 10" Dia.

APPLICATIONS DISCUSSED FOR ACOUSTIC SENSOR TYPE LOGGING TOOLS:

1. Downhole flow meter is needed for measuring 800-1200 GPM flow in 10" dia. pipe; 10 GPM resolution would be satisfactory; desired sensitivity threshold ~ 10 GPM. Presently use spinner type; problems with seized bearings, sensitivity threshold too high.

2. Bore hole televiewer/Acoustic Caliper (combination) tool highly desirable for locating and characterizing production zone. Acoustic caliper viewed as major improvement over mechanical type because 1.) can measure wider range of hole sizes, 2.) provides cross-section shape of hole and useful for correlating with televiewer output.

OTHER PERTINENT INFO:

Satisfactory characterization of production zone now typically requires the following logging: Caliper (mechanical), Temperature, Gamma, Neutron, SP, Resistivity, Acoustic Log. It was estimated that nearly all of the most important production zone mapping and characterization could be provided with a good BHTV/Caliper and Flow meter.

PRIORITIES:

1. BHTV/Caliper
2. Flow meter

ORGANIZATION: Lawrence Livermore Labs.
P.O. Box 808
Livermore, California 94550
(415)-447-1100

DATE: 28 February 1977

CONTACTS: A.L. Austin - x 3946
L.B. Owen - x 4124
C. Crowe
T. Alger

MAJOR ACTIVITY AREA(S):

Investigation of total (geofluid) flow concept. Steam (10-40%) extracted, processed, passed through axial flow impulse turbine, re-injected.

DOWN HOLE ENVIRONMENT:

Temperature 300°C-370°C; 3000-7000 psi; 150K-300K ppm; Acidic/ Chlorides (50%); down hole pH ~ 4-4.5; reinjection well ~ 100°C. 2-phase flow in formation region, single (liquid) phase on reinjection side.

APPLICATIONS DISCUSSED FOR ACOUSTIC SENSOR TYPE LOGGING TOOLS:

1. Need method for measuring mass flow rate of 10-40% quality steam, not necessarily downhole; 5% accuracy.
2. BHTV predominantly for casing inspection on reinjection side where clogged perforations and casing damage must be detected.
3. Sediment transport measurement device for indicating approximate flow of particulate (1 μ m $\rightarrow$ 1/32" Dia.) through piping.

PRIORITIES:

1. Flow meter (2-phase flow on inlet side).
2. Flow meter (liquid, downhole for reinjection flow mapping).
3. BHTV (reinjection side).
4. Passive listening device for sediment transport indication.

ORGANIZATION:

Chevron Oil Company
P.O. Box 3722
320 Market Street
San Francisco, California 94119
(415)-894- (BELOW)

DATE:

1 March 1977

CONTACTS:

L. Mann - 4141
W.S. Campbell - 0268
D.R. Butler - 3590

MAJOR ACTIVITY AREA(S):

Geothermal (hydrothermal) resource development throughout western U.S.

DOWN HOLE ENVIRONMENT:

Temperature ~ 550°F; 4,000-5,000 psi; worst salinity roughly that of sea water; claim cooling logging tools relatively easy by circulating cooling mud.

APPLICATIONS DISCUSSED FOR ACOUSTIC SENSOR TYPE LOGGING TOOLS:

1. Identification and characterization of fractures by BHTV very important to their efforts during resource evaluation phase.

2. Flowmeter (down-hole) is needed for mapping source/thief zones; 5% of total flow resolution; typical production well ~ 1500 gpm (500K #/hr.). Presently use spinner types which are pushed up borehole when large enough to be accurate and are too inaccurate when small enough to stay in place.

PRIORITIES:

1. BHTV/Caliper
2. Down-hole flow meter

ORGANIZATION: Union Oil Co. of California
Union Oil Center
461 S. Boylston Street
Los Angeles, California 90017

DATE: 2 March 1977

CONTACTS: C. Otte (213)-486-6260
N.J. Stefanides - 7740
R. Ransom
R. Dondanville

MAJOR ACTIVITY AREA(S):

Hydrothermal resource development including specialized methods for air-drilling and gas discharge treatment.

DOWN-HOLE ENVIRONMENT:

Liquid dominated (mostly); 600°F @ 5000 psi; occasionally gas dominated @ Geysers.

APPLICATIONS DISCUSSED FOR ACOUSTIC SENSOR TYPE LOGGING TOOLS:

1. Borehole televiewer expected to be valuable for fracture characterization and aid in production zone mapping. BHTV/Acoustic Caliper considered especially attractive combination.
2. Down hole flow metering for production zone flow mapping was considered important.

OTHER INFO:

Mentioned lack of instrumentation for checking particulate content in a gas discharge containing moisture and damp particles. They do not believe that many economically significant (under present economics) hydrothermal resources will be located in the future which exceed 600°F and thus consider this a practical upper limit for tool development.

PRIORITIES:

1. BHTV/Caliper
2. Downhole flow meter.

ORGANIZATION: U.S. Bureau of Reclamation
Boulder City, Nevada 89005
(702)-293-2161

DATE: 2 March 1977

CONTACTS: K.E. Mathias (@ East Mesa Test Site/Holtville, Calif.)

MAJOR ACTIVITY AREA(S):

Production and reinjection wells being used primarily for investigating fluid reinjection process.

DOWN HOLE ENVIRONMENT:

Production and reinjection formations typically sand/clay without fractures; 370°F @ 6000' and 396°F @ 8000'; Salinity 2.5K to 25K ppm; 2300-2400 psi @ 6000' (shut-in pressure); Casing 7-5/8", 9-5/8" Diameter.

APPLICATIONS DISCUSSED FOR ACOUSTIC SENSOR TYPE LOGGING TOOLS:

1. BHTV considered important for determining some aspects of casing conditions for both production and reinjection. Clogged perforations, wall deformation, cracked casing, wall thickness, erosion/corrosion, etc.

2. Down hole flow meter is needed for mapping flow profiles in both production and reinjection wells. 100-400 gpm (typical) on production side, with 600 gpm (max.) @ reinjection side (180°F @ surface). Flow rates for 7-5/8" pipe.

3. Several triaxial geophone stations are buried (20') and FM radio telemetered to central data recorder/logger for seismic monitoring of test site. A form of the Passive Listening Device was discussed as a means for providing improved sensitivity at higher frequencies and methods for reducing unwanted cultural noise were discussed.

OTHER INFO:

Due to mechanical instability of sand/clay formation in this region, wells are cased as soon as possible to prevent wall collapse. As such, logging tools only suitable for uncased wells are of little interest.

Mr. Mathias also provided copies of three reports:

"The Mesa Geothermal Field - A Preliminary Evaluation of Five Geothermal Wells" - K.E. Mathias

"Future Well Testing and Injection at the East Mesa Field" - K.E. Mathias

"Geothermal Resource Investigations @ East Mesa Test Site - Status Report" - Bureau of Reclamation.

PRIORITIES:

1. Downhole flow meter
2. BHTV
3. Microseismic Passive Listening Device (Detector)

6. DISCUSSION

One approach to selecting the most appropriate tool for development is to evaluate each tool under various categories, and arrive at a resulting priority list. At one point in Task 1 this method was attempted but results appeared questionable. The categories were 1.) tool importance, 2.) developability (relative estimated probability of success), 3.) number of unknowns (e.g., specific functional design requirements, etc.). The major problem with this evaluation method appeared to be in selecting the weighing factors used to reflect the significance of each category. Assigning weighing factors appeared to be somewhat arbitrary and subjective and had a significant impact on resulting rank ordering. It is also believed that the input data was too coarse for making such a sophisticated evaluation process valid.

The process has been reconsidered and simplified to focus on what is believed to be the most significant factor-user priorities.

LOGGING TOOL USER PRIORITIES have been established by asking those contacted which (acoustic) tool would solve their most significant problem(s) and so on. A table has been prepared summarizing the priorities expressed by various sources.

Table 2
Expressed Priority Summary

<u>SOURCE</u>	<u>PRIORITIES EXPRESSED</u>				
	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#4</u>	<u>#5</u>
1. U.S.G.S. - Water Resources	BHTV	AVL	DHFM	PL	
2. U.S.B.M.	BHTV	AVL	DHFM	PL	
3. Sandia	DHFM	AVL			
4. Los Alamos	BHTV	PL	AVL	DHFM	CAL
5. Idaho Nat'l. Engr. Labs.	BHTV/CAL	DHFM			
6. Lawrence Livermore Lab.	DHFM	BHTV			
7. Chevron Oil Co.	BHTV/CAL	DHFM			
8. Union Oil Co.	BHTV/CAL	DHFM			
9. East Mesa Test Site	DHFM	BHTV	PL		

Blanks reflect no specific preference.

BHTV = Borehole Televiewer
 BHTV/CAL = BHTV in combination with Acoustic Caliper
 DHFM = Down Hole Flow Meter
 AVL = Acoustic Velocity Logger
 CAL = Acoustic Caliper
 PL = Passive Listening Device

Without exception, the first priority column identifies BHTV (or BHTV/CAL) or DHFM .

Hydrothermal investigators consistently identified BHTV (or BHTV/CAL) and DHFM as the two highest priority tools. Other sources identified other tools as second priority.

Drawing meaningful conclusions from these data requires establishing certain qualifying assumptions. The following is a list and explanation of the specific assumptions used by the project investigators.

1. The most significant input is from sources involved in hydrothermal activities (1, 5, 6, 7, 8, 9). This assumption is made in response to current near-term ERDA priorities.

2. Validity of input data is a function of the priority with the #1 priority column considered to be the most valid and the #5 priority data of little significance. It became evident during the survey that those interviewed would often have increased difficulty in ranking of progressively lower priority tools. Blanks in the table indicate low interest or no meaningful preference in non-high priority tools.

PROBABILITY OF SUCCESS in developing high temperature sensors for any of the five subject tools is believed to be high. Supporting this statement is the fact that for each development area identified in Section 4, one or more potentially applicable technologies or methods can also be identified. The major difference from one tool to another is the variation in total number of system elements requiring severe environment development effort and the relative ease or difficulty anticipated in incorporating improved sensors into various tools. As such, BHTV/Caliper is potentially the most complex to develop. On the other hand, it may be a much less involved effort if attempts at hardening the existing configuration are successful.

7. CONCLUSIONS AND RECOMMENDATIONS

Using the assumptions listed, the survey data suggest that development of a severe environment BHTV would provide the most beneficial effect on geothermal well logging in general and would be especially appropriate for hydrothermal activities. BHTV relates to a wide range of down hole geothermal problems and its impact ranges from a major improvement over existing methods (or alternatives) to representing the only foreseeable means for acquiring certain data (e.g., fracture details of number, size, shape). The recommended configuration is a combination televiwer and acoustic caliper (BHTV/Caliper). This combination has obvious functional advantages and it is expected that basic acoustic data for both measurements can be acquired by a single sensor type. Thus, incorporating caliper capabilities essentially involves signal processing variations only.

The results of Task 1 also indicate that BHTV is probably the most complex candidate tool and therefore its development is believed to be potentially the most involved. The relative difficulty relates to 1) the wide variety of acoustic components comprising the present tool (T/R sensor, internal coupling fluid, acoustic window, damping materials, etc.) and 2) the relatively high frequency, short duration pulses used (~ 2.5 MHz) and 3) the multitude of peripheral components and devices which may require direct interfaces (e.g., scanning motor, slip rings, probe-case).

The Task 1 survey also revealed that of nearly equal importance is the need for a suitable downhole flow meter (DHFM). While the importance of DHFM is evident, the potential of non-acoustic flow metering techniques should be further assessed before making final commitment toward acoustic DHFM development.

While the original thrust of the Task 1 survey was in tools for resource characterization, it soon became apparent that there is already an urgent need for similar tools required for solving existing problems associated with injection of geofluids and general monitoring and maintaining experimental geothermal installations. Successful development

of BHTV/Caliper and Flow meter (DHFM) would have a major impact in these areas as well. Flow mapping in injection wells turns out to be nearly as important as in production wells. BHTV/Caliper was consistently identified as an important tool for its potential capabilities of examining (in-situ) casings for damage, searching for occluded perforations, etc.

Acoustic Velocity Logger (AVL) and Passive Listening (PL) appear to be tools for solving lower priority geothermal resource characterization problems. Nonetheless, development of severe environment configurations would be a significant contribution to upgrading geothermal well logging capabilities.

These conclusions relate to an overall development effort approach. The highest priority tools all require relatively high frequency sensors (BHTV/CAL, DHFM) while the lower priority tools would make use of relatively low frequency devices. As such, solving the highest priority problems to a major extent would involve basically similar technology. Likewise for the lower priority problems.

Based upon the preceding discussion it is recommended that Task 2 (Sensor Development and Optimization) should initially focus on high frequency sensors suitable for BHTV/CAL (and DHFM if necessary). Five Task 2 initial program elements have been suggested in order to provide the input needed for confining the development effort to the most appropriate embodiment and identify those specific sensor features which require improvement:

1. Measure performance characteristics of present embodiment of BHTV. Ideally, performance of the geothermal BHTV would equal or exceed the present device. As such, this data is necessary as design evaluation criteria. This element should be scheduled early enough to make the analytical work maximally relevant. Through prior contact with USGS, it appears that their BHTV can be made available for such evaluation testing.

2. Analytical investigation of the potential of at least three possibilities: a) harden existing configuration, b) down-looking element (stationary) with rotating, possibly focused reflector, c) multi-element

array with electronic beam forming/steering. Extensive computer programs developed by Westinghouse for analysis of complex transducer configurations can be applied directly with minor modification to study basic capabilities and parameter effects on optimum configurations. This element will help establish concept feasibility, establish parameter/performance relationships, and further define individual areas of required development.

3. Relate the three above possibilities and analytical results to anticipated tool performance and implied tool configurations. Accomplishing this element will involve additional discussions with tool manufacturers (e.g., Simplec) and those involved with geothermal applications of BHTV (e.g., USGS). Dialogue with these organizations has been established during Task 1. Early and frequent contact with contractors involved in severe environment circuitry development is viewed as critical. This element is intended to aid in keeping optimization trade-offs consistent with performance and manufacturability (implementation) requirements.

4. Establish and/or maintain contact with scientific groups involved in relevant technology developments. Several high-temperature sensor programs are currently underway and several severe-environment materials investigations appear to be potentially applicable.

5. Investigate potential of non-acoustic flow measuring devices which may provide severe environment alternatives to present spinner device. This element should include assessing feasibility of improving the spinner type. It is expected that sufficient feasibility information could be gathered by discussions with application specialists within various commercial flow meter manufacturing organizations. This element appears to be a fundamental part of a decision regarding acoustic DHFM sensor development.

It is apparent that some laboratory experiments should coincide with these elements to 1.) provide key material parameters in support of the analytical work, 2.) begin testing of candidate piezoelectric materials at elevated temperatures, and 3.) begin verifying important results of analytical work.

The Task 1 conclusions and Task 2 recommendations are believed to be consistent with those measurement priorities identified in the 1975 Sandia Geothermal Workshop. Of the eight parameters considered to be essential for geothermal resource evaluation the suggested approach would address flow rate and fracture system (televiwer). Of the six additional important physical parameters identified, the suggested approach addresses hole size (acoustic caliper).

Westinghouse believes that the approach recommended for Task 2 can provide the most significant improvement in geothermal well logging capabilities with the most efficient use of effort.

8. TASK 2 SCHEDULE

A tentative work/manpower schedule is shown for the various initial Task 2 elements. Elements 1, 2, 3, 4, 6 are interactive to varying extents and are thus scheduled concurrently. As element 5 is essentially independent of the others, it is suggested that it be deferred until after August 1977. The manpower estimate reflects an approximate equivalent level of two full-time professional personnel over four calendar months.

Table 3

WORK/MANPOWER SCHEDULE

TASK 2 ELEMENT	MAY 77	JUNE 77	JULY 77	AUG 77	RES. ENGR.	RES. TECH.	INTERDIV TRANSFER	\$ MAT'L
1. Measure Performance Characteristics of Present BHTV	Δ	Δ			1.0 mm	0.5 mm		100
2. Analytical Investigation	Δ			Δ	0.5 mm		2.2 mm.	\$2500 (Computer)
3. Periodic interface with tool users & manufacturers	Δ		Δ	Δ	0.5 mm		0.5 mm	
4. Establish/maintain contact with relevant technology development programs	Δ		Δ	Δ	0.5 mm		0.5 mm	
5. Determine feasibility of non-acoustic DHFM	(BEGIN AFTER AUG. 1977)							
6. Lab Experiments	Δ			Δ	2.0 mm	3.0 mm	0.5 mm	200
				TOTALS	4.5 mm	3.5 mm	3.7 mm	\$2800

APPENDIX I

ACOUSTIC CALIBRATION OF VELOCITY LOGGING TOOLS

GENERAL

Contacts during Task I indicated that the Acoustic Velocity Logger is a frequently used device which works well under normal conditions but users lack information regarding specific acoustic characteristics. As these characteristics relate to 1) better understanding of results and optimum use of the present tool, and 2) design requirements for a severe-environment configuration, tests were planned for experimentally determining certain parameters.

Two tools were made available for testing. A 2" diameter tool (U.S. Geological Survey - Water Resources) and a 1-1/2" diameter unit (U.S. Bureau of Mines).

Transmitter characteristics measured were 1.) launched signal (temporal and spectral response), 2.) power output, 3.) beam shape. The measured receiver characteristics were 1) hydrophone sensitivity, 2) frequency response, and 3) beam shape.

METHODS

Test methods used are schematically indicated in Fig. 9, showing a typical logging tool, a spherical reference source, and a standard reference hydrophone. The hydrophone is a calibrated receiver and is used for evaluating the tool transmitter. The spherical source is used to produce reference pressure waves for evaluating the tool receiving sensors. The two reference devices were scanned vertically for determining beam shapes and locating maximum response directions. Figure 10 is a photograph of the 2" diameter tool suspended over the test tank prior to immersion and testing.

TEST RESULTS

Transmitter Output - Time Domain. Figure 11 shows the time varying waveforms launched by the magnetostrictive transmitters of the two tools. These oscillographs are characteristic of typical broadband, low Q

Fig. 9 — Velocity logging tool test methods

Figure 10. 2" Diameter Tool Suspended Over Test Tank Prior to Immersion and Testing.

Signal launched
from 2" diameter
tool.
50 μ sec/horiz. div.
5 Volts/vertical div.

Signal launched
from 1-1/2" diameter
tool.
50 μ sec/horiz. div.
5 Volts/vertical div.

Figure 11. Launched Pressure Waveforms for 1-1/2" and 2" Diameter Tools.

(electro-mechanical) emitters with rapid rise and fall envelopes. It is apparent from Figure 11 that the 2" diameter tool exhibits somewhat higher output and contains lower predominant frequencies than the 1-1/2" diameter tool.

Transmitter Output-Frequency Domain. The signals of Figure 11 were also processed through a narrow band (1 KHz) filter with variable center frequency. The absolute power output of the transmitter as a function of frequency can be determined in this way. For the 2" diameter tool, center frequency of the narrow band filter was varied from 20 KHz to 40 KHz at discrete 1 KHz increment. For the 1-1/2" diameter tool, the examined frequency range was 20 KHz to 60 KHz increments. The data has been reduced to provide a Transmitted Sound Pressure Level (SPL) vs. Frequency plot in the maximum output direction for both tools as shown in Figure 12. The two plots quantitatively show the amplitude and frequency differences which are qualitatively apparent in Figure 11.

Transmitter Beam Shape was measured for the purpose of estimating the directivity of the emitters so that acoustic power output of the tools could be established. The beam shapes were measured at respective maximum output frequencies and were determined by scanning the receiving (reference) hydrophone over a range of angles with respect to the maximum output direction (acoustic axis). Figures 13 and 14 show the measured beam patterns and cursory tests (tool rotation about its longitudinal axis) indicate that the beams shown are essentially symmetrical about the longitudinal axis of the tools. It is emphasized here that these patterns are for far-field (Fraunhofer zone) radiation and may not be representative of near-field (Fresnel zone) pressure distributions at a typical bore hole interface. The beam patterns show the -3dB (half-power) beamwidth of the 1-1/2" diameter probe is $\sim 1/2$ that of the 2" diameter probe. This is not surprising as the aperture (in the longitudinal direction) for both tools was approximately the same while the predominant output frequency of the smaller diameter tool was higher.

Fig. 12 — Transmitted SPL vs. frequency for 1 1/2" and 2" diameter tools

Figure 13. 2" Diameter Probe Transmit Beam

Figure 14. 1-1/2" Diameter Probe Transmit Beam

Transmitter Power Output, based upon directivity indices estimated from beam patterns are between 50 and 250 watts (acoustic).

Receiver Sensitivity. Figure 15 shows the relative response of the three receiving hydrophones as a function of reference source depth for the 2" diameter tool. The increase in sensitivity evident for sensors successively farther from the transmitter (T) is consistent with standard tool design practice (increases in electronic amplifier gains) to account for compounded signal attenuation expected through additional formation. Some difficulties were encountered in making similar measurements on the 1-1/2" diameter tool.

USGS provided measurements to determine overall tool electrical gain from the receive sensors to the output of the surface package. By accounting for the gains of the other signal processing devices used for these measurements and calculating the sound pressure levels produced at the receivers by the spherical source, absolute receiver sensitivities can be calculated. Absolute receiver sensitivity is normally specified in the maximum sensitivity direction and is called free-field voltage sensitivity (FFVS). It is approximately -215 dB re 1 Volt/ μ Pascal. This means that the receiver sensor output is approximately 1.8×10^{-11} volts when exposed to a sound field pressure of 10^{-6} Pascal.

Receiver Sensitivity vs. Depth (USGS Tool)

Tx = 2" Sphere; 60 Volt P - P Drive @ 35 kHz

Rx = Simplex; #2 Gain Step

Fig. 15 — Receiver Sensitivity (2" Diameter Tool)

APPENDIX II

LITERATURE REVIEW

A low level effort was devoted to literature review via computer data search and other means. Those references which appear to have project relevance are listed in the following bibliography. This activity included contact with manufacturers of high temperature transducer materials and procurement of available physical properties data sheets.

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