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LOGGING TECHNOLGY FOR HIGH-TEMPERATURE GEOTHERMAL BOREHOLES

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ABSTRACT

Research in materials, equipment, and instrument development was required in the Hot Dry Rock Energy Extraction Demonstration at Fenton Hill located in northern New Mexico. Results of this extensive development advanced the logging technology in geothermal boreholes to present state-of-the art.

The new Phase II Energy Extraction System at the Fenton Hill Test Site will consist of two wellbores drilled to a depth of about 4570 m (15,000 ft) and then connected by a series of hydraulic-induced fractures. The first borehole (EE-2) was completed in May of 1980 at a depth of 4633 m (15,200 ft) of which approximately 3960 m (13,000 ft) is in Precambrian granitic rock. Starting at a depth of approximately 2930 m (9600 ft), the borehole was inclined up to 35° from vertical. Bottom-hole temperature in EE-2 is 320°C. The EE-3 borehole was then drilled to a depth of 4236 m (13,900 ft). Its inclined part is positioned directly over the EE-2 wellbore with a vertical separation of about 450 m (1500 ft) between them.

Many of the geophysical measurements needed to develop the hot dry rock concept are unique. Most of the routine instruments used in petroleum drilling fail in the hot and abrasive environment. New equipment developed includes not only the downhole sonde that houses the transducer and associated line driving electronics, but modifications also were needed on the entire data retrieval systems and associated data analysis technolgy.

Successful performance of wellbore surveys in the EE-2 and EE-3 boreholes depended upon the capacity of the sensors, instrument sonde, cablehead, and armored logging cable to work in this severe environment.

The major areas of materials development for surveying the boreholes in the high-temperature environment were on elastomeric seals, electrical insulation for logging cables, downhole sensors, and associated downhole electronic and electro-mechanical components.

INTRODUCTION

The Earth Science Instrumentation Group at the Los Alamos National Laboratory is developing instrumentation and new tools that can withstand downhole temperatures in excess of 300°C and pressures greater than 138 MPa (20,000 psi).

This group was formed in 1973 to provide geophysical measurement support for the Hot Dry Rock (HDR) Geothermal Project at Fenton Hill, New Mexico.

The HDR Project traces its beginning to Los Alamos geoscientists who believed there was a huge underground reservoir of hot, dry rock that could become another large source of energy if the technology to use it could be developed. Volcanic activity in the Fenton Hill area a million years ago had created the Valles Caldera when a volcano there collapsed into its empty magma chamber. Preliminary tests at the Fenton Hill site, located 55 miles from the Laboratory, confirmed the existence of a large volume of hot rock deep underground. It was an ideal place to test the HDR concept. Basically, the concept involved:

- o drilling two holes deep into the hot rock,
- o connecting them with fractures produced by hydraulic pressurization,
- o pumping cold water down one hole and bringing the fluid up the other hole as super-heated steam, thus recovering heat (and energy) from the rock.

Funded by the U.S. Department of Energy, the first phase of the project was completed in 1977. One test hole was drilled to a depth of (2724 m) 8936 ft and a temperature of 200°C. The second hole reached a final depth of (3183 m) 9339 ft and a bottomhole temperature of 205°C. A subsequent fracture completed the loop, and an experimental heat-extraction system was established between the two holes in 1979. This research system demonstrated the technical feasibility and environmental acceptance of the HDR concept.

A second engineering system is under construction. It is larger, hotter, and deeper than the first research system. One borehole was drilled to a depth of 4633 m (15,200 ft), of which about 3962 m (13,000 ft) is in Precambrian granitic rock. Starting at a depth of 2926 m (9600 ft), the borehole was inclined up to 35° from vertical. Bottomhole temperature is 317°C. The other borehole was drilled to 4237 m (13,900 ft). Its inclined part is positioned directly over the first wellbore, with a vertical separation of 457 m (1500 ft) between them. A series of hydraulic-induced fractures will connect the two wellbores and create an extremely large reservoir of hot rock. Upon completion, this engineering extraction system will produce enough heat to represent a useful energy source or demonstrate the costs of extracting thermal energy from the naturally heated rock beneath the Earth's crust.

The DOE funds the materials development program for the HDR Project that covers all aspects of geothermal energy extraction. Materials and components, high-temperature tools and instrumentation are needed to support research on drilling, hydraulic fracturing, and wellbore logging. Some of this equipment developed by the petroleum industry can be modified or upgraded for work in hot, dry rock.

When it is feasible, Los Alamos contracts with private industry and other commercial organizations to develop the geothermal equipment needed at Fenton Hill. The Earth Science Instrumentation Group is developing a wide spectrum of high-temperature equipment for geothermal research, as well as sophisticated techniques for geophysical measurements and data acquisition and analysis.

In addition to the Fenton Hill operations, work has been performed using the Los Alamos equipment on a number of other projects in cooperation with industrial contractors. Some of these projects include:

- o Fluid Sample in the Oceanic Rift, East Pacific Rise
- o Crosswell Acoustic Imaging in the Western Gas Sands, Rifle, CO
- o Microseismic Mapping for Union Geothermal at the Baca Location in New Mexico
- o Temperature/Fluid Velocity Survey at Ontario, OR for the ORE-IDA Food Company
- o Fluid Samples/Temperature/Fluid Velocity Surveys for Geothermal Resources, Inc. at Thompson's Ridge, NM
- o Temperature/VSP Surveys for Phillips Petroleum in Brawley, CA
- o Microseismic Studies for Republic Geothermal in Beowawe, NV

FACILITIES

Offices, shops, and laboratories of the Earth Science Instrumentation Group are located at TA-33, a technical area that is outside the main Laboratory complex in the county of Los Alamos and borders the Bandelier National Park. Technical Area 57 is the technical area at Fenton Hill west of Los Alamos in the Jemez Mountains. Fifty-five miles separate the two sites. The group designs, builds, and tests the equipment at the TA-33 site before taking them to TA-57 for field assembly and operation. Well equipped facilities at both sites support the group's complete capability to develop unique, high-temperature geothermal tools and instrumentation.

At TA-33, engineers and designers routinely use sophisticated CAD (computer-aided design) systems for tool design. Machinists and technicians who are skilled in geothermal instrumentation and electronics work in two highly-specialized fabrication shops.

Technicians check out subassemblies and downhole equipment components in an Instrument Sonde Test Facility where conditions can be varied to simulate deep geothermal wellbore temperature and pressures. At the Cable Test Facility, high-temperature well logging cable is evaluated for physical and electrical characteristics in water over the temperature ranges up to 350°C and pressure ranges up to 17.2 MPa (2500 psi). Temperature and pressure in the 7.6 m (25-ft) long, horizontal autoclave are remotely controlled from an adjacent control room. Pressure-testing equipment in the Calibration Facility calibrates pressure transducers to 103 MPa (15,000 psi) and temperature-testing equipment calibrates thermocouples and other types of temperature sensors from up to 350°C. Strain-gage installation equipment is located there, in addition to measurement systems for materials testing and performance tests on accelerometers and geophones used in downhole acoustic instrumentation.

Data acquisition systems are located at both technical areas and in the group's Wellside Service Units, which are well-equipped logging trucks. Each logging truck carries 6096 m (20,000 ft) of TFE-Teflon insulated, armored, 7-conductor cable capable of operating at temperatures exceeding 300°C.

The data acquisition and control equipment for downhole measurements located at Fenton Hill uses a Hewlett Packard 9845B computer for the central processing unit. Up to three downhole instruments may be deployed simultaneously in three different boreholes. There are two trailer-mounted diesel-driven drawworks with 6096 m (20,000 ft) of high-temperature, 7-conductor, armored cable at the Fenton Hill Test Site in addition to the two Wellside Service Units. The data acquisition systems presently in use are designed for low-level signal measurements from the remote downhole sensors where the 7-conductor, armored, logging cable provides the signal transmission link. All signal-conditioning grounding and shielding uses guarded differential techniques to optimize maximum signal-to-noise and common-mode rejection. Data is digitized, normalized, and fitted to calibration information, then displayed and stored in engineering units.

The signal conditioning and data acquisition system for acoustic detection is unique. Signals detected by triaxial geophones and accelerometers are transmitted to several special purpose storage scopes with circulating memories. This unit triggers on the present amplitude of the incoming microseismic signal and provides a delay sweep that allows display of several milliseconds of signal obtained prior to the trigger. An interface bus designed at the Laboratory allows the computer equipment to talk to the scope units, control the entire acoustic detection system, and store the desired signals on disc units for on-line processing to determine source orientation and distance from the detector. Now fracture growth can be observed on-line in real time. The technology developed here to perform acoustic mapping in a geothermal environment is rapidly gaining interest in the industry.

A data acquisition and control system that duplicates the downhole instrumentation system installed at Fenton Hill is located at TA-33. This system is used to check out downhole tool operations in the laboratory and to write the computer programs required for each tool. With this system, members of the geothermal team design and develop special computer and peripheral equipment interfaces for such things as PCM, FM multiplex, and FFT analyzers. Programs are written and checked out here for the acoustic detection systems interfacing the data recording equipment.

COMPONENTS

The most critical components required to produce an operational geothermal well-logging system are the cable, O-ring seals, and sensors that can withstand the high bottomhole temperatures and pressure. Their development paved the way for upgrading all the downhole instrument systems at Fenton Hill.

L'Garde, Inc. developed a high-temperature elastomer called EPDM-Y267 compound for O-rings and other components used in the Laboratory's high-temperature downhole tools. The O-rings were tested by temperature and pressure cycling to determine operating characteristics at 300°C and 65 MPa (10,000 psi). These O-rings are now commerically available from Parker Seal Company.

Small, high-temperature direct current motors were designed by American Electronics, Inc. The motors are used in various devices such as the fluid sampler, geophone tools, and tracer injector on an intermittent basis.

An armored, 7-conductor cable with TFE Teflon used for the electrical insulating material was manufactured for the Laboratory by the Rochester Corporation. TFE Teflon, although non-extrudable, has been shown by extensive testing to be the best wireline insulation material for use above 300°C at the present time.

Extensive frequency response tests were conducted on the new 7-conductor, TFE-Teflon insulated, armored cable. Tests conducted over 6100 m (20,000 ft) of the cable show a corner frequency response of greater than 10 KHz, which is a factor of 10 better than either the standard Tefzel or the PFA-Teflon insulated logging cables. The data also shows that the response is down only 20 dB at 100 KHz. Frequency response enhancement may be achieved by careful selection of particular conductors for signal lines coupled with proper cable termination impedance.

One of the most critical components of the downhole instrument package is the cablehead. The cablehead provides the downhole termination of the armored, 7-conductor, logging cable and completes the transistion to the instrument sonde. The cablehead ensures water tight integrity of the electrical wire terminations so very important in the high-temperature environment. It also allows a disconnect from the armored cable should the sonde become stuck in the borehole. The cablehead, designed by the Laboratory, has been subjected to numerous logging runs in geothermal environments in fluid temperatures exceeding 300°C.

A significant improvement in electrical connectors for downhole instrument packages was made by Reynolds Corporation under contract to the Laboratory. The new connectors are configured like the standard Amphenol but uses a ceramic insert. The ceramic insert is unique in that it is made from a mold and is machineable during the curing process. This insert will accept the crimped pins that are readily inserted and removed from the ceramic feedthrus. This feature allows the connector to be reused many times. The connectors have been tested to 350°C with no observable degradation.

Acoustic tools developed at Los Alamos were designed to "map" fractures and characterize geothermal reservoirs. The series of downhole instruments include geophone acoustic detectors, acoustic transceivers, accelerometers and explosive detonators to simulate seismic sources for calibration purposes.

The high-temperature geophone technology developed at Los Alamos has been transferred to industry. High-temperature geophones may be purchased from Mark Products in Houston, TX. Low-frequency geophones (corner frequency below 30 Hz) are affected by tilting the axis more than 14° from the vertical. However, high-frequency geophones may be used in inclined positions greater than 80° from the vertical.

An accelerometer acoustic detector may be used to complement the triaxial geophone array. Results of extensive testing has shown that the high-temperature Endevco piezoelectric accelerometer is best suited for the tools developed at Los Alamos. This accelerometer has a greater frequency range, the required electrical isolation, and proper size for mounting in the limited space provided in the downhole sonde.

The explosive detonator system provides acoustic signals from a known fixed location in one of the wellbores. These signals are used to calibrate the high-temperature triaxial geophone array deployed in adjacent wells. The downhole sonde is modular in design and is used to fire up to four detonators in sequence. Each of the detonators contain pellets of hexanitrostilbene (HNS) explosive. The detonator is a modified version of the Reynolds Industries RP-84 slapper initiator used in other high-temperature explosive devices. The detonator is initiated by a downhole capacitive discharge firing unit, which is controlled through the armored instrumentation cable from the surface control unit. The firing circuit and detonator has operated successfully in wellbores where temperatures exceed 300°C.

Other explosive devices use a thermally stable explosive shaped to perform specific functions. One such tool leaves a bell-shaped cavity in hard rock for sidetracking the wellbore. A second tool uses a shaped charge to cut off drill pipe leaving a clean circumferential edge for overshot tools and a fracture initiation tool is used to detonate a small explosive charge in a preselected zone in the open-hole section of the wellbore to initiate the fracture system by reducing the wellbore impedance. The thermally stable explosive has been tested to temperatures exceeding 340°C.

DOWNHOLE INSTRUMENTS

A variety of high-temperature downhole instruments have been developed for use in the HDR Fenton Hill boreholes. These downhole systems have been designed to operate at temperatures above 300°C and pressures up to 20,000 psi. A brief summary of the downhole instruments that have been used for numerous wellbore surveys is given below.

Temperature Probes

Temperature probes are for borehole temperature surveys to provide diagnostic measurements and geothermal reservoir characterization. The measurements determine thermal gradient along the borehole, locate borehole/fracture intersections, and calculate thermal drawdown and recovery rates of the circulating systems. Temperature probes give diagnostic data during drilling, cementing, pressurization, and fracturing operations.

The high-temperature probe, fabricated in various sizes, is one of the simpler wellbore survey tools that is readily fielded to allow on-line analysis of changing conditions. It uses a thin-walled, stainless steel thermistor probe as the sensor. The thermistor is essentially a semiconductor that behaves as a temperature-sensitive electrical

resistance, providing a high degree of resolution that is well suited for continuous measurement in temperature environments exceeding 300°C.

Borehole Fluid Sampler

One of the first high-temperature tools developed for the HDR Project. Using three conductors of the high-temperature armored instrument logging cable, the tool takes two separate samples of 270 cc or one large sample of 780 cc. Chemical analyses of the fluid samples, which are taken at various depths in a borehole, show geothermal reservoir properties.

Downhole Injector and Gamma-Ray Detector

Radioactive tracers injected at specific locations in the borehole show fluid circulation in the fractured geothermal reservoir. Radioactive Br^{82} or any other tracer is injected into the injection well with the injector system developed at Los Alamos. A gamma-ray detector is mounted in the same sonde as the injector. When the sonde is positioned in the borehole at a predetermined location, a motor-propelled rod smashes the quartz ampoule that contains the tracer. The integral gamma-ray detector tracks the radioactive tracer as it leaves the injection well into the fracture system. A second gamma-ray detector monitors the arrival of the tracer in the production well. This tool also shows fluid flow velocities and residence time in the fracture system.

Fluid-Velocity (Spinner Probe)

The fluid velocity (spinner) probe yields accurate data about complete fluid-flow patterns in a borehole. A typical borehole will have fractures in several zones. The fluid velocity, as measured by the sensor, can help characterize the man-made reservoir by determining the nature and locations of the fractures, where and how much fluid leaves the borehole reservoir, and the relative contribution of each fracture to the total reservoir.

Caliper Tool

An independent multiarm caliper tool designed to define the profile of geothermal boreholes such as those at Fenton Hill. Development began with the design and fabrication of a prototype 3-arm sonde, which can readily be modified to have six independent arms. The arms are evenly spaced circumferentially and are capable of measuring radii from 2-1/2 to 7 in. at a common depth. Arm length can be varied to measure hole diameters up to 30 in. or can be designed for maximum sensitivity at given diameters. The arms are activated by a motor and can be extended or retracted on command from the surface.

Acoustic Transceiver System

The acoustic transceiver system consists of a transmitter and associated electronics consisting of two magnetostrictive transponding heads. One head transmits a frequency of 8.5 KHz, and the second heat transmits at 17 KHz. The receiver electronics include an automatic gain control system operating over a range of attenuation from 1 to 100 in eight

steps (6 decibels/step). The assembled sonde incorporates a suitable pressure housing and thermal protection to ensure operation in the geothermal borehole environment of up to 20,000 psi external pressure and 275°C external temperature.

Geophone Acoustic Detector

The geophone acoustic detector incorporates a triaxial geophone array to map source locations of microseismic signals generated during pressurization and hydraulic fracturing. The sonde also includes a downhole switching system to allow multiplexing of additional pertinent data to monitor internal dewar temperature, sonde orientation, and downhole power supply voltages.

Downhole Acoustic Detonator

The downhole acoustic detonator is used to calibrate geophone acoustic detectors deployed in adjacent boreholes. A geophone sonde, used in conjunction with the detonator package, registers the acoustic signals generated by the explosive. The two tools are lowered into separate boreholes. The detonator can set off up to 4 charges sequentially at any desired location. The firing system consists of a downhole firing module, surface control unit, detonator rack, and high-temperature detonators.

Explosive Sidetracking Tool

The explosive sidetracking tool rubblizes rock and leaves a bell-shaped cavity to facilitate sidetracking in hard rock at a specific location. The entire system is rated for operation at boreholes temperatures about 260°C. The downhole firing unit uses a capacitive discharge system (charged from the surface after insertion) to fire the high-temperature detonators. A dual firing unit gives redundancy. The firing unit is housed in a Laboratory-designed dewar flask of the type incorporated in many high-temperature packages to protect sensitive electronics.

Explosive Cut-Off Tool

The explosive cut-off tool severs the drill pipe string. The device uses a high-temperature/high-explosive shaped charge, a high-temperature detonator, and a dewared firing unit. The tool's shaped carge is designed to leave a clean circumferential edge where it cuts off pipe.

Explosive Fracture-Initiation Tool

Deploys and detonates a small explosive charge at a preselected position in the open borehole section of a geothermal wellbore. Detonation of a shaped-charge explosive can reduce the wellbore impendance of existing fractures or initiate fractures in the selected zone, after which hydraulic pressurization extends the fractures into the formation. The device is rated for wellbore temperatures of 300°C, a pressure limit of 15,000 psi, and incorporates a downhole firing module, high-temperature detonator, and shaped high-explosive charge. The tool's diameter is 3-1/4 in. and it is 222-in. long.

CONCLUSION

State-of-the-art for geophysical measurements in high-temperature geothermal environments is presently limited to wellbore temperatures of 300°C. Development of well-logging systems in the temperature ranges of 400°C to 500°C will require research in materials for transducers, components, electronics and data transmission links. Several developments on the horizon include metal sheathed logging cable that could advance data transmission capability. A program now in the advance development stages at Los Alamos using integrated thermionic circuits that have proven successful for electronic systems that will operate continuously at 500°C.

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