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Symposium on High-Temperature Well-Logging Instrumentation

Los Alamos National Laboratory
Los Alamos, NM 87545
November 13–14, 1985

Compiled by
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SYMPOSIUM ON HIGH-TEMPERATURE WELL-LOGGING INSTRUMENTATION

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ABSTRACT

The Earth Science Instrumentation Group at the Los Alamos National Laboratory is developing borehole logging instrumentation that can withstand downhole temperatures in excess of 300°C and pressures greater than 103 MPa (15 000 psi).

The group was formed in 1973 to provide geophysical measurements supporting the Hot Dry Rock (HDR) Geothermal Project at Fenton Hill, New Mexico. The HDR Project needed high-temperature materials, components, transducers, and instrumentation for borehole logging tools for its drilling, hydraulic fracturing, and acoustic fracture-mapping programs. In some instances Los Alamos contracted with private industry and other commercial organizations to develop the equipment required for the operations at Fenton Hill. Now numerous Department of Energy and private industry programs other than the HDR Project are using this equipment.

The purpose of the symposium was to inform interested persons from industry, government, and universities of these successful developments in high-temperature well-logging instrumentation.

Many individuals and organizations in the private sector and the Department of Energy contributed to the success of the symposium. We deeply appreciate their support. The abstracts in this report were prepared for presentation at the symposium.

WELCOME TO LOS ALAMOS

by

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Welcome to the Symposium on High-Temperature Well-Logging Instrumentation. My objective this morning is to provide the answers to the following two questions:

1) Why is the Department of Energy interested in Hot Dry Rock technology?

2) Why should you be interested in the technology developed as part of this program?

As John Whetten inferred in describing the capability of the Los Alamos National Laboratory, the responsibilities of the Department of Energy are quite broad. An important part of those responsibilities is to assume the availability of a range of energy options. We pursue those options that are high risk but potentially high payoff. The risks could be either technical, economic, or institutional. In the case of geothermal energy, the potential resource is huge.

The energy provided from geothermal is primarily thermal or electrical. This is not a substitute for portable fuels or energy sources used in chemical processes. It can, however, be a substitute for imported fuels used for electrical production or thermal application.

The U.S. Geological Survey has rendered the size of the geothermal resource in the contiguous U.S. and provided the following estimates:

Hydrothermal connection systems	116 000 quads
Geopressured-geothermal resource	113 000 quads (thermal)
	67 000 quads (methane)
Hot Dry Rock resource	430 000 quads
Magma energy resource	530 000 quads

Energy consumption in the U.S. last year was approximately 75 quads. In addition to being listed according to size, the resource estimates are also listed according to accessibility. Some of you are smiling about magma. We have already drilled into a magma lake and shown that it is technically feasible. Now we have a series of difficult technical issues to resolve.

Geothermal energy has several attractive characteristics. It is broad based, relatively clean and safe, reliable, and increasingly competitive. In addition, it is a base-load resource and requires a short lead time.

In order to show the feasibility of a number of geothermal concepts, it became necessary for us to call on industry for services. When the services were not available, we worked with industry to develop them. Where industry was not interested, we developed the services here at the Los Alamos National Laboratory. As a result, many components and techniques have been developed that should be of interest to the service industry.

On a worldwide basis, the installed geothermal electrical capacity has increased at the rate of 17% per year for the past six years through 1984 to above 5000 MW(e). This is not yet a large market, but it is a rapidly growing one. So there are two reasons why you should be interested in the technology:

1) Because it is pushing the state-of-the-art, it can enhance your application.

2) The geothermal market is small but rapidly growing; the resource is huge.

DESIGN AND MANUFACTURING CONSIDERATIONS FOR TFE-INSULATED CABLES

by

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The Rochester Corporation (TRC) has been a manufacturer of oil and gas logging cables for over 30 years. During this time, the technology of cable materials and design has changed to accommodate increasing depths of operation, varying corrosive environments, developments in tool and equipment electronics, and increasing operating temperatures. Rochester has remained a leader by developing procedures, investigating new materials, and installing equipment to meet these changing requirements. Toward this end, the capability to produce high-temperature TFE-insulated cables has been developed. This included not only TFE processing but also investigation of other cable components, such as the metallic conductors, fillers, and armor, that are affected by the expected environments. The various technical considerations regarding this development are related in this paper.

One of the primary considerations for logging cable has been the maximum temperature at which it must perform without significant physical or electrical degradation (temperature rating). The dielectric material is usually the limiting factor for the maximum temperature at which a typical logging cable can be utilized.

Common logging cables have been of single- and 7-conductor construction and have provided operating temperature ranges up to 500°F (260°C). Each of these designs has used an extruded thermoplastic material as the primary dielectric. Above 500°F, the extruded insulations were unacceptable due to mechanical failure (melting) or extreme cost and difficulty in processing.

TFE, tetrafluoroethylene, had demonstrated the ability to withstand operating temperatures above 500°F. Characteristics of TFE included resistance to corrosive agents, nonflammability, flexibility at low temperatures, and stability at high temperatures. Electrical properties included low dielectric constant, low dissipation factor, and high volume resistivity. These permitted TFE to mechanically operate in the expected harsh environments while maintaining electrical integrity.

TFE can be processed by ram extrusion or by taping around an electrical conductor. Since ram extrusion severely limited the length of continuous conductor that could be insulated, taping was generally the best method for applying the TFE.

Bare copper conductors oxidize rapidly at elevated temperatures and must be plated with silver or nickel for protection during exposure.

Since the mechanical requirements were identical to standard logging cable practice, a double layer of contrahelical armor was used to provide strength, abrasion resistance, and torque balancing.

The 7/16-in., 7-conductor TFE cable, as manufactured by The Rochester Corporation, follows established logging cable design, with certain design and manufacturing details incorporated to assure performance in the expected environment. The TFE insulation, electrical conductors, fillers, and armor have demonstrated the ability to operate successfully in 600°F geothermal wells. The cable is expected to perform equally well in similar high-temperature oil and gas wells. With proper application of materials, high corrosive wells are within its capability.

FM MULTIPLEX FOR ARMORED LOGGING CABLE

by

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ABSTRACT

Exploration of the universe has been a major goal of mankind since his beginning. Modern technology has allowed today's scientist to extend his observations to the planets and actually measure many of the physical phenomena. Modern science has launched the instrumentation industry into space, made possible by communications from rockets and satellites with aerospace telemetry systems.

The development of aerospace telemetry has also opened new communication data links for making measurements in deep boreholes in the earth's crust. However, now a transmission line must be used since high-frequency signals will not propagate through this medium. Further restrictions are imposed upon well-logging transmission lines in high-temperature boreholes. It is possible to extend the bandwidth and number of data channels to enhance measurements in geothermal boreholes by combining aerospace telemetry techniques with thermal protection systems and careful selection of wireline data transmission configurations.

I. INTRODUCTION

The Phase II energy extraction system now being developed for the Hot Dry Rock Geothermal Project has encountered bottom-hole wellbore temperatures exceeding 300°C and pressures exceeding 103 MPa (15 000 psi). It is imperative that the geophysical parameters be monitored and the dimensions and orientation of the Phase II fracture reservoir be measured in order to optimize the fluid-flow and heat-transfer properties. The most severe limitations to the use of measuring equipment in the geothermal wellbores are the high-temperature and high-fluid pressure effects on the downhole instrumentation cable. To investigate these limitations, two programs were started at the Los Alamos National Laboratory, namely (1) the development of a downhole multiplexing system and (2) a well-logging cable test program (HDR Project Staff, 1980).

II. MULTIPLEX SYSTEMS

Several constraints had to be considered in the design of the multiplex system. Downhole power requirements, component size, shock, and heat dissipation were the major factors. Presently, our downhole measurements have a wide variance in data bandwidth, accuracy, and signal-conditioning requirements. Different multiplexing techniques were compared. Universally accepted standards and availability of components were also important considerations. Another major factor was the large investment in the existing data acquisition equipment and associated software.

It was decided to design the downhole multiplex system around standards and components that were readily available for aerospace telemetry applications. This approach provided equipment and components that are governed by the standards set by the Inter-Range Instrumentation Group of the Range Commander's Council. Known generally as "IRIG Standards," the documents set forth the performance specifications for telemetry equipment on missile ranges under the jurisdiction of the Department of Defense (IRIG Standard). Using IRIG standards ensures compatibility between manufacturers of the downhole components and surface recording equipment, as well as future expansion and design. Manufacturers of microminiature components for space applications could provide components that are small in size and low in power consumption, operate from a universal, unipolar, 28-V power supply, and can withstand 85°C or higher temperatures and severe shock. The electronic equipment would be compatible with the thermal protection systems designed for the downhole instrument packages presently used at the Fenton Hill site.

The IRIG standards cover several types of multiplexing schemes and formats that could be combined and would satisfy all of the downhole measurement requirements. Two primary multiplexing techniques for these applications include FM (frequency modulation) and PCM (pulse code modulation).

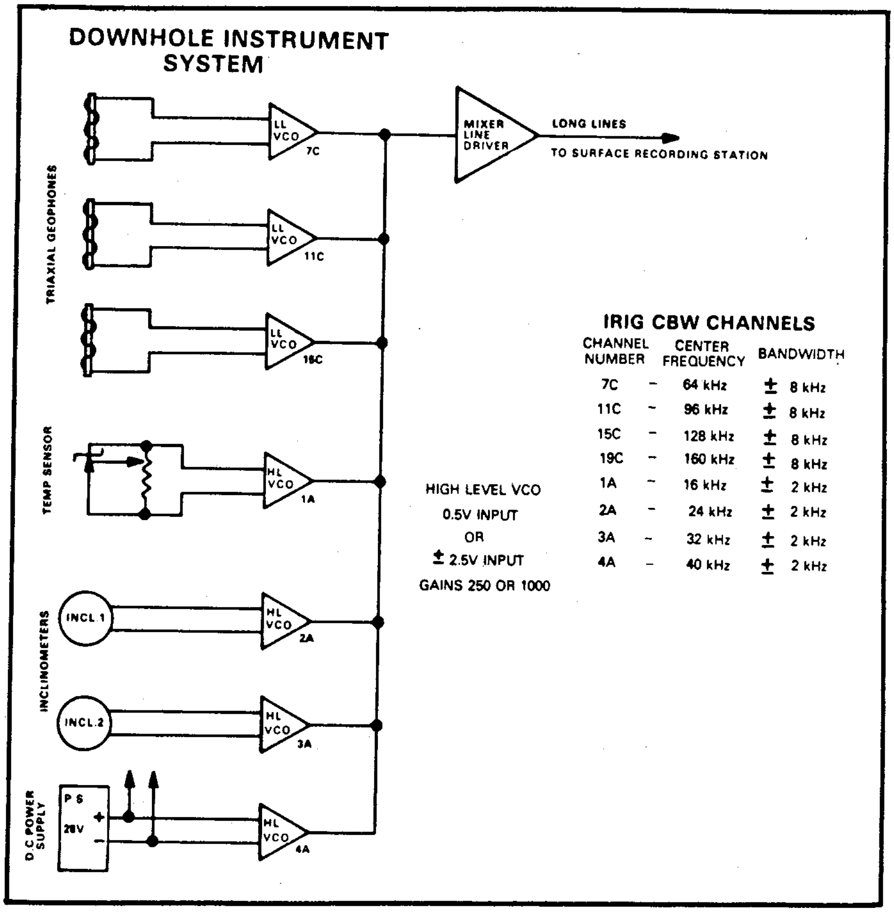
FM multiplexing is the most common analog technique used in telemetry. It has the advantage of greater data bandwidth and better time correlation between channels.

PCM is a digital multiplex technique that is more suitable for data that has a lower bandwidth but requires better measurement accuracy. PCM also results in a lower signal-to-noise ratio since demultiplex equipment needs only to detect the presence or absence of a pulse and does not have to detect amplitude or shape. The PCM system has a larger data channel capacity and is more convenient for digital data processing. An optimum data transmission system can be achieved using a hybrid PCM/FM multiplex configuration.

FM multiplex data transmission is presently used in the Laboratory's borehole acoustic tools. The downhole triaxial geophone sonde uses three high-frequency, constant bandwidth data channels (±8 kHz) for the geophone outputs and four lower frequency data channels to transmit ancillary information, including dewar temperature, inclinometer (sonde orientation), and the downhole power supply voltage (Fig. 1). A similar system is used in the accelerometer sonde configured with accelerometers instead of geophones. A fourth accelerometer, positioned at 45° between the vertical and horizontal, is used to evaluate the signal coupling from the borehole to the tool and uses a fourth high-frequency channel. The FM multiplex system is also used in the Laboratory's crosswell acoustical receiver. The piezoelectric receiver has a very broad dynamic range, which is separated into four data channels with different gain settings. Using the FM multiplex technology has increased the signal-to-noise ratio very significantly and has improved data bandwidth since only the subcarriers must be detected at the surface and the roll-off characteristics of the logging cables do not affect data response.

III. WIRELINE TRANSMISSION LINK

The "standard," well-logging, armored wireline presents the greatest limitation to data transmission from the downhole instrumentation to the surface acquisition and display equipment. The armored cable used at the



IRIG CBW CHANNELS

CHANNEL NUMBER	CENTER FREQUENCY	BANDWIDTH
7C	64 kHz	± 8 kHz
11C	96 kHz	± 8 kHz
15C	128 kHz	± 8 kHz
19C	160 kHz	± 8 kHz
1A	16 kHz	± 2 kHz
2A	24 kHz	± 2 kHz
3A	32 kHz	± 2 kHz
4A	40 kHz	± 2 kHz

Fig. 1. FM multiplex system for use with the downhole geophone acoustic detectors.

Fenton Hill Test Site conforms to the standard 7-conductor configuration used in the well-logging service industry. The conductor insulation determines to a large extent the transmission characteristics of the cable. For operations in geothermal environments, it is necessary to have an insulation material with excellent high-temperature electrical properties, good mechanical properties, and high resistance to geothermal borehole fluids. The dielectric constant between conductors should be less than 3.0 and the dissipation factor at 1.0 MHz should be less than 0.001.

The armored instrument cable used for logging the geothermal wellbores at the HDR Fenton Hill site is a 7-conductor TFE-insulated core with a galvanized Plow Steel torque-balanced armor package. The cable is ~20 000 ft in length with No. 19 AWG nickel-plated copper conductors. The nickel plating is used to deter hydrogen sulfide embrittlement of the copper. The conductors have a dc resistance of 9.2 ≡/1000 ft at ambient temperature. The capacitance between conductors is about half that of the other insulation materials.

A major concern for transmission of high-frequency signals over the 7-conductor armored logging cable is the attenuation of the transverse electromagnetic waves (TEM) in the principal mode of propagation. The losses associated with the logging cable are comparable to the Lecher parallel-wire transmission line. The Lecher-type wireline has serious limitations at high frequency as far as losses are concerned. A coaxial transmission line is far superior to the parallel wire and is preferred at higher frequencies, but it is not yet available with the TFE Teflon materials (HDR Program Staff, 1981).

Attenuation can be primarily attributed to the following losses: conductor losses or skin effect, dielectric losses, and hysteresis losses. These losses are absorptive by nature, which means they dissipate energy. Mismatch losses and losses due to radiation reflect and guide energy away from the transmission line. It is very difficult to match impedance in the 7-conductor cable since both the dc resistance and the dielectric constants vary significantly with temperature while logging geothermal boreholes. At the higher frequencies, the skin effect becomes more critical and the current is restricted to travel in only the surface layer of the conductor, effectively reducing the electrical cross-sectional area of the conductor. For copper with a conductivity of $\gamma = 6 \times 10^7$ M≡/m at a frequency of H hertz, the skin depth may be approximated to $\delta \approx 1/15\ H^{1/2}$ m. For example, at a frequency of 1 MHz, the skin depth is approximately 0.067 mm (0.0026 in.) and at the power frequency (60 Hz), the skin depth is about 8.5 mm. For the No. 19 AWG wire used in the logging cable, the diameter of the wire is 0.90 mm (0.03589 in.) and at 100 kHz, the skin depth is about 0.21 mm (0.0083 in.). The nickel plating affects the skin effect slightly because of its ferromagnetic properties. Using the armor as part of the transmission line causes much greater skin effect losses because the resistivity of the Plow Steel is much higher than copper.

It is possible to configure the 7-conductor cable to optimize high-frequency transmission and reduce the radiation losses. The best configuration would be to connect the six outer conductors together and use the inner conductor to approximate a coaxial configuration. The outer conductors are wrapped around the inner conductor providing some, although minimal, shielding. This configuration, however, leaves no conductors available for other uses.

A second configuration where conductors 1 and 3 are tied in parallel for the return is presently used as the transmission line in the Laboratory's acoustic systems for the FM multiplexed data. Conductors 2, 4, 5, and 6 are used for other functions.

The third configuration parallels conductors 2 and 6 and conductors 3 and 5. This is the worst case response presenting complex attenuation characteristics which can be attributed to induced EMFs in adjacent conductors producing complicated phase shifts coupled with the other loss modes. A diagram of the conductor configuration and resulting frequency response is shown in Fig. 2.

IV. PRESENT AND FUTURE APPLICATIONS

FM multiplex data transmission now used in the Laboratory's borehole acoustic systems is well within the operating characteristic of the 7-conductor cable. The highest frequency of interest is 168 kHz (IRIG Channel 19C 160 kHz ±8 kHz), which is well within the detectable range of the surface data acquisition system. The FM multiplexing was incorporated in the acoustic tools because of the high-frequency data rate required. A PCM multiplex system will be used in a new spinner/ temperature/pressure sonde. The PCM digital format will be transmitted on a FM subcarrier to improve signal-to-noise ratio. A combination of PCM for direct digital formatting with the FM subcarrier for significant improvements in signal-to-noise will enhance the capabilities to log deep boreholes in the geothermal environments.

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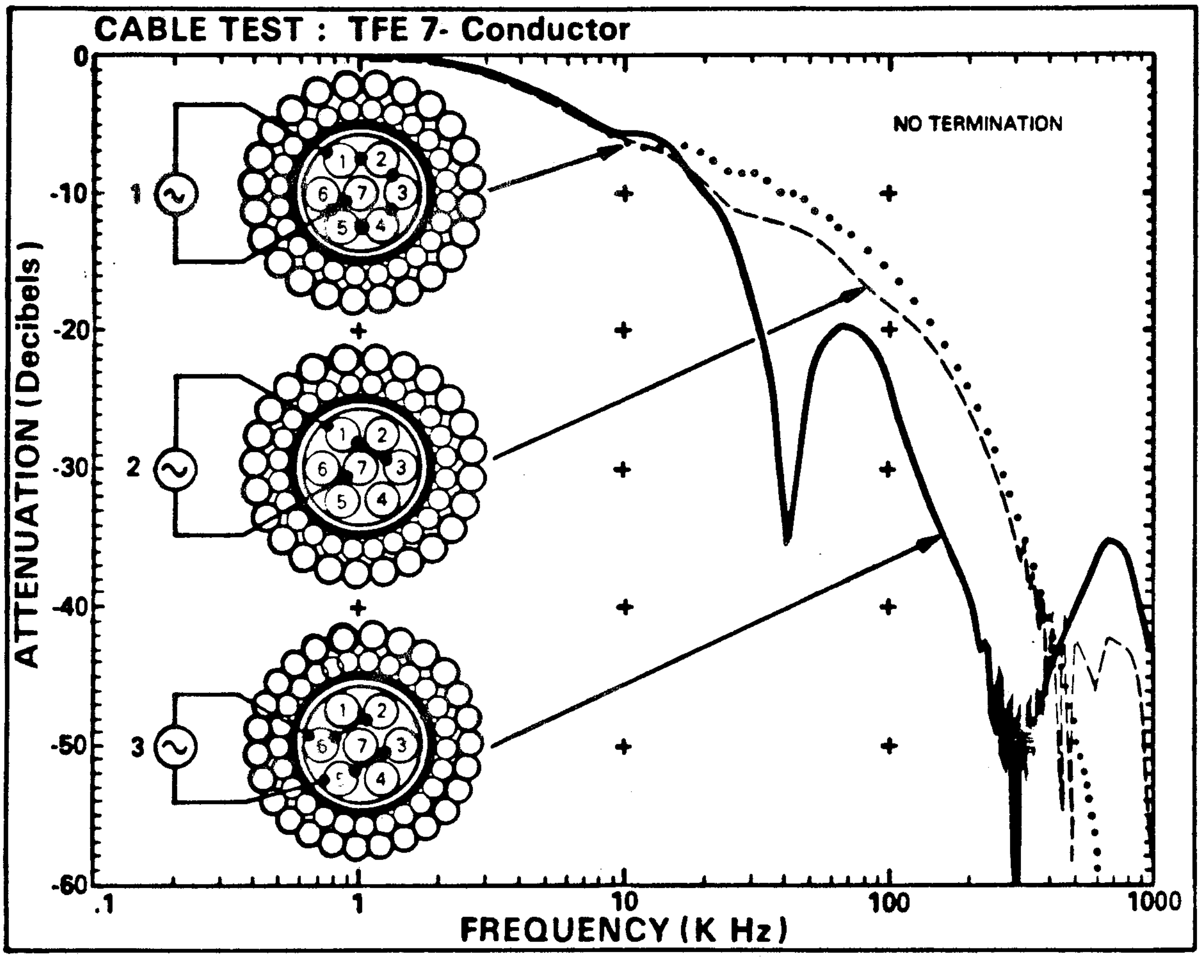

Fig. 2. [1]Dotted line is conductor 7 to 1, 2, 3, 4, 5, 6 parallel.
[2]Dashed line is conductor 7 to 1, 3 parallel.
[3]Solid line is conductor 2, 6 parallel -- 3, 5 parallel.

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MINERAL-INSULATED CABLES

by

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The basic construction of mineral-insulated cables is a metal jacket encasing tightly compacted magnesium oxide powder, which in turn surrounds one or more conductors.

This cable was developed nearly 100 years ago but not manufactured until 1937. The use of mineral-insulated cable may be considered a new application for a well-proven product. BICC Pyrotenax, now 49 years later, is the largest manufacturer of mineral-insulated cables in the world.

Transducer lead-out cables, with stainless steel jackets and copper conductors, have been available for some time but in relatively short lengths.

In 1982/83 we developed and installed a production unit to produce continuous cable in lengths of up to 30 000 ft. This launched the slicksender range; the range was further extended by armoring the cables, thus offering a high-temperature logging cable.

The manufacturing process to produce such a cable is called weld-fill draw or conform.

Slicksender cables are available in 1-4 conductors, the standard jacket being 316L stainless steel. Long-length thermocouples are also available with Type K conductors.

By armoring these cables, we are able to offer a range of high-temperature logging cables with either galvanized or stainless steel armor wires and finished sizes of 7/32 or 5/16-in.; minimum sheave diameters for these are 12 and 15 in., respectively.

TABLE I

WIRELINE CABLES[a]

	Single Conductor 18AWG 7/32-in. Diam	Single Conductor 18AWG 5/16-in. Diam
Cable diameter	7/32 in.	5/16 in.
Cable weight	95 lbs/1000 ft	200 lbs/1000 ft
Breaking strength	4200 lbs	10 000 lbs
Elongation (for every 1000 ft with 224-lb load)	12 in.	15 in.
Minimum sheave diameter	12 in.	15 in.
Maximum continuous operating temperature--galvanized	900°F	900°F
Maximum continuous operating temperature--stainless steel	1100°F	1100°F
Voltage rating	600 Vdc	600 Vdc
DC conductor resistance	6.4 ohms/1000 ft	6.4 ohms/1000 ft
Armor+jacket resistance	4.1 ohms/1000 ft	1.7 ohms/1000 ft
Capacitance	118 pF/ft	118 pF/ft
Cable reference	MTCA1T307.32	MTCA1T305.16

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[a] Other sizes of single, twin, and four core are available upon request.

These logging cables have been successfully used in Japan for temperatures up to 640°F and are part of a "super high-temperature geothermal well logging system" developed by Japan Petroleum Company.

MP35N -- Strip is not available at this time in sizes required to manufacture cable. Annealing temperatures are too high for copper, therefore nickel would have to be used. Conductor resistance for 4-conductor cable is estimated at 325/375 ohms/1000 ft. If cable size is increased to 6 mm, conductor resistance would drop to 75 ohms/1000 ft.

Manufacturing trials are needed to determine if modifications are necessary to our existing plant. We would also need assurance from the trade that such a cable is required.

Advantages of slicksender cables include the following:

1) withstand temperatures up to 800°C for the thermocouple and 600°C for the wireline;
2) withstand pressures in excess of 45 000 psi;
3) corrosion resistant stainless steel 316L jacket or other materials upon request;

4) available up to 30 000 ft in length;

5) unique construction assures complete performance reliability and resistance to mechanical damage;

6) cable available with 1, 2, or 4 conductors;

7) small size, less than 1/8 in. over jacket;

8) available with either stainless steel or galvanized armor in standard diameters of 7/32 and 5/16 in.; and

9) suitable for geothermal wells.

MATERIALS TESTING/ARMORED LOGGING CABLE

by

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This paper stresses the importance of testing and analyzing materials before and after they have been used, especially in geothermal wells. Materials have been tested at the Los Alamos National Laboratory not only for the Hot Dry Rock Geothermal Energy Project at Fenton Hill but also because logging other wells is sometimes required. Since the environment at these other locations is usually more corrosive than the environment at the Fenton Hill Site (FHS), it is important to study every possible parameter that may be encountered.

The electromechanical armored logging cable is one of the most vital tools in any logging operation. The three main components of the cable - the outer cable armor, the insulation, and the electrical properties of the conductors - are used as prime examples for tests and analysis. Also, two different systems, used for conducting tests on the armored logging cable and its components, are presented. These systems are explained first.

The first system consists of a 0.5-ℓ pressure vessel made of Hastelloy C-276 able to operate at a temperature of 200°C with a pressure unit of 2000 psi. Also, a load frame, load train, and the drive mechanism are used to apply a constant strain rate to the specimen in the vessel while it is exposed to a simulated geothermal fluid (see Fig. 1). In this case, single wire strands of various metal alloys that could be potential candidates for the outer cable armor will be tested. Constant strain-rate time-to-failure results will be obtained as well as the effects of certain key species in the fluid of a critical stress level of the alloy. Similar results may also be

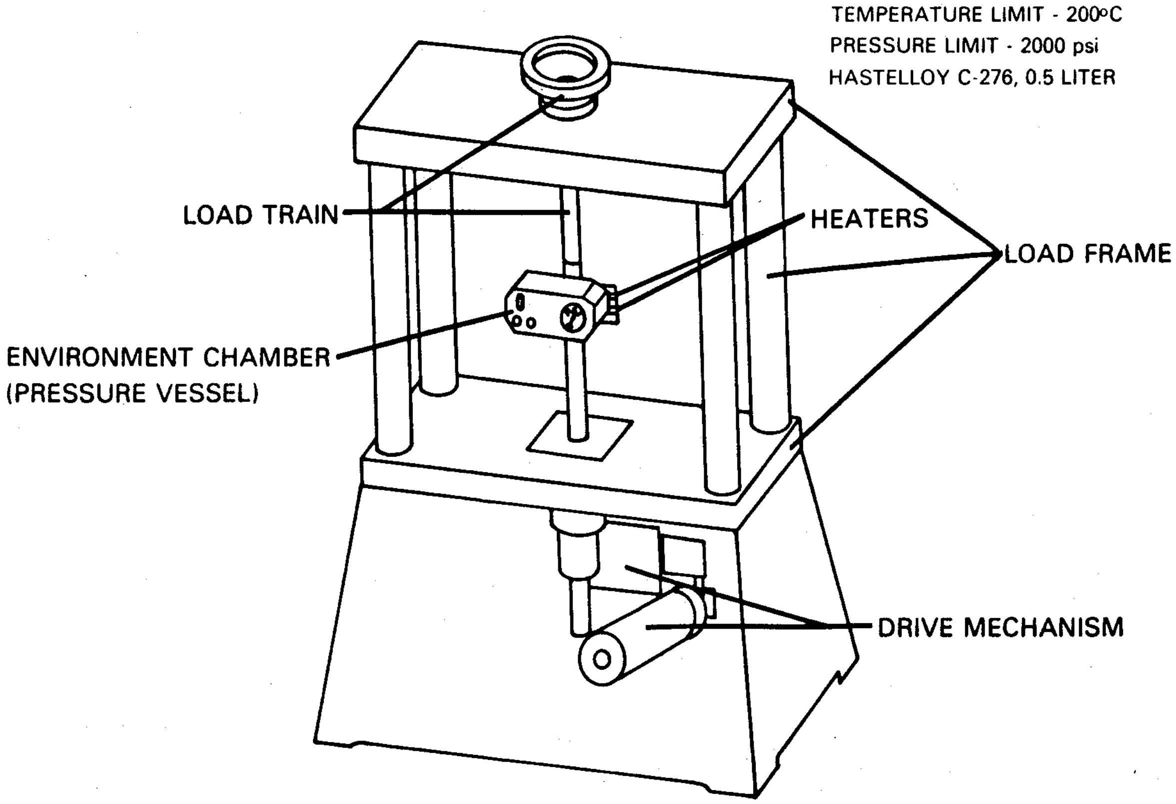

Fig. 1. Constant extension rate tester.

obtained when standard "dog-bone" samples of metal alloys are placed in the vessel and used to determine materials selections for downhole tools.

The second system is a high-pressure/high-temperature (3000 psi/350°C) autoclave used to test a whole section of logging cable (see Fig. 2). The cable test facility is available for testing the effects of neutral-to-high pH geothermal fluids on the outer cable armor, the insulation properties at high temperatures, and the electrical properties of the cable. In using this facility, the entire cable is placed under a constant static stress in the vessel and tested for the various properties.

Several materials tests have been conducted on the armored logging cable and its components. One example of testing the cable relates to its overall strength. The cable head is the component at which the connection between the downhole instrument package and the cable bringing information to the surface is made. When the cable is attached to a downhole instrument and that instrument is lodged in the well, it is important to be able to pull the cable out of a cone basket which is in the cablehead so the entire cable won't break

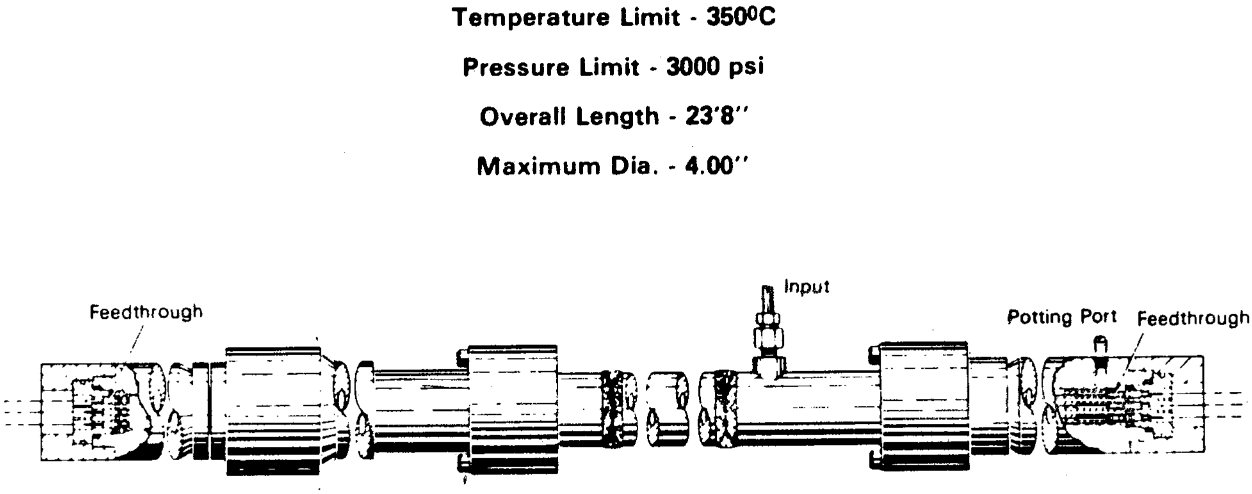

Fig. 2. Cable test autoclave.

and get lost downhole. Several cables were headed and pull-tested to obtain a pull-out load that would be dependable everytime. In testing the cable that is frequently used at the FHS, a standard configuration was devised. It was found that by terminating 11 of the 22 outer wire strands (every other strand) over the cone in the cone basket and using a certain size of cone and cone basket everytime, a repeatable load of 4000 lbs could be placed on the cable before the 11 strands would break and release the cable.

The next example is presented to emphasize the importance of testing materials to avoid surprise complications. In this case, a high-temperature electrical connector, which is used to make the connection between the downhole instrument package and the logging cable, was placed in distilled water, heated, and pressurized. The test was conducted initially to study the effects of this environment on an elastomer piece of the connector which is housed by metal. After approximately 2 h of exposure at 220°C, the elastomer did show signs of decay. However, the surprising result was that the outer metal housing, which was thought to be stainless steel, became slightly corroded in the form of pitting. Since this is unusual for stainless steel in distilled water, a simple qualitative analysis was performed on the metal which showed it to be aluminum. In this situation, if the aluminum connector had been used in an alkaline environment for example, it would have been rapidly attacked and the electrical connection lost.

One last example of analyzing materials after they have been used involves the insulation used on the conductors in the cable. Three types of insulation were analyzed using a Scanning Electron Microscope to determine the mode of wear to each. Each of these materials was used extensively on logging cables mainly at the FHS. The trade names of these three fluoroplastics are polytetrafluoroethylene (PTFE or TFE), polyfluoroalkoxy (PFA), and ethylene tetrafluoroethylene (ETFE or Tefzel). All are Teflons made by DuPont.

The experiences with each of these materials at the FHS agreed fairly closely with the published data. All properties of the Tefzel insulation functioned properly up to around 200°C; however, above that temperature the electrical properties began to fail. The PFA cable was exposed to temperatures as high as 320°C, but it was noticed that the mechanical properties began to fail around 260°C. The TFE-insulated cable has proved to withstand the Fenton Hill environment very well. It has been used extensively at temperatures as high as 320°C with no signs of electrical or mechanical degradation.

Physical wear to each of the insulating materials was examined extensively. It was found that the TFE and PFA materials had grooves formed into them which were caused by the force of the outer cable armor. All of the grooves were fairly uniform with the shape and diameters of the inner layer of armor. The Tefzel insulation showed no signs of physical wear. Also, cross-sectional views of each conductor core indicated that the insulating materials molded to the conductor fibers.

With this type of materials analysis, the mode of wear to each of the insulation types was examined. If the deformation were to continue as it has in the TFE and PFA cables, the conductors would eventually get so close to the surface of the insulation that they would begin to touch each other or the outer cable armor and short-out. This type of physical deformation is not likely to occur to the Tefzel insulation; however, it will not withstand the higher temperatures.

HIGH-TEMPERATURE CABLEHEAD

by

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Engineers at the Los Alamos National Laboratory have designed and successfully operated a cablehead that can function in temperatures and pressures greater than 320°C (608°F) and 103 MPa (15 000 psi). The cablehead assembly provides a cable-to-sonde electromechanical coupling device, which protects the electrical conductors from the high-pressure/high-temperature environment. It establishes a transition area from the downhole fluid, high-pressure environment to a dry, low-pressure instrument chamber. The cablehead assembly is a protected area for splicing the cable conductor ends to the high-temperature bulkhead.

Should the instrument sonde become lodged in the wellbore, the cablehead is designed to allow separation of the sonde and cable. The fishing bell housing then provides a positive gripping area for overshot fishing tools for retrieval from the borehole.

I. INTRODUCTION

The major function of the Hot Dry Rock (HDR) engineering group is to characterize the underground heat exchange system. The project engineers found that the most useful and accurate method of mapping the reservoir is to lower sensitive tools into the boreholes. These tools measure the physical properties of the reservoir and transmit data to surface recording and computation facilities via the high-temperature multiconductor armored cable.

The HDR borehole environment is harsh: all downhole equipment must survive exposure to 320°C (608°F) and 103 MPa (15 000 psi). Since most commercially available tools are not designed for extended use in such high-temperature pressurized environments, the Los Alamos engineers had to modify existing tools or develop new ones that could operate under severe conditions.

The success of any tool used in the HDR system depends partially on the quality of the electrical and mechanical connections between the tool and the cable. Should the cable conductors come in contact with the fluid, the electrical connections break down and the tool's ability to collect accurate data deteriorates. To provide a quality connection, the HDR engineering staff had to design a cablehead assembly that could operate in the harsh downhole geothermal environment.

II. FUNCTIONS OF THE HIGH-TEMPERATURE CABLEHEAD

The primary function of the high-temperature cablehead is to provide a waterproof environment for the electromechanical coupling device between the tool and the armored cable. Other functions of the cablehead are

1) to establish a transition area from the downhole fluid high-pressure/high-temperature environment to a low-pressure environment in the tool,

2) to provide a protected area for splicing the cable conductor ends to the high-pressure bulkhead,

3) to allow for a quick downhole separation between the tool and the cable should the tool become stuck, and

4) to provide a gripping groove (for commercial overshot tools) for fishing the stuck tool out of the borehole.

III. THE LOS ALAMOS DESIGN

The Los Alamos-designed cablehead is a four-piece assembly. It is comprised of a cable retaining section, cable packoff/breakaway section, splicing cavity, and high-pressure bulkhead housing. The interior components are designed so as to minimize the amount of time required to assemble, clean, or replace when making repairs.

IV. SECURING THE CABLE

It is important that the cable is held tightly within the cablehead so that it does not twist free from its electrical and mechanical connections with the tool.

To prevent the cable from rotating within the subassemblies, an EPDM grommet (Compound Y267) made by L'Garde, Inc., is fitted around the cable where the cable retainer and the cable packoff/breakaway subassemblies join. At the lower end of the cable packoff/breakaway subassemblies, the cable armor is terminated. The armor is wedged into a cone basket with a cone placed between the outer and inner armor.

The tool is jointed to the cablehead by a swivel nut. This allows the tool to be connected to the cablehead without rotating or coiling the wires via the multipin bayonet electrical connector. The bayonet connector also allows for a quick change of tools.

V. WATERPROOFING THE CABLEHEAD

Water is most likely to seep into the cablehead through the top of the retaining subassembly housing. To prevent leaks once the cable has been attached, a high-density silicon oil is used to prevent water from seeping into the cable conductors and destroying the electrical connections. A Krytox oil is poured into the packoff/breakaway subassembly and the splicing cavity through injection ports. Liquid Krytox has a specific gravity of 1.5. Any moisture that is in the vicinity of the conductors will float uphole and away from the electrical connections. The oil injection ports are sealed off with a stainless steel pipe plug.

Water is prevented from seeping into the cable packoff cavity by an elastomer grommet. The grommet will also thermally expand downhole.

Parker O-rings, using the L'Garde EPDM compound, are used to prevent leaks at all the subassembly junctures and around each of the feedthroughs in the high-pressure bulkhead. The bayonet electrical connector between the tool and the cablehead is sealed by a Parker O-ring and Bal-Seal.

VI. THE CABLEHEAD BREAKAWAY SYSTEM

Should the tool become wedged downhole, the cablehead's breakaway design allows for the retrieval of the entire length of cable and the subsequent fishing of the stuck tool.

The breakaway design uses the method where only the outer armor is secured to the cablehead cone basket assembly. The inner armor is not secured in the cablehead. This method of terminating the armor would allow the cable to pull out at 4000 lbs from the cablehead, leaving the entire head assembly attached to the instrument sonde. The cone basket is submerged in oil and is not exposed to corrosive fluids, preserving repeatability of breakaway pull forces.

SMOOTHWALL LOGGING CABLES

by

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The purpose of this paper is to present various design alternatives in the general field of downhole logging and instrumentation cables, particularly those that are subjected to high temperatures and corrosive environments. The central theme that runs through the presentation is the capability of covering different configurations of cables with smoothwall stainless steel sheaths. This technique is a natural progression from many years of manufacturing mineral-insulated, stainless-steel, sheathed-heater cable, although the lengths involved are considerably greater than the relatively short runs of cable used in pipe and vessel temperature maintenance.

The different cable designs all exhibit certain characteristics: high-corrosion resistance, high-temperature capability, high-compressive strength, long lengths, self-supporting, smoothwall, and hermetically sealed sheathing.

The sheath material can be varied to obtain the maximum corrosion resistance. The sheath thickness can be increased to provide greater tensile strength.

The sheath can be placed over polymer-insulated conductors as well as mineral insulated. It can also be placed over counterhelically wound wire armor.

Engineers involved in downhole investigations should give consideration to the many design alternatives provided by the "oversheathing" system and enjoy its economic advantages.

MATERIALS ISSUES IN HIGH-TEMPERATURE ELECTRONICS

by

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Materials, individually and in combination, play a key role in determining the elevated-temperature characteristics and operating temperature limits of electronic devices and systems. Achieving adequate performance is a challenge because most materials properties decline as temperature is increased for electronic applications. Furthermore, degradation mechanisms accelerate so that lifetime is inversely related to temperature. Present capabilities are typically in the 200°C to 300°C-range for hundreds of hours. The fundamental limitation for semiconductor-based electronics arises from the physics of the semiconductor material itself. In theory, silicon devices can be used to about 300°C, gallium arsenide devices could be used to 450°C, and other semiconductor materials, although presently unavailable, could be used to temperatures as high as 1000°C. For most semiconductor devices and electronic systems, however, the practical limit is less than this and is determined by associated technology. In some instances this relates to inherent properties of a single material, while in others it is determined by interactions when different materials are interfaced. Examples include the following: on-chip metallization systems; materials used for interconnecting, mounting, and packaging semiconductor chips and other components; and materials for conductive, resistive, and dielectric functions in hybrid circuits. Inorganic materials, i.e., ceramics, glasses, and metals, are reliable standbys; the use of systems involving polymers much above 200°C is more difficult, although progress is being made for this class of materials. In conclusion, through judicious selection and evaluation, presently available materials, materials systems, and technologies are already meeting many of the needs of high-temperature electronics, and extension of the temperature range and lifetime is possible through further research and development.

BURR-BROWN WIDE-TEMPERATURE PRODUCTS

by

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In the late 70's, Burr-Brown recognized two potentially large markets for data acquisition components that could withstand temperatures well above the normal maximum of 125°C (which had been defined by the military): instrumentation for downhole oil well logging and electronics for motor and engine monitoring and control. At the same time, improvements in hybrid technologies, CMOS logic availability, and linear IC's based on dielectric isolation made it possible to design standard data acquisition components for operation at up to 200°C with reasonable yields. The perceived markets and improving technologies led Burr-Brown to introduce a series of high-temperature products: a complete analog-to-digital converter (ADC10HT), a related digital-to-analog converter (DAC10HT), and two complementary op-amps (OPA11HT and OPA12HT).

The market for electronics for engine/motor monitoring and regulation has never taken off, and the decline in the intensity of oil exploration in the early 80's has reduced the growth of demand in that area, so that the real market for high-temperature components in the first half of the 80's has been stable, at best, at a level much lower than our expectations. Only within the past year have the market conditions improved to the point that Burr-Brown and the other firms supplying wide-temperature-range products are seriously investing in major new product development programs.

But the intervening "down" years have not been a time of no progress. At Burr-Brown, our ADC10HT sales have remained strong. This indicates a continuing market desire for integrated solutions that reduce design difficulty by reducing board size as compared with an A-to-D built out of several packages and also reduce compatibility problems for the designer. Since Burr-Brown tests and guarantees performance of the complete converter, the designer is relieved of responsibility for making sure the individual subcomponents work together even at 200°C. In fact, Burr-Brown has probably made the most progress in the area of testing converters at high temperatures. Careful combination of a Thermostream System from Temptronic Corporation with our standard production LTX test systems yields reproducible test results for a wide variety of parameters. This compares very favorably with earlier drift oven systems that were prone to frequent breakdown and inconsistent data. In fact, for earlier drift systems we were forced to rely on expensive custom printed circuit boards designed to operate at 200°C that proved to be regular problem sources in production.

At the same time, hybrid assembly methods for components destined for wide-temperature excursions have improved significantly over the last five years. The combined effect of these advances is that 200°C products can be produced under more standard manufacturing conditions, which ultimately means more reliable parts delivered on time (more often) and at stable prices. When volumes finally do start to increase, what we have learned should also help prices follow the downward trend more common in electronics.

For a number of reasons, including the requirements of the high-temperature markets, Burr-Brown has also used the last several years to build up expertise in several technologies. The most visible of these is dielectric isolation (DI), which has strong performance advantages over the more standard, and less costly, junction isolation processes. Burr-Brown has already introduced a variety of linear IC's using DI, and several converter products are on the drawing boards at the moment. All of these are candidates for gradeouts, or modifications, for 200°C operation. Equally important for building more complete circuits and converters is our growing experience with CMOS designs. The low-power advantages of CMOS translate directly into reliable performance at higher ambient temperatures since the delta from chip temperature to ambient is reduced by the lower consumption. Burr-Brown will be using CMOS to make converters that are increasingly "user-friendly" by adding increased logic to hybrid converters. At the same time, we are soon going to introduce our first CMOS D-to-A IC's and plan to rapidly pursue wide-temperature versions of these.

While it is premature to discuss introduction schedules or specifications for specific products, it is not too soon to outline the types of wide-temperature products we are focusing on over the next year or so. Burr-Brown's first CMOS MDAC (multiplying D-to-A converter) will be the industry standard 7541A, and we expect to have a wide-temperature range grade of this device. We also believe the time is right for the next generation of 200°C A-to-D converters with faster conversion times (to allow more data to be collected) and probably with more logic for interfacing with microprocessors. We intend to develop something like our ADC574A for these requirements. We also recognize a need for multiplexer and sample/hold circuits, especially in engine/motor where input signals may change very rapidly. The specific products will be defined in early 1986, based on the results of several development projects now under way.

HIGH-TEMPERATURE MICROELECTRONICS

by

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White Technology, Inc., has been involved in the design and development of hybrid microcircuits for high-temperature applications for over ten years, extending back to its previous name of Custom Devices.

Many materials have been researched with respect to their use and reliability at temperatures exceeding 200°C. Polymers, glasses, ceramics, and thick film compositions were selected from these evaluations to provide a material technology base for high-temperature hybrid development and production.

Semiconductor device evaluations also played a significant part in White's success in high-temperature hybrid technology. Combining reliable device selections with materials capable of performing at high temperatures along with the unique circuit design expertise, White Technology, Inc., has come up with a standard product line of regulators, oscillators, amplifiers, references, microprocessor modules, memory modules, and other peripheral devices for 200°C applications.

The criteria for new standard product designs are as follows:

1) must have a minimum 1000-h usable lifetime at 200°C;

2) must pass 225°C testing in development to guarantee 200°C performance;

3) must be capable of meeting mechanical shock, vibration, and thermal shock conditions normally encountered in downhole measurement tools (screened to MIL-STD methods);

4) must provide a usable building block for high-temperature tool

designers (this provides the access to years of technology at a nominal cost and eliminates the need to "reinvent the wheel"); and

5) must provide a cost competitive approach to the user.

For the past two years, White Technology, Inc., has been developing a microprocessor system for downhole applications. While not limited to this use, it provides a very powerful mechanism to collect and process data at extreme environmental conditions.

The current system is based on a 80C85 processor with a clock oscillator, memory, and mux, all on board in a 40-pin hybrid package. Memory add-ons in 16 K-byte increments are available (RAM's) as are 2 K x 8 EEPROM modules, which can be reliably written to at 150°C and read without error at 200°C. A dual parallel/dual serial port module gives IO expandability where required.

In development are a 16-bit processor module, VF converters, A-D converters, timing modules, and DA converters, all for 200°C performance.

Besides our standard product developments, White Technology, Inc., provides many custom designs built to customer specifications. Our experience, technology, and intense interest in 200°C-circuit challenges have made White Technology, Inc., a reliable source for solving high-temperature problems.

NEW CAPABILITIES IN PYROFLASKS

by

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PYROFLASKS refer to high-temperature dewars used for thermal protection of sensitive downhole equipment. Although flask fabrication techniques have been well established for many years, Vacuum Barrier has continued to make state-of-the-art advances. To better understand these, basic flask construction and operating principles are first reviewed.

Shown in Fig. 1 is a cross section of a typical PYROFLASK assembly, comprised of two concentric shells, welded vacuum tight at each end. The annular space surrounding the inner shell is pumped out through the evacuation tube, which is subsequently pinched, or cold welded, creating a permanent high-vacuum seal. Also, in this annular space, Vacuum Barrier utilizes a multilayer insulation consisting of alternate layers of aluminum and glass fibers. The combination of high vacuum and multiple reflective layers results in extremely low heat loss through the walls of the PYROFLASK.

Below the inner shell is the radial support, a high-strength, low-heat-loss structure designed to hold the inner shell concentric within the outer while permitting axial differential expansion and contraction during temperature changes.

Shown above and below the internal equipment are thermal storage materials or "heat sinks." These can take a variety of forms, i.e., solid metals, low-melting temperature alloys, or other phase change materials, and are basically used to absorb heat dissipated by the equipment and/or the heat leaked into the flask, thereby extending downhole time capability.

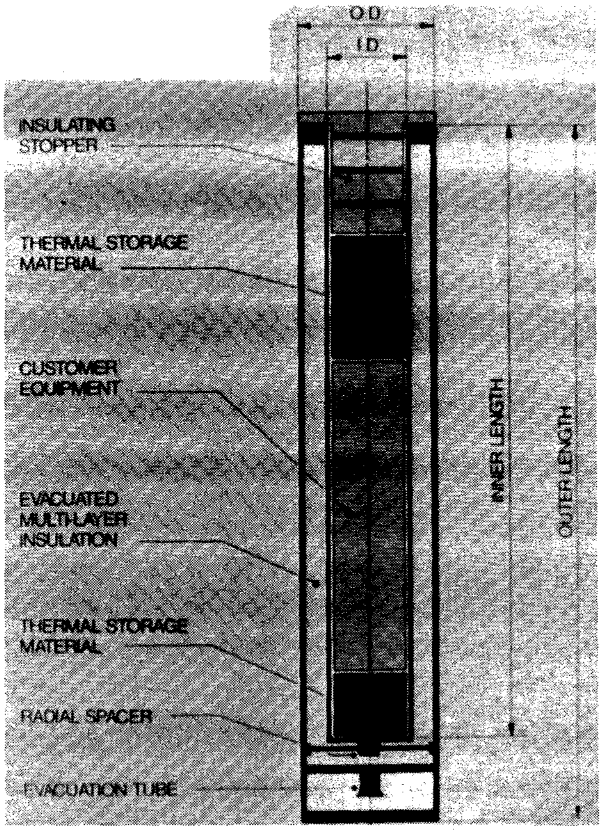


Fig. 1. Cross section of a typical PYROFLASK assembly.

The insulating stopper at the open end of the flask is characterized by low thermal conductivity (and sometimes high heat capacity) and functions to limit heat flow into the open end of the flask.

The overall heat loss of the flask is composed of several individual components:

1) conduction through the insulating stopper,
2) conduction down the inner shell or neck,
3) conduction through the radial support,
4) conduction and radiation through the walls, and
5) conduction through wires or other connections penetrating into the flask.

Figure 2 is a photograph of a portion of the VBC manufacturing area containing the ovens in which flasks are evacuated at elevated temperatures. Using routine techniques of this "outgassing," PYROFLASKS are rated for operating temperatures of up to 600°F, while upon request, special processing

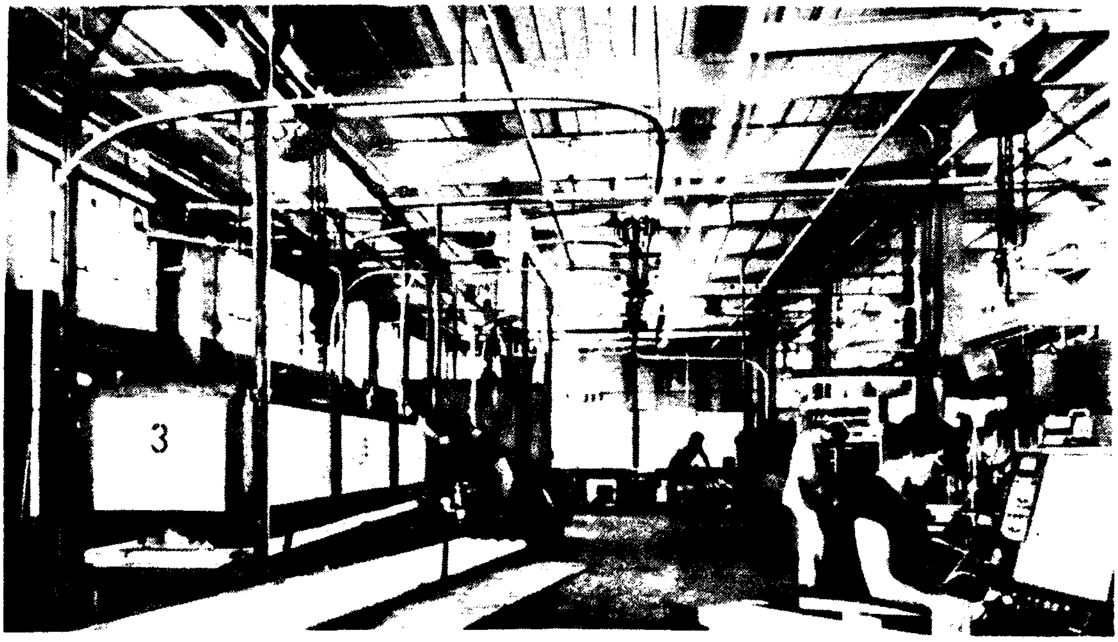


Fig. 2. Evacuation ovens in the VBC manufacturing area.

enables the PYROFLASKS rating to be increased to 850°F. The large capacity of these ovens allows VBC to respond rapidly to high-quantity requirements.

Today it is common to approve downhole equipment including PYROFLASKS for hostile environments through shock and vibration testing. This has led Vacuum Barrier to perform shock and vibration tests on some representative units. Shown in Fig. 3 is a PYROFLASK on a shake table during development testing conducted by VBC. With resulting upgrades made in the mechanical characteristics, PYROFLASKS are now fabricated that undergo extensive shock and vibration tests with no thermal or mechanical degradation.

In the testing oven pictured in Fig. 4, each PYROFLASK receives at least three thermal performance tests after pinch-off and before shipment. The test consists of positioning a temperature sensor inside the flask with an insulating stopper in the open end. The oven temperature is then elevated and the internal temperature is monitored over a period of five hours. By performing a series of these tests, any flask with a possible problem can be detected and rejected. Although the procedure may appear somewhat laborious,

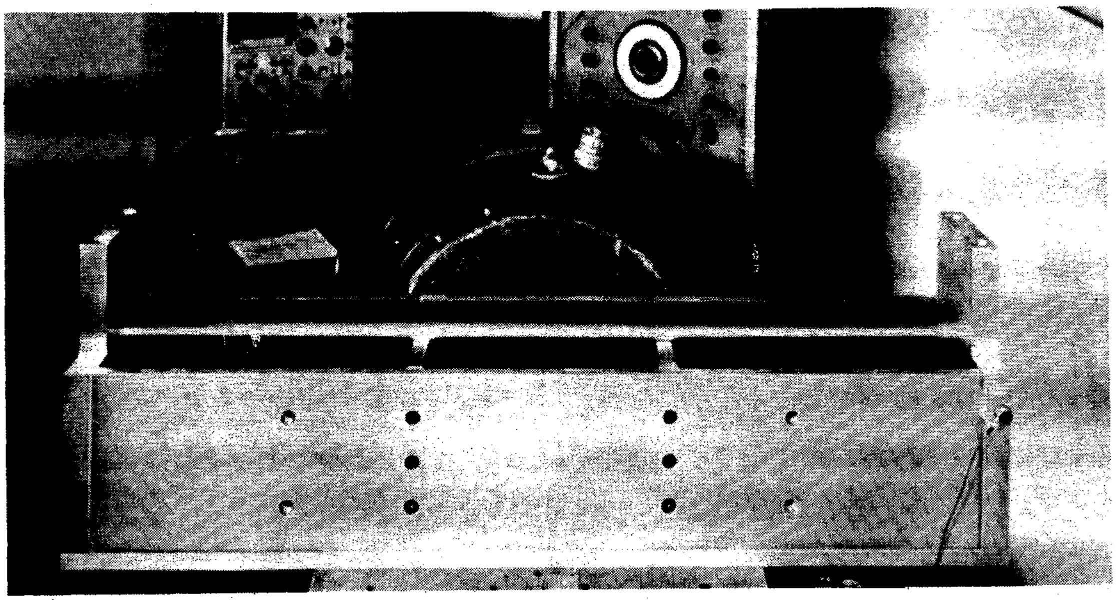


Fig. 3. PYROFLASK on shake table during development testing.

it has proved well worthwhile over the years in furnishing reliable and consistent PYROFLASKS.

A standard form utilized for evaluating flask application is shown in Fig. 5. Requested are the important parameters or constraints from which we can quickly determine the feasibility of a flask design and heat sink requirements. Typical information listed includes dimensional requirements (inside diameter, outside diameter, and length), thermal parameters (downhole temperature, maximum operating temperature of equipment, and time required downhole), and other important features such as power dissipation of the equipment and the size and number of wires required to pass into the flask.

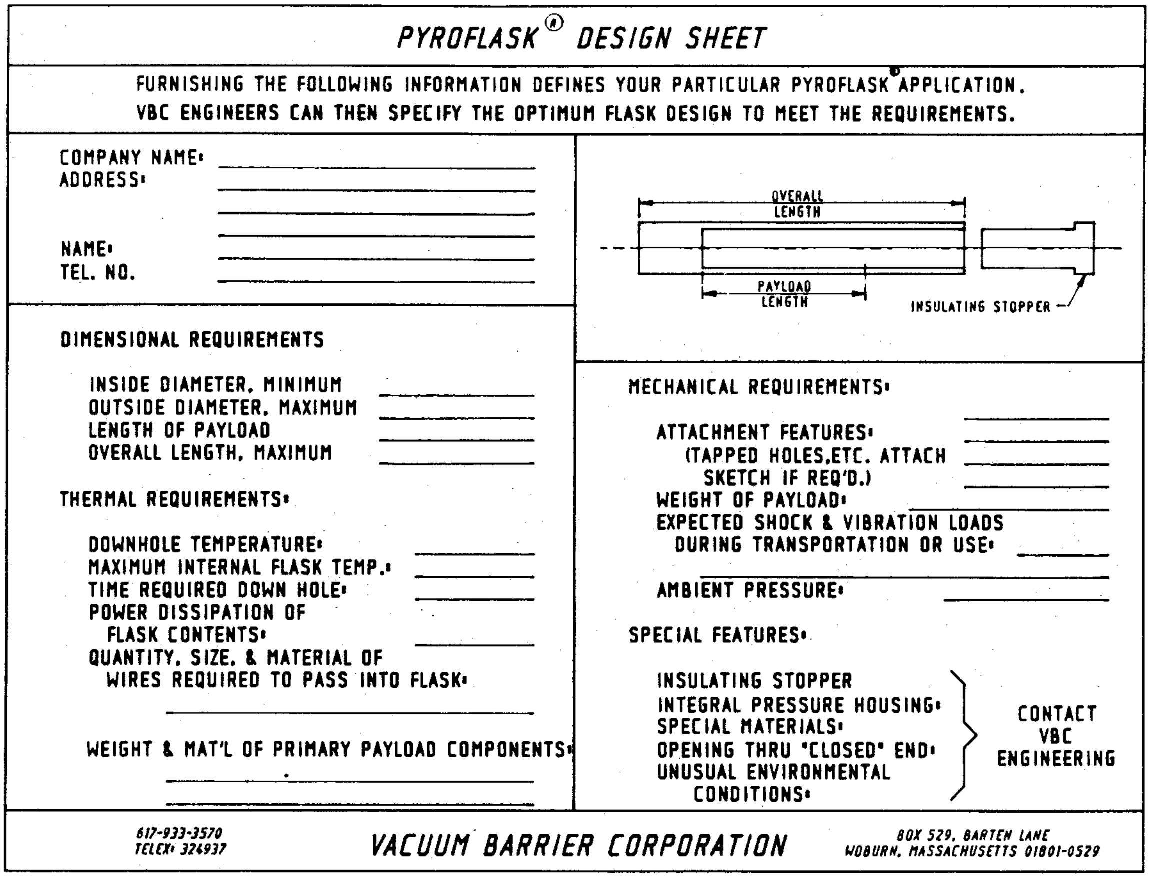
In applications where overall tool diameter must be kept to a minimum, a situation can be encountered where there is simply not enough room to feasibly include a PYROFLASK. In these instances, consideration can be given to the integral PYROFLASK/pressure housing. Note that in this design the outer shell is not thin but a thick, high-strength material that not only functions as the pressure housing but also saves considerable space.

Fig. 4. Thermal performance testing.

Figure 6 shows an actual flask made by VBC, which has a 1.688-in. o.d. and a 1.210-in. i.d., representing a total annular thickness of less than 0.25 in. while exhibiting a pressure rating of 20 000 psi. This combination of diameters and external pressure capability would be virtually impossible if the flask and pressure housing were two separate components.

This unit also illustrates the incorporation of a feedthrough or penetration through the closed end of the flask. With this feature, wires which run into the flask can pass through the closed end to equipment beyond.

Figure 7 shows actual oven-test data for this integral PYROFLASK/pressure housing. While in a 450°F environment, the internal temperature is maintained below 250°F for 15 h and below 325°F for 24 h. Note that the internal equipment was simulated by 5.1 lbs of aluminum. To illustrate the effect of heat capacity within the flask, consider this same test but with the internal equipment simulated by the same size bar of stainless steel. The higher heat capacity per unit volume exhibited by the steel results in the internal temperature being maintained below 250°F for 23 h, or 8 h longer than with the aluminum.



PYROFLASK® DESIGN SHEET

FURNISHING THE FOLLOWING INFORMATION DEFINES YOUR PARTICULAR PYROFLASK® APPLICATION. VBC ENGINEERS CAN THEN SPECIFY THE OPTIMUM FLASK DESIGN TO MEET THE REQUIREMENTS.

COMPANY NAME: ______
ADDRESS: ______

NAME: ______
TEL. NO. ______

DIMENSIONAL REQUIREMENTS

INSIDE DIAMETER, MINIMUM ______
OUTSIDE DIAMETER, MAXIMUM ______
LENGTH OF PAYLOAD ______
OVERALL LENGTH, MAXIMUM ______

THERMAL REQUIREMENTS:

DOWNHOLE TEMPERATURE: ______
MAXIMUM INTERNAL FLASK TEMP.: ______
TIME REQUIRED DOWN HOLE: ______
POWER DISSIPATION OF FLASK CONTENTS: ______
QUANTITY, SIZE, & MATERIAL OF WIRES REQUIRED TO PASS INTO FLASK: ______

WEIGHT & MAT'L OF PRIMARY PAYLOAD COMPONENTS: ______

MECHANICAL REQUIREMENTS:

ATTACHMENT FEATURES: (TAPPED HOLES,ETC. ATTACH SKETCH IF REQ'D.) ______
WEIGHT OF PAYLOAD: ______
EXPECTED SHOCK & VIBRATION LOADS DURING TRANSPORTATION OR USE: ______
AMBIENT PRESSURE: ______

SPECIAL FEATURES:

INSULATING STOPPER
INTEGRAL PRESSURE HOUSING:
SPECIAL MATERIALS:
OPENING THRU "CLOSED" END:
UNUSUAL ENVIRONMENTAL CONDITIONS:

} CONTACT VBC ENGINEERING

617-933-3570
TELEX: 326937

VACUUM BARRIER CORPORATION

BOX 529, BARTEN LANE
WOBURN, MASSACHUSETTS 01801-0529

Fig. 5. A standard form utilized for evaluating flask application.

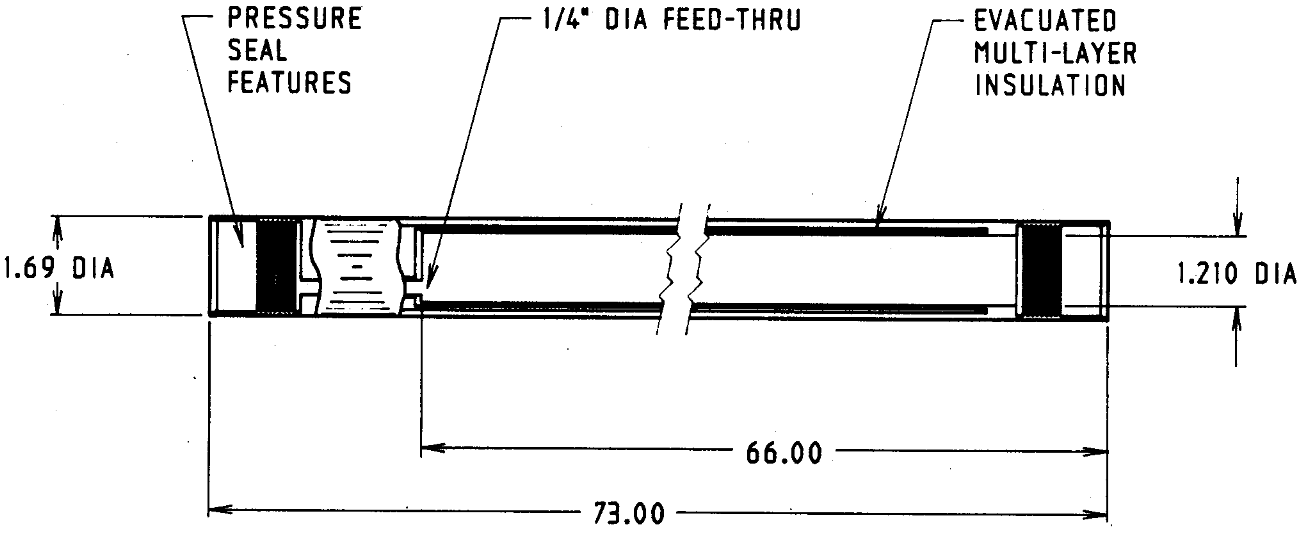


Fig. 6. Integral PYROFLASK/pressure housing.

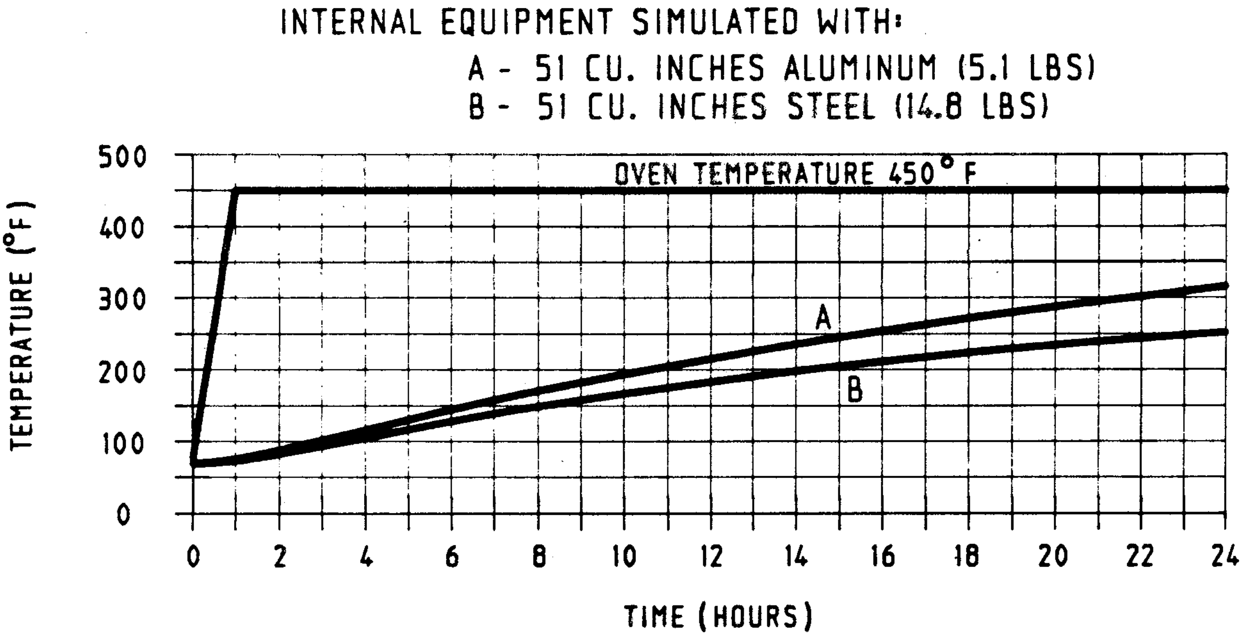


Fig. 7. Thermal performance.

Over the years, Vacuum Barrier has created PYROFLASK designs to solve particularly difficult applications. Our design versatility allows the use of unique, high-performance materials to meet individual requirements. Also, to assist in development of designs, Vacuum Barrier offers thermal analysis through use of our computer program.

We hope this brief overview of PYROFLASK features and capabilities will be of assistance when you are considering future thermal protection requirements.

GEOTHERMAL INSTRUMENT THERMAL PROTECTION

by

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The development of the geothermal energy resource depends in part on the success in gathering accurate data that will aid in characterizing a geothermal wellbore and its associated reservoir -- both during reservoir growth and during its useful lifetime. Instrumentation capable of providing geophysical data from a hot wellbore must repeatedly and reliably survive hostile thermal conditions. The purpose of the analytical work on these systems is to (a) extend the thermal lifetime of an instrument at a stated temperature or (b) increase the survival temperature for a stated thermal lifetime. The Los Alamos National Laboratory thermal protection system design goal is 320°C.

Thermal protection systems presently used in the industry can be divided into three categories: (a) none, (b) single trip, and (c) passive protection. The instruments with no thermal protection system are either purely mechanical or have hardened sensors or electronics that require no protection. The instruments good for a single trip are protected by a massive sonde that provides enough thermal lag time for one round trip. The passive thermal protection systems are specifically designed to provide extended thermal protection at high temperature.

The Los Alamos National Laboratory is involved in and has completed an extensive modelling effort of the passive thermal protection systems presently in use. The numerical methods used encompass both the finite element models and the finite difference models of the major system components, which are the hot service dewar, a heat sink, and their associated heat transfer paths. The models are used to generate parametric data as to changes in the behavior of the thermal protection system caused by changes in any of its components. The changes can be mounting hardware material changed from steel to brass or aluminum on a heat pipe, change in a heat sink material from aluminum to a fusible material, changes in the relative size of a heat sink, and changes in the physical arrangement of components inside a dewar flask. This method of arriving at a design change is costly in terms of research and development effort, which might appear as a "hunt and peck" method. But the extensive modelling provides information from which to make an intelligent choice for a design change that leads to improvements in thermal performance. In this way, the "hunt and peck" process is confined to an engineer and his models rather than involving numerous electrical and mechanical technicians, designers, draftsmen, and machinists.

Results from the models provide data about the heat flux entering the instrument, the temperature history for any point in the model, and the temperature field at any time during the simulation.

Design improvements that have been realized include the following: (a) a reversal of the thermal potential between the electronics compartment and the heat sink to allow heat flow from the electronics into the heat sink and (b) an increase in the conductance of the heat transfer path by a factor of 100X. The resulting improvement in thermal lifetime is a factor of 4X.

Thermal modelling will continue to be used at Los Alamos National Laboratory to sort through design ideas before they are committed to hardware.

THE THEORY AND DESIGN OF DOWNHOLE THERMAL PROTECTION SYSTEMS FOR DOWNHOLE INSTRUMENTATION

by

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The continuing search for natural gas and petroleum reserves, as well as searches for geothermal energy, has forced drillers to continually go deeper and to encounter hotter formations than ever before. The increase in well temperature leads to all manner of problems, not the least of which is the inability of downhole instrumentation to survive exposure to these temperatures. While advances in electronics, batteries, and film have produced state-of-the art instrumentation capable of sustained 300°F exposure or more, many of the deeper wells, geothermal wells, and steam injection wells have a downhole temperature of 500°F or more, and it does not appear that electronics will catch up with the higher well temperatures in the near future.

Insulated housings for the instrumentation provide a viable means of logging or surveying the high-temperature environments with low-temperature instrumentation. A properly designed insulated housing can provide many hours of time downhole before the internal temperature approaches the instrument's limit.

Insulated housings are governed by the following thermodynamic principle:

$$\text{System temperature rise rate} = \frac{\text{system heat input rate}}{\text{system specific heat}}.$$

The goal of an insulated instrument housing is to minimize the system temperature rise rate. Hence, the goal in designing an insulated system is to minimize the heat input rate and maximize the system specific heat. That is, minimize or eliminate heat paths and maximize the internal heat storage (heat sink).

Figure 1 summarizes the three modes of heat transfer: conduction, convection, and radiation. Dewar flasks, double-wall containers with reflective internal surfaces, and evacuated space between the walls successfully address each of the heat transfer modes and provide a very low overall heat transfer coefficient. Work initiated by NASA during the space program of the 60's resulted in the development of "super insulation," a blanket of alternating layers of reflective surfaces and insulating material as shown in Fig. 2. When used in combination, a super insulation/dewar housing provides a very effective insulating barrier. Effective wall heat transfer coefficients of 3.8×10^{-5} Btu/h-ft-°F are possible.

Heat sinks can be utilized to provide additional heat storage and improve the system specific heat. Figures 3 and 4 summarize the properties of various materials useful as heat sinks. Phase change materials can provide a very good means of heat storage and temperature plateaus that may be useful with certain instruments.

Dewar flasks retain internally generated heat as well as keep out external heat. Instrument power dissipation will dominate the system

CONDUCTION: $Q_{\text{COND.}\,1\text{-}2} = \frac{Ak}{L}(T_1 - T_2)$

MINIMIZE: $Q_{\text{COND.}}$:

i) MINIMIZE CONDUCTION PATH AREA A
ii) MINIMIZE CONDUCTIVITY
iii) MAXIMIZE CONDUCTION PATH LENGTH L

$Q_{\text{COND.}} \Longrightarrow 0$ ELIMINATE CONDUCTION PATH - O

CONVECTION: $Q_{\text{CONV}_{1\text{-}2}} = h_c A (T_1 - T_2)$

MINIMIZE $Q_{\text{CONV.}}$

i) MINIMIZE CONVECTION COEFFICIENT h_c (DEPENDENT UPON MEDIUM AND GEOMETRY)
ii) MINIMIZE AREA A

$Q_{\text{CONV.}} \Longrightarrow 0$ ELIMINATE CONVECTING MEDIUM

RADIATION: $Q_{\text{RAD}\,1\text{-}2} = \mathcal{F}_{1\text{-}2}\,\sigma\, A (T^4 - T_2^4)$

MINIMIZE Q_{RAD}:

i) MINIMIZE EMISSIVITY
ii) MINIMIZE AREA A
iii) MINIMIZE SHAPE FACTOR $\mathcal{F}_{1\text{-}2}$

$Q_{\text{RAD}} \Longrightarrow 0 \quad \epsilon \Longrightarrow 0$ = HIGHLY REFLECTIVE SURFACES

Fig. 1. Modes of heat transfer and means to minimize heat transfer.

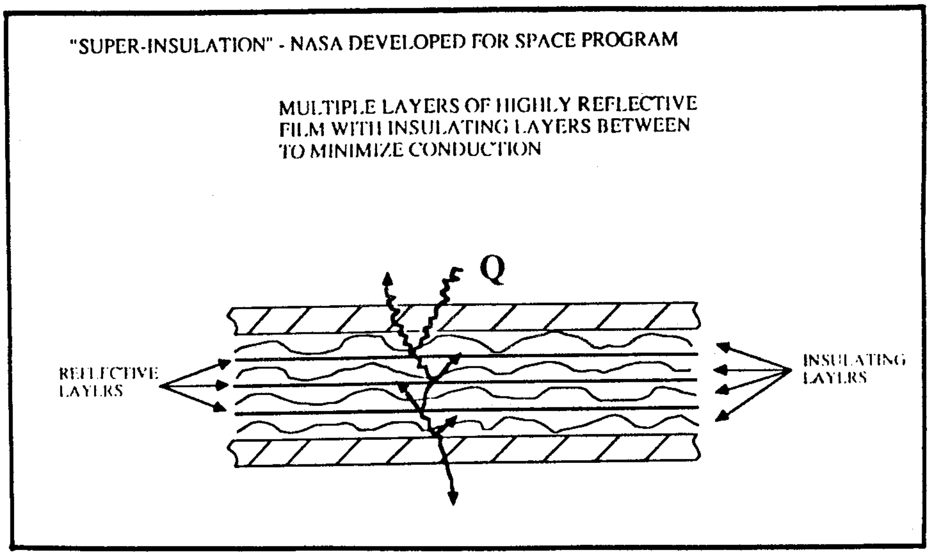


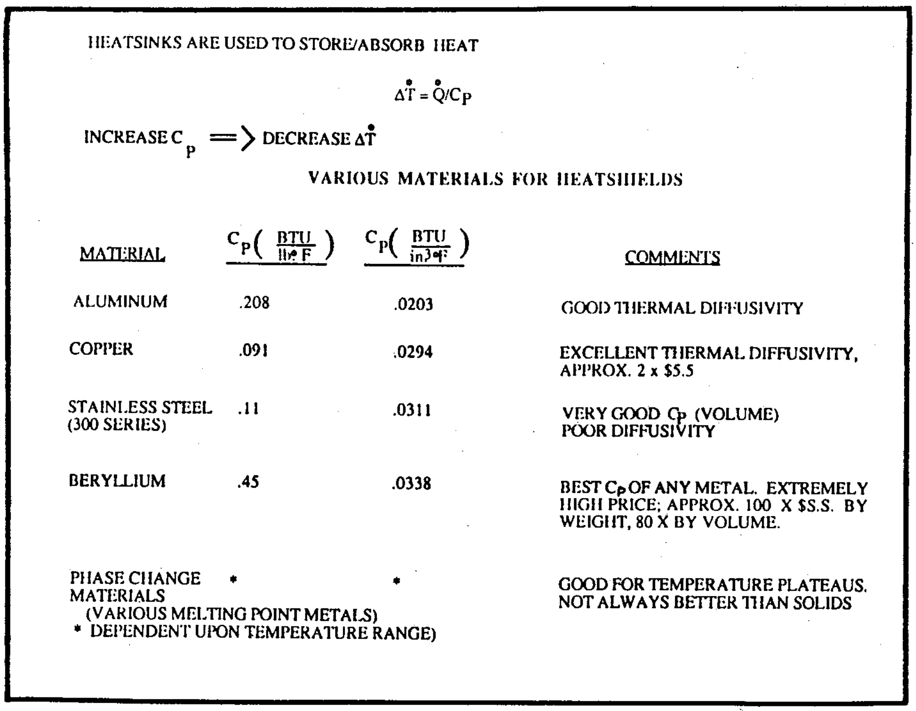
Fig. 2. A blanket of alternating layers of reflective surfaces and insulating material.

performance at levels higher than 5 W and, in many cases, is the main factor in influencing the system performance.

Aside from the power dissipation, the instrument provides a major contribution to the overall system specific heat. Electronics and PC boards provide little heat sink while the metal chassis and housing offer more heat storage.

Figure 5 details the modes of heat transfer for a Thermoshield. Knowing the various modes of heat transfer, internal dissipation, and the contributions to the system specific heat from housing, heat sink, and instrument, a prediction of the overall system performance can be made. Adjustments to the heat transfer paths or the heat sink can be made to tailor the performance to the specific requirements.

Thermoshields can be constructed with both electrical and mechanical feedthroughs. However, any feedthrough provides another heat transfer path to the payload compartment that ultimately degrades the system's performance. Thermoshields can also incorporate an integral pressure vessel rather than require a separate pressure housing. Figure 6 details the configuration of an integral pressure vessel Thermoshield.



HEATSINKS ARE USED TO STORE/ABSORB HEAT

$$\Delta\dot{T} = \dot{Q}/C_P$$

INCREASE $C_p \Longrightarrow$ DECREASE $\Delta\dot{T}$

VARIOUS MATERIALS FOR HEATSHIELDS

MATERIAL	$C_P\left(\frac{BTU}{lb\,°F}\right)$	$C_P\left(\frac{BTU}{in^3\,°F}\right)$	COMMENTS
ALUMINUM	.208	.0203	GOOD THERMAL DIFFUSIVITY
COPPER	.091	.0294	EXCELLENT THERMAL DIFFUSIVITY, APPROX. 2 x \$S.S
STAINLESS STEEL (300 SERIES)	.11	.0311	VERY GOOD C_P (VOLUME) POOR DIFFUSIVITY
BERYLLIUM	.45	.0338	BEST C_P OF ANY METAL. EXTREMELY HIGH PRICE; APPROX. 100 X \$S.S. BY WEIGHT, 80 X BY VOLUME.
PHASE CHANGE MATERIALS (VARIOUS MELTING POINT METALS)	*	*	GOOD FOR TEMPERATURE PLATEAUS. NOT ALWAYS BETTER THAN SOLIDS

* DEPENDENT UPON TEMPERATURE RANGE)

Fig. 3. Properties of various materials useful as heat sinks.

The need for instrument dewar housing will always exist. However, the increased desire to stay down longer at higher temperatures will eventually step beyond the capabilities of dewar systems. Microrefrigeration systems used in conjunction with dewars will provide virtually unlimited exposure to the high temperatures now being encountered. However, a viable microrefrigeration system has not yet been developed.

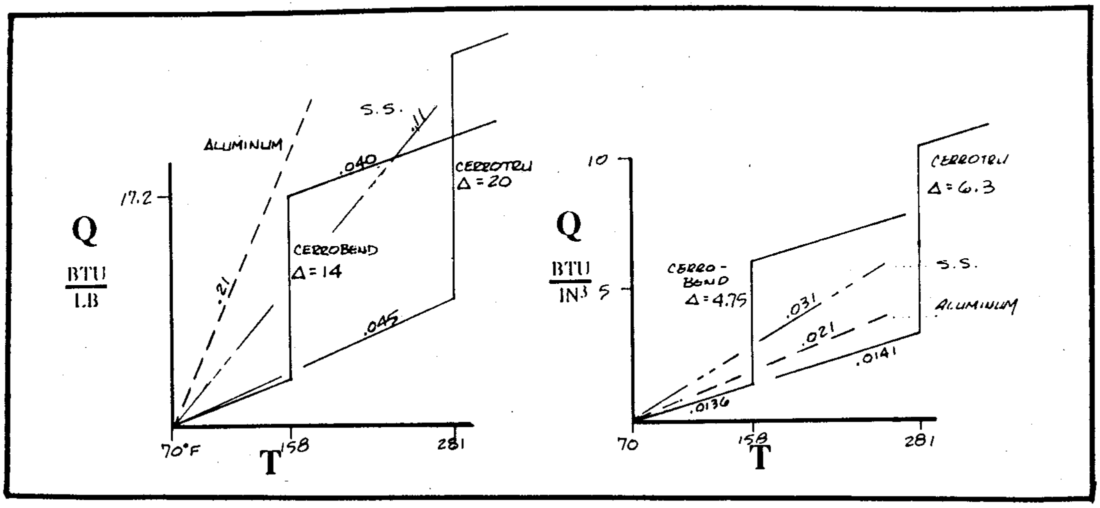
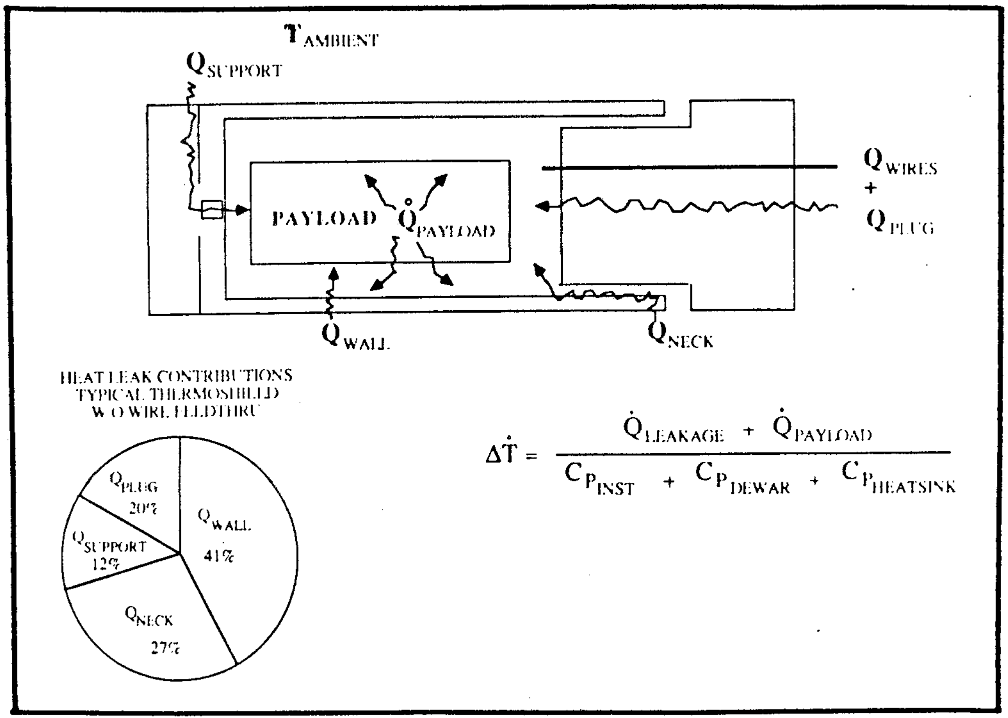


Fig. 4. Graphs of sensible heat gain phase change vs solid weight and volume.



$$\Delta \dot{T} = \frac{\dot{Q}_{LEAKAGE} + \dot{Q}_{PAYLOAD}}{C_{P_{INST}} + C_{P_{DEWAR}} + C_{P_{HEATSINK}}}$$

Fig. 5. Thermoshield performance analysis.

☐ **Integral one-piece design**
☐ **Reduced weight and outside diameter**
☐ **Increased internal space**
☐ **Durable**
☐ **Choice of pressure housing materials**
  - Nitronic 50
  - 17-4 PH
  - Inconel 718
  - Other material available to meet your strength and environment needs
☐ **Customer specified ambient ratings:** 20.000 psi. 500°F typical
☐ **Electrical and mechanical feed-thru's available**

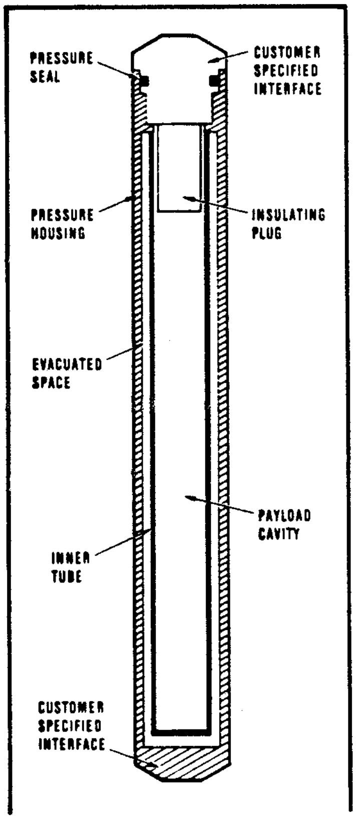


Fig. 6. Integral pressure vessel flask.

CROSSWELL ACOUSTIC TRANSCEIVER

by

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I. INTRODUCTION

Crosswell acoustic surveys are the optimum method of measuring the properties of rock between adjacent wellbores. Because of this fact, the Earth Science Instrumentation Group (ESS-6) decided to design and field a high-temperature crosswell acoustic transceiver or CAT system.

The CAT system consists of three major subsystems: the transmitter -- a constant, repetitive, controlled acoustic source; the receiver -- to measure the acoustic wave arrival in the adjacent borehole; and the surface data acquisition and control system.

The geophysists for whom the system was designed supplied us with the following specifications.

1) Environment
   a) Geothermal fluid -- 250°C at 10 000 psi
2) Transmitter
   a) Magnetostrictive type
   b) >3 joules of energy per pulse
   c) Variable fire rate (1 to 5 shots/sec)
   d) Source frequency centered at ∼10 kHz
   e) Downhole transmitter output monitor (shotbreak)
3) Receiver
   a) Piezoelectric crystal transducer (0-5500)
   b) Frequency response within 1 dB from 1 to 20 kHz
   c) Gain controlled manually or automatically from the surface

In order to facilitate the design and fabrication of the downhole sections of the system, the modular design approach was utilized. Modular design allows for simplified wire routing, minimizes the number of high-pressure feedthroughs and electrical connectors, and greatly simplifies assembly and disassemblies for easy breakdown of tools for field servicing, shipping, etc.

The downhole assemblies consist of four main modules.

1) Centralizers -- The centralizers hold the tool in the center of the wellbore. Centralizers are identical for both the transmitter and receiver.

2) Transducer Cavities -- These special stand-alone units hold the transducer and Teflon windows. To keep the windows at a very low differential pressure, a pressure equalization piston balances borehole fluid pressure and silicon oil pressure inside the cavity.

3) Electronic and Dewar Assemblies -- Electronics mounted inside a dewar flask are thermally protected by a eutectic material heat sink.

4) Cablehead Subassemblies -- These subassemblies are used to interface tools to the 7-conductor wireline.

II. TRANSMITTER (see Fig. 1)

Electrically, the transmitter is fairly simple. Up to 200 V of alternating current are sent downhole via two wireline conductors. The ac voltage is stepped up in a voltage trippler and charges the two 6-uf capacitors to ∿600 V. A fire pulse generated uphole is sent downhole on a single wireline conductor. The fire pulse is delayed and shaped in the firing circuit and fires the SCR. The SCR firing discharges the capacitors through the scroll windings, generating the acoustic wave. An accelerometer mounted on a bulkhead near the scrolls generates a shotbreak signal, which is amplified in the tool and transmitted uphole. Dewar temperature is also measured and sent to the surface.

III. RECEIVER (see Fig. 2)

Electronically, the receiver is more complex than the transmitter. The crystal, located in the transducer cavity, converts the acoustic wave from the transmitter into an electrical signal. The signal is amplified by a charge amplifier and two stages of digitally programmable, variable-gain amplifiers.

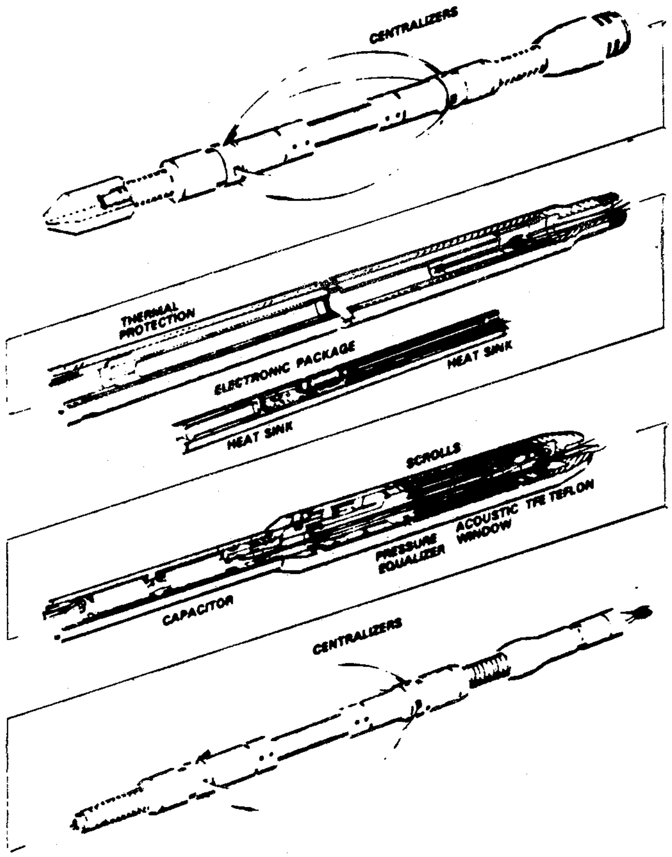

Fig. 1. Acoustic transceiver transmitter.

A low-gain signal taken from the output of the first variable gain amplifier and a high-gain signal from the second stage are fed to VCO's along with the output of a dewar temperature sensor. The VCO's are mixed, and the FM composite signal is transmitted to the surface via wireline conductors for storage and processing. A serial gain word from uphole feeds a UART circuit. The parallel output bus of the UART is then used to set the gain of the digitally programmable amplifiers.

Variable gain is necessary in the receiver for several reasons. The ceramic piezoelectric material used in the crystal transducer experiences an appreciable loss in sensitivity at elevated temperatures. Tests of these crystals show the output is -11 dB at 150°C from room temperature. Therefore, due to changes in acoustic transmissability of geologic strata in the borehole and the fact that transducer sensitivity is indirectly proportional to the

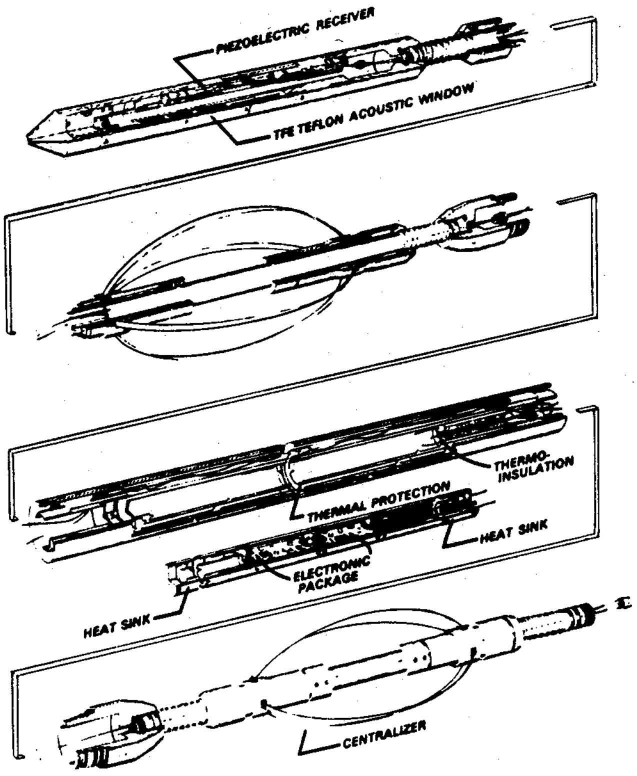

Fig. 2. Acoustic transceiver receiver.

temperature gradient of the borehole, variable gain becomes a very useful feature.

Acoustic coupling is enhanced by oil filling the transducer cavities. A TFE Teflon window separates oil inside the cavity from borehole fluid and offers excellent coupling. Also, to keep the receiver signal free of unwanted noise, a Faraday shield around the transducer crystal is utilized along with specially designed centralizers. Foam metal is used in the interface area between the centralizers and the tool body to minimize surface noise traveling down the wellbore from entering the tool.

IV. SURFACE SYSTEM

The surface system is the controller for both the transmitter and receiver. The FM composite signal from the receiver is fed through discriminators, and the raw signals are then stored on magnetic tape. The signals are also fed into a gain control box where the amplitude is measured and the gain changed if necessary. Dewar temperatures for the tools are also displayed.

A computer controls the firing rate of the transmitter as a function of depth or time and also starts and stops the tape recorder. Computer control of the firing rate and recorder expedites logging and conserves precious downhole operating time.

A crosswell survey consists of a collection of scans in which a repetitive signal source, or transmitter, is moved in one well between positions at comparable distances above and below the depth of a receiver stationed in a neighboring well. Stacking receiver waveforms to their corresponding depths produces a scan as illustrated in Fig. 3. Since data is stored on magnetic tape, geophysists can process it using a Fourier analyzer. From this processing, tomographic images can be produced as well as other forms of analysis.

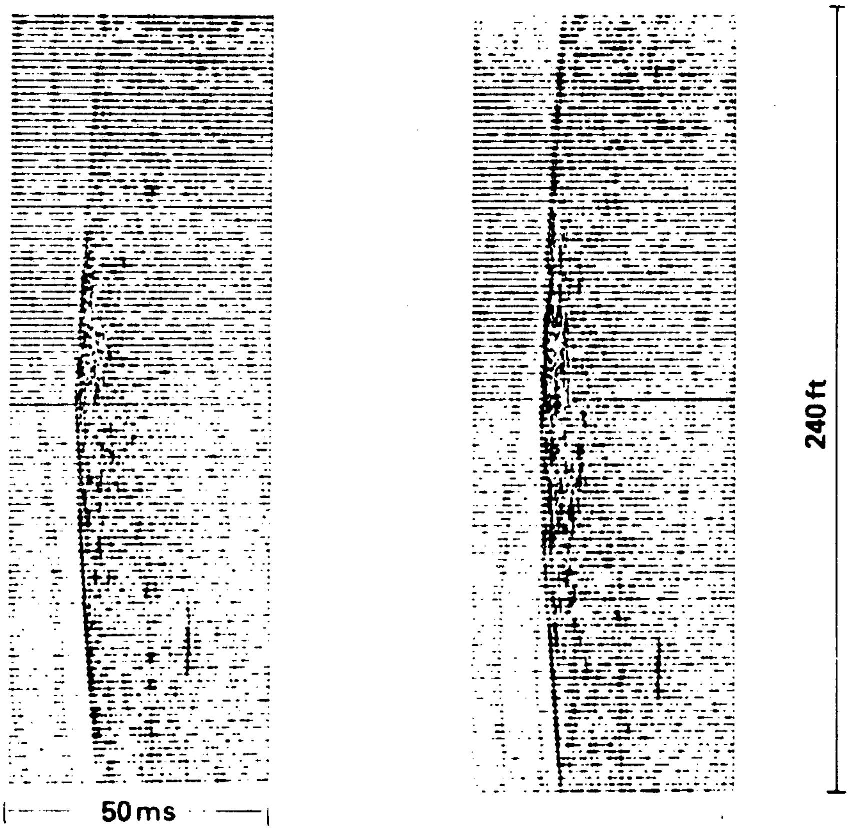

Fig. 3. Scan of stacking receiver waveforms to their corresponding depths.

DEVELOPMENT OF A NEW BOREHOLE ACOUSTIC TELEVIEWER FOR GEOTHERMAL APPLICATIONS

by

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ABSTRACT

Currently Westfalische Berggewerkschaftskasse (WBK) of West Germany and the Los Alamos National Laboratory of the United States are jointly developing a borehole acoustic televiewer for use in geothermal wellbores. The tool can be described as five subsystems working together to produce a borehole image. Each of the subsystems will be described.

I. INTRODUCTION

The tool described in this paper is an extension of the SABIS (Scanning Acoustic Borehole Image System) developed by WBK (Hinz and Schepers, 1983). The new version not only will be temperature hardened for geothermal applications but will incorporate several new ideas.* General tool specifications are found in Fig. 1. The scope of this paper will be to describe in general the subsystems of the televiewer.

The borehole televiewer can be broken into five subsystems. The acoustic part transmits and receives each acoustic pulse used to map the borehole wall. The reflected signal is processed by the downhole electronics. Resulting data are PCM encoded and transmitted to the surface via a logging cable. Once the

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*Information provided to K. Hinz by B. Dennis, Los Alamos National Laboratory (1985).

data arrive at the surface, the uphole control unit records the data on tape as well as provides the user with real-time outputs. Since the data will reside on tape, mission specific off-line processing procedures are easily applied.

In addition to mentioned design specifications, two other criteria have been addressed. The acoustic part of the tool has been placed as far forward on the tool as possible in order to provide a "look-down" perspective (Fig. 1). Also, subassemblies have been modularly designed to aid in field assembly.

II. ACOUSTIC SUBASSEMBLY

The acoustic system houses two piezoelectric crystals mounted 180° apart on a rotating block. Either the 1.3-MHz or the 625-kHz crystals may be selected via the uphole control unit. The crystals are rotated in a silicon oil-filled cavity at 360 rpm by an ac synchronous motor.

A Teflon window maintains separation between the silicon oil and borehole fluids. Pressure balance is preserved using a floating piston arrangement. Communication with the motor and transducer travels through a slip ring assembly and a high-pressure connector before reaching the downhole electronics.

III. DOWNHOLE ELECTRONICS

The downhole electronics subsystem is based around an Intel 8085 microprocessor responsible for control of the downhole data collection and transmission. Heat developed internally by the downhole electronics and heat from the environment are stored in a heat sink. The electronics and heat sink are packaged in a dewar for thermal protection.

For each shot, the travel time of the first arrival and the peak amplitude of the reflected signal are measured. To initiate a shot, the microprocessor triggers the selected crystal with a pulse. After ringdown, the crystal is reconfigured to act as a receiver of the reflected signal. At a predetermined time, the electronics begin listening for the return. The received signal is processed by an amplifier with an adjustable gain. The peak amplitude detected is retained. Both the time to begin the listening window and the amplifier gain are determined, based on previous shots, by the CPU.

GENERAL SUMMARY

O. D. 2.75 ″ 70 mm
(W/O CENTRALIZERS)

O. D. 3.375 ″ 86 mm
(W/CENTRALIZERS)

CENTRALIZERS 15″ 381 mm

LENGTH 14 ft 4.3 M

PRESSURE 9000 psi

TEMPERATURE 275 ° C

4-6 HOUR RUN AT 260° C

LOGGING RATE (FAST SCAN)
10 ft/min 3 m/min

TRANSDUCER ROTATION
360 rpm

CRYSTAL FIRE FREQ 3072 Hz
(OR 512/REVOLUTION)

MAX HOLE DIAMETER
20 in 50 cm

(USING C_{water} = 60,000 in/sec)

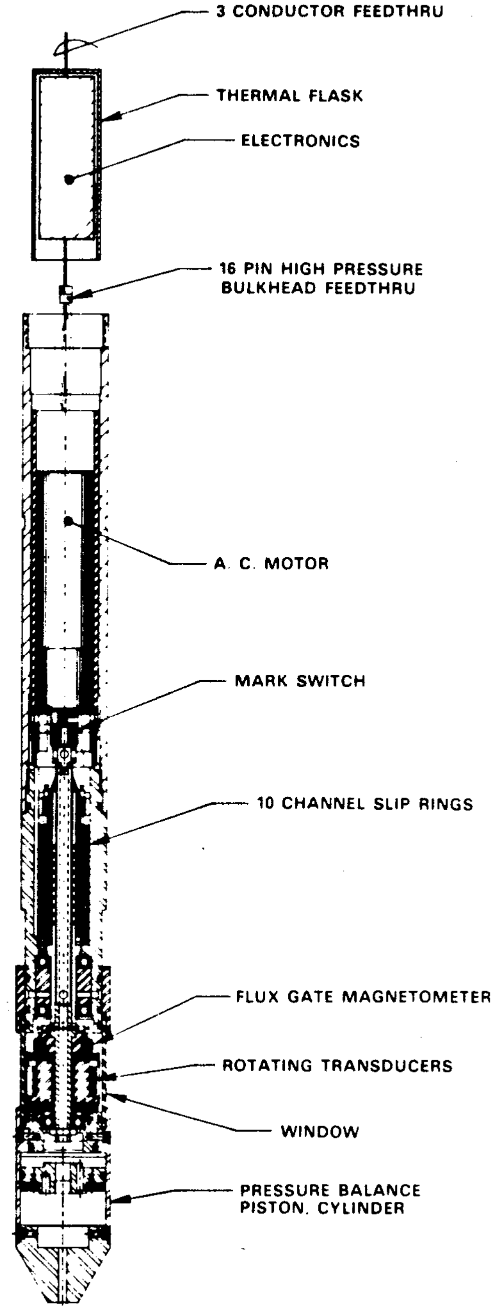

Fig. 1. Borehole acoustic televiewer.

Travel time of the first arrival is the time between firing the crystal and the reflected signal amplitude exceeding a threshold. The threshold is selected based on previous shots. To reduce noise in the received signal, the microprocessor synchronizes the signals driving the ac motor with receiver activities. This will guarantee that listening for a return and switching the motor current are mutually exclusive events.

Borehole temperature, temperature inside the dewar, and output from the three inclinometers represent data required only once per revolution. At specific times during a revolution, these conditions are sampled and available for encoding. A mark is generated to indicate a complete revolution of the acoustic part. Output from the fluxgate coil is interpreted to determine which shot most nearly aligns with magnetic north.

For uphole transmission, the peak amplitude and travel time values are appended together. Two additional bits are added to allow serial encoding of once per revolution parameters. The resulting data word is then PCM encoded.

IV. LOGGING CABLE

The PCM-encoded data are transmitted to the uphole control unit via 6600 m of 7-conductor or coaxial logging cable. Power for the downhole electronics is supplied using the logging cable.

V. UPHOLE CONTROL UNIT

The uphole control unit (Fig. 2) is constructed around the Siemens PMS-T 85D Microprocessor System (Intel 8085 CPU). This subsystem provides the user interface, controls the real-time outputs, and records the collected data on tape.

The uphole control unit provides the interface between the tool and the user. To initiate and control tool operation, commands are entered at the system terminal. The format of the real-time outputs can be changed at any time. Once-per-revolution parameters displayed on the system terminal provide insight into the condition and operation of the tool.

Upon arrival at the surface, the data stream is decoded, and the serial data are stripped off and placed in a parameter buffer. Travel time and peak amplitude values are separated and written to buffers. Date/time and logging rate values are input from external sources and included in the parameter buffer.

Data collected by the tool are displayed on a color monitor. A hardcopy may be generated by the gray scale recorder. Data are mapped to intensities via a user-selected look-up table. Using mark and magnetic north information,

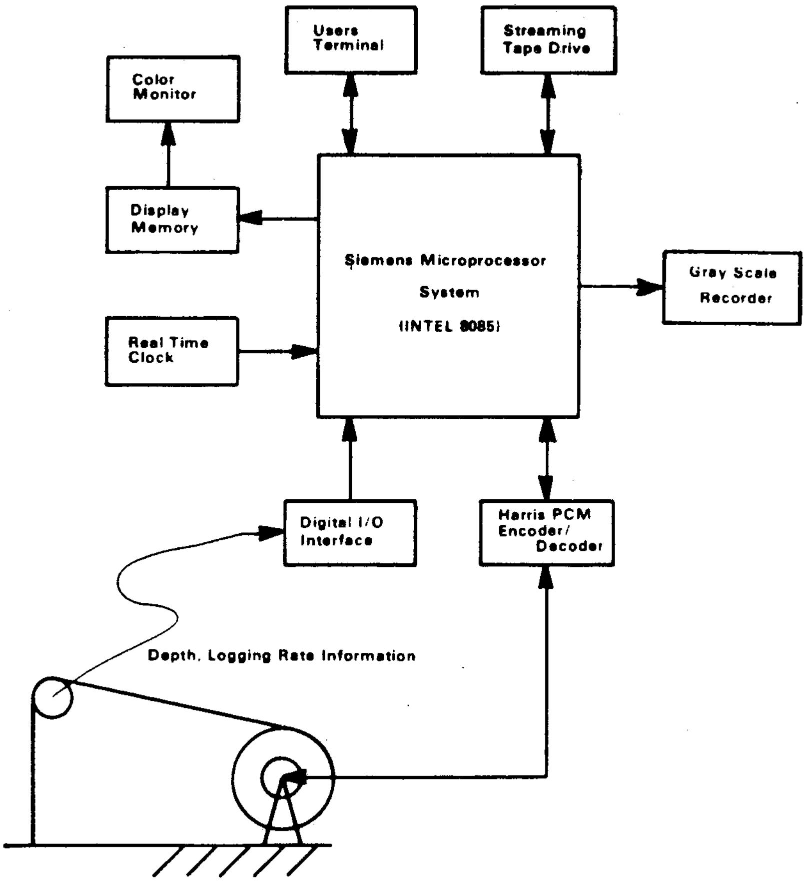

Fig. 2. Uphole control system.

data from a revolution are rotated to position the shot representing north as the first pixel in a raster scan line. Values from successive revolutions are inserted into the graphics controller such that the output of the color monitor will illustrate moving along the borehole.

Data are written to a 1/4-in. streaming tape on a revolution (mark-to-mark) basis. When all data from a revolution are present, the three buffers are written to tape as three records. A second set of buffers are present to allow concurrent I/O operations.

VI. OFF-LINE PROCESSING

Real-time outputs may not provide sufficient information for an application. Off-line processing allows the user to manipulate collected data to meet specific needs.

The 1/4-in. tape provides a medium for transferring data to a minicomputer for further analysis. A first step may be to organize the data into a standard format before any additional processing. Operations involved may include (1) data calibration, (2) rotating data using north information, (3) evaluation of borehole deviation, and (4) correction for tool not centered in borehole. Once initial processing has occurred, the data collection may be broken up into segments and placed in directories representing ranges of depths.

At this point, mission specific software may be applied. Such algorithms may include image enhancement, statistical analysis, pattern recognition, etc.

VII. SUMMARY

A borehole acoustic televiewer is being developed jointly by West Germany and the United States. As the tool moves along the borehole, ultrasonic pulses are fired from a rotating head. The amplitude and travel time of the reflected pulse are measured by the downhole electronics and transmitted to the surface via the logging cable. The uphole control unit records the data and provides real-time output to the user.

REFERENCES

1. K. Hinz and R. Schepers, "SABIS (Scanning Acoustic Borehole Image System) -- The Digital Version of the Borehole Televiewer," Eighth SPWLA London Chapter Europe Formation Evaluation Symposium Transactions (1983).

SPUTTERED THIN-FILM STRAIN-GAGE PRESSURE TRANSDUCER FOR HIGH-TEMPERATURE APPLICATIONS

by

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CEC's sputtered, thin-film, strain-gage pressure transducers are specifically designed for severe environment applications. They are widely used on rocket launch vehicles where they are subjected to high levels of shock and vibration. They tolerate highly corrosive pressurizing fluids and operate at temperatures ranging from that of liquid hydrogen (-423°F) to high-pressure steam above 500°F. The successful performance of these transducers in such severe environments results from a variety of design factors, stringent control of fabrication processes, and special aging operations to stabilize the entire sensing structure.

The processing steps that are essential to production of these stable, wide-temperature-range sensors are outlined herein.

The sensor beams or diaphragms are carefully machined to tight tolerances, annealed, age-hardened, and stress-relieved. The surfaces to be gaged are lapped flat and polished to a mirror finish free of surface strain and mechanical defects. A number of these beam or diaphragm substrates are then placed in a sputtering chamber for deposition of the thin-film sensor components.

In the sputtering chamber, low-pressure argon gas is ionized by an rf field. The ionized gas molecules are accelerated toward a flat plat target made of the material to be deposited where they impact, dislodge, and ionize atoms of the target material. The dislodged atoms are, in turn, accelerated toward the substrates arriving with sufficient energy to produce strong intermolecular bonds between themselves and the substrate atoms. Before deposition, however, the process is momentarily reversed to sputter-etch the surface of the substrates. This removes any remaining surface contaminants that might interfere with the adhesion of the deposited layer.

A thin layer of silicon dioxide (SiO_2) is deposited first to provide electrical insulation between substrate and strain gages. The gage material, a cermet, is next deposited over the entire surface of the substrates. The sensor elements are then removed from the chamber and are fitted with thin metal masks which have openings only where electrical contact pads are required for connection to the gage elements. These are again placed in a sputtering chamber where nichrome is sputtered onto the gage material, through the mask openings. The sensor elements are again removed from the chamber, coated with a layer of photoresist material and exposed to ultraviolet light through a photographic mask to define the gage elements. All unexposed photoresist is then removed, leaving only that which defines gage geometry and a portion of the metallic contact pads. The assemblies are again placed in the sputtering chamber for sputter-etch removal of all gage material except that protected by the photoresist. On removal from the chamber, the gages are probed to verify resistance, matching, and dielectric isolation. After thermocompression ball bonding of 0.002-in.-diam gold leads to the contact pads, the completed sensors are annealed and thermally aged well above maximum operating temperatures and then welded into transducer assemblies.

After assembly, the completed transducers go through an extensive pressure and temperature-aging process before compensation and final calibration to ensure their long-term operational stability.

The high-temperature CEC 1000-0009 assembly contains only metallic and ceramic materials, consequently it will operate continuously at temperatures up to 600°F.

USE OF HIGH-TEMPERATURE TRANSDUCERS IN GEOTHERMAL WELL LOGGING

by

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ABSTRACT

During the month of September 1985, Group ESS-6 of the Los Alamos National Laboratory was involved in logging several geothermal wells in the Miravalles Geothermal Field of Costa Rica. This operation was in association with the U.S. aid program to Central America. This report describes some of the high-temperature transducers and components used in this operation and defines some of the data taken with the use of these transducers.

I. INTRODUCTION

The purpose of this report is to demonstrate the use of various transducers and components in a geothermal environment. In all cases, the transducers and components were purchased by the Los Alamos National Laboratory for use in their downhole geothermal logging instruments.

The place chosen to demonstrate this usage is the Miravalles Geothermal Field in Costa Rica.

II. OPERATIONS

The logging operations in Costa Rica were performed with the following Los Alamos logging tools:

1) casing collar locator (CCL),

2) water-sampler,
3) 3-arm caliper,
4) spinner-temperature-pressure (STP) tool with CCL, and
5) temperature-pressure (TP) tool.

The logging tools used in Costa Rica contained the following major components and transducers:

1) thermistors,
2) dc motors,
3) potentiometers,
4) potentiometric pressure transducers,
5) strain-gage pressure transducers,
6) casing collar locators, and
7) reed switches.

The logging operations were performed with a logging unit that was outfitted with a Hewlett Packard data acquisition system, a 7-conductor, TFE-insulated logging cable, and a Los Alamos-designed cablehead.

III. LOGS

A. Temperature

On the average the production zone temperature at the Miravalles Geothermal Field was approximately 240°C. Figure 1 is representative temperature data of Well PCM-3 under nonflowing conditions. The plot is depth in feet versus temperature in degree centigrade. The water level with an isothermal layer of steam above the water level can be seen at 850 ft.

B. Water Sampler

One of the most important logging tools used in the Miravalles logging operation was the Los Alamos water sampler. The major components in this tool consist of a thermistor to measure the temperature of the sample and a dc motor for opening and closing the sample bottle.

During the first logging operation in Costa Rica, the water sampler acquired six samples in different wells under shut-in and dynamic conditions. The sample bottle used has a capacity of 817 mℓ. On the average, 550 mℓ of fluid was obtained with the remainder being gases.

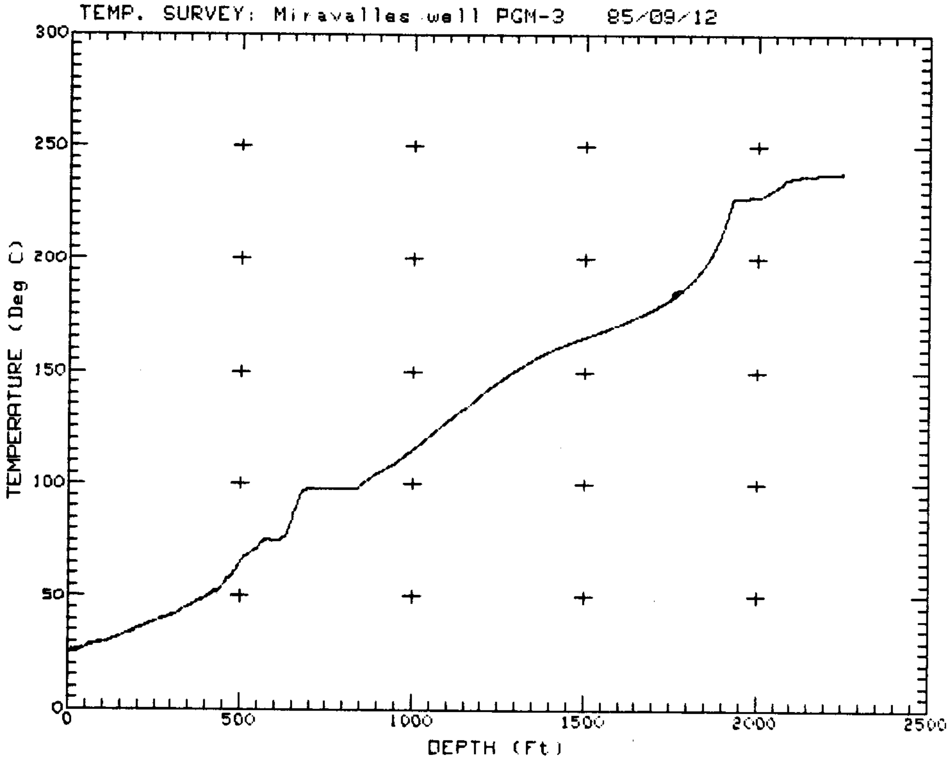

Fig. 1. Temperature data of Well PCM-3.

C. 3-Arm Caliper

The Los Alamos 3-arm caliper tool was used in Costa Rica primarily for the investigation of calcite buildup. The major components in this tool consist of rotary potentiometers and a dc motor to extend the arms when ready to log.

Figures 2, 3, 4, and 5 are representative of the caliper data taken in the Miravalles wells. The figures are data plots of the average radius in inches from tool centerline versus depth in feet.

Figure 2 is a plot of a 100-ft section of a 7-5/8-in. slotted liner in Well PGM-10. The nominal inside diameter of the 7-5/8-in. liner is 6.966 in. or 3.48 in. from tool centerline. From this plot you can see that this section of liner is nearly 0.4 in. under nominal inside diameter with little evidence of slots. The results suggest calcite buildup.

Figure 3 is a plot of a 100-ft section in the well above the plot in Fig. 2. Here we can see the gradual increase in inside diameter to near-rated values, and we can now see open slots in the liner.

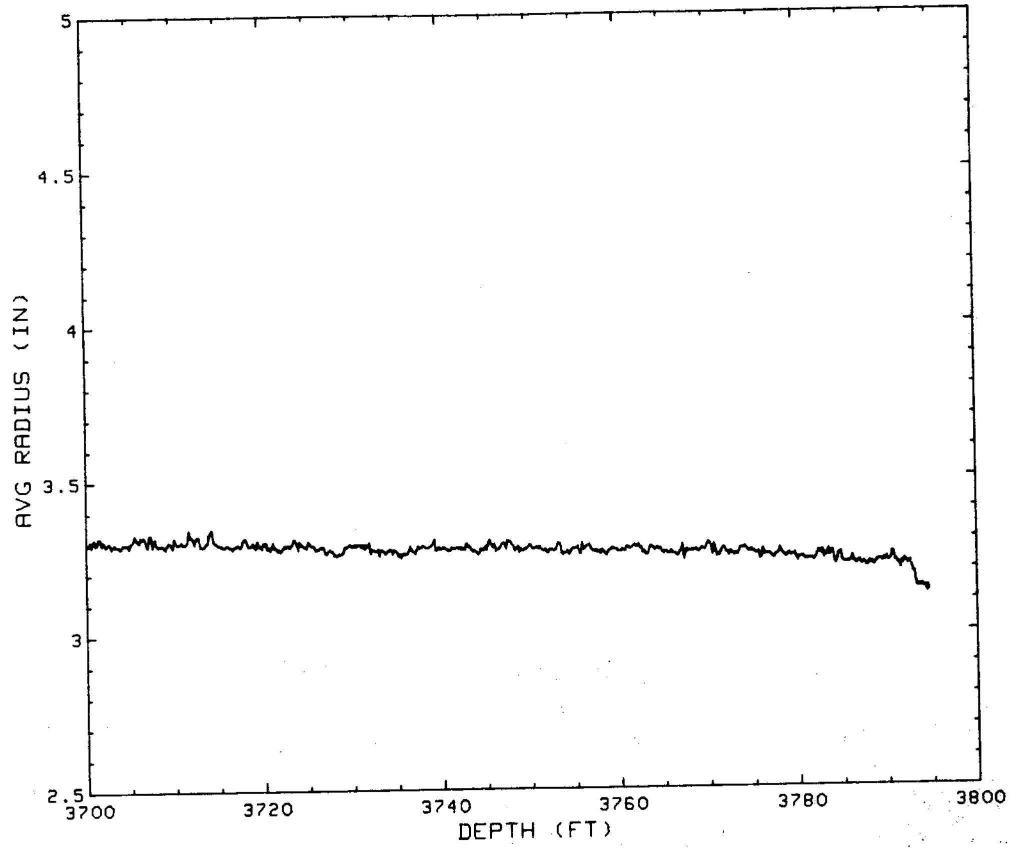

Fig. 2. Caliper data from Well PGM-10.

Figure 4 is a plot of a caliper survey of a 300-ft section of Well PGM-3. Starting from the left side of the plot, we have a 9-5/8-in. casing with a liner hanger and 7-5/8-in. liner top at approximately 1925 ft. Moving to the right, we have a blind liner to 2100 ft and a slotted liner from there down. In the middle of this plot above 2100 ft, we see two joints of 7-5/8-in. blind liner that should be smooth but show evidence of being pitted.

To show you that we do have individual 3-arm capability with readouts, Fig. 5 is a plot of the 3 arms from the section of the well in the previous plot, Fig. 4.

D. STP Tool

A logging tool that was used a great deal in the Miravalles logging operations was the spinner-temperature-pressure tool, or STP tool, with casing collar locator. The tool consists of the following transducers and components:

1) thermistor,

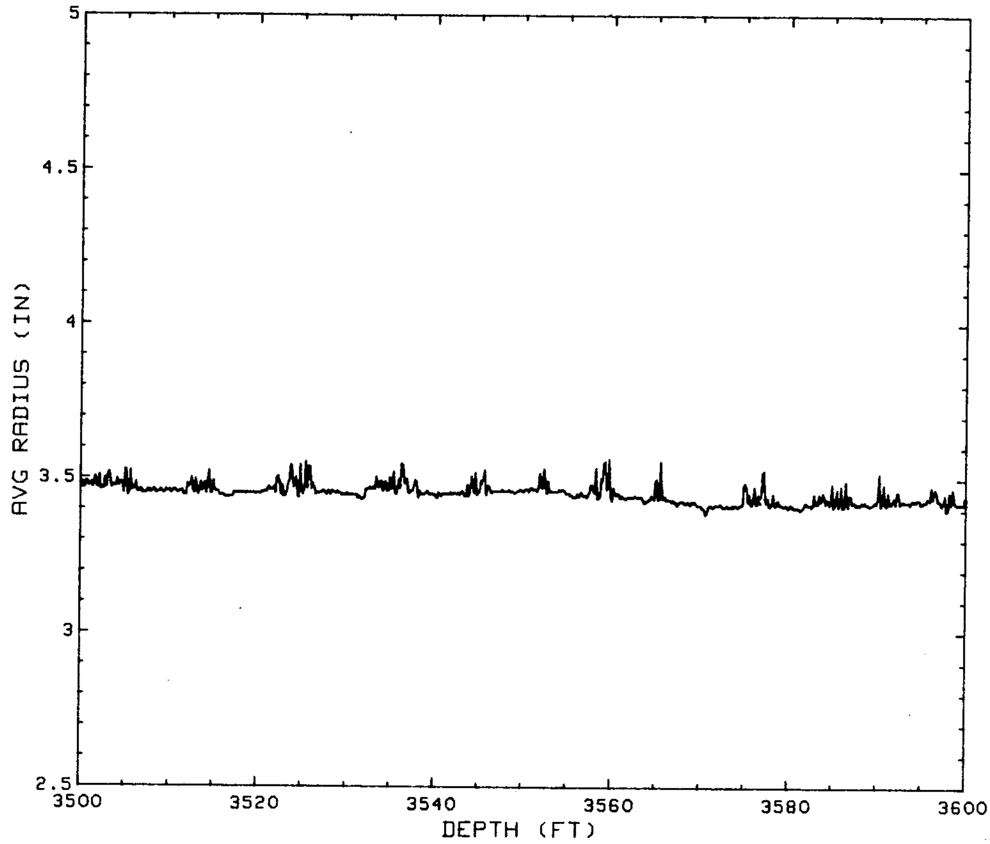

Fig. 3. Caliper data from Well PGM-10.

2) potentiometric pressure transducer,

3) casing collar locator, and

4) reed switches.

The instrument is strictly analog with no dewar or active electronics downhole. All four functions are recorded continuously without any switching using a 7-conductor logging cable.

Figure 6 is a plot of an STP survey in Well PGM-10 under shut-in conditions. Depth is 0 to 1200 m. The top trace is pressure in bars, the middle trace is spinner output in hertz, and the bottom trace is temperature in degree centigrade. The plot shows a wellhead shut-in pressure of about 5 bars with a fluid level of about 300 m. The only flow out of the well during this log was some gas flow through our control head. We can see this outgassing on the spinner output at the water level and below for about 150 m.

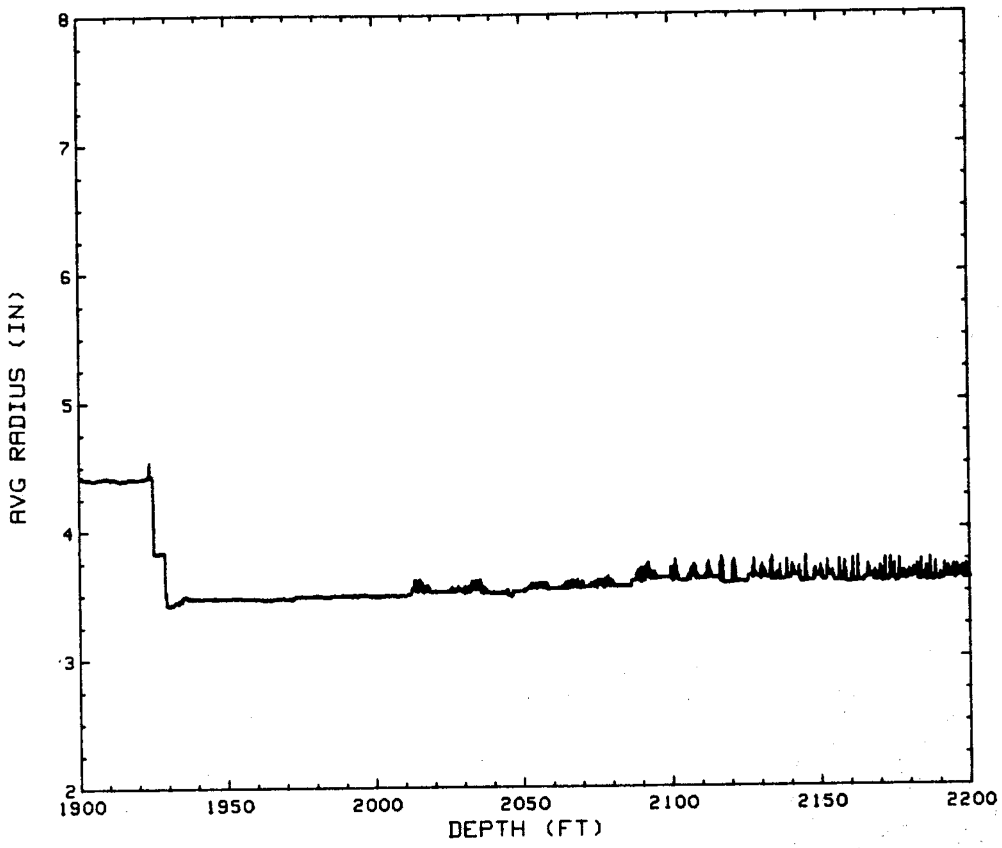

Fig. 4. Caliper data from Well PGM-3.

Figure 7 is a plot of the same well from 0 to 1200 m under dynamic or flowing conditions. Figure 6 has a spinner scale of 0 to 50 Hz. This plot is scaled from 0 to 800 Hz. Here we can see the spinner response in two-phase flow in the upper portion of the well, a velocity change at a liner top at 730 m, and the boiling point at approximately 850 m defined by all three functions. This data was recorded while logging down at a constant 50 ft/min rate.

An additional note on the spinner output shows an increasing velocity from the boiling point down. This can be attributed to a steadily decreasing pipe diameter due to calcite buildup.

The major production zone in this well is below our logging depth. Because of calcite buildup, the diameter of our logging instrument would not pass through the zone of interest.

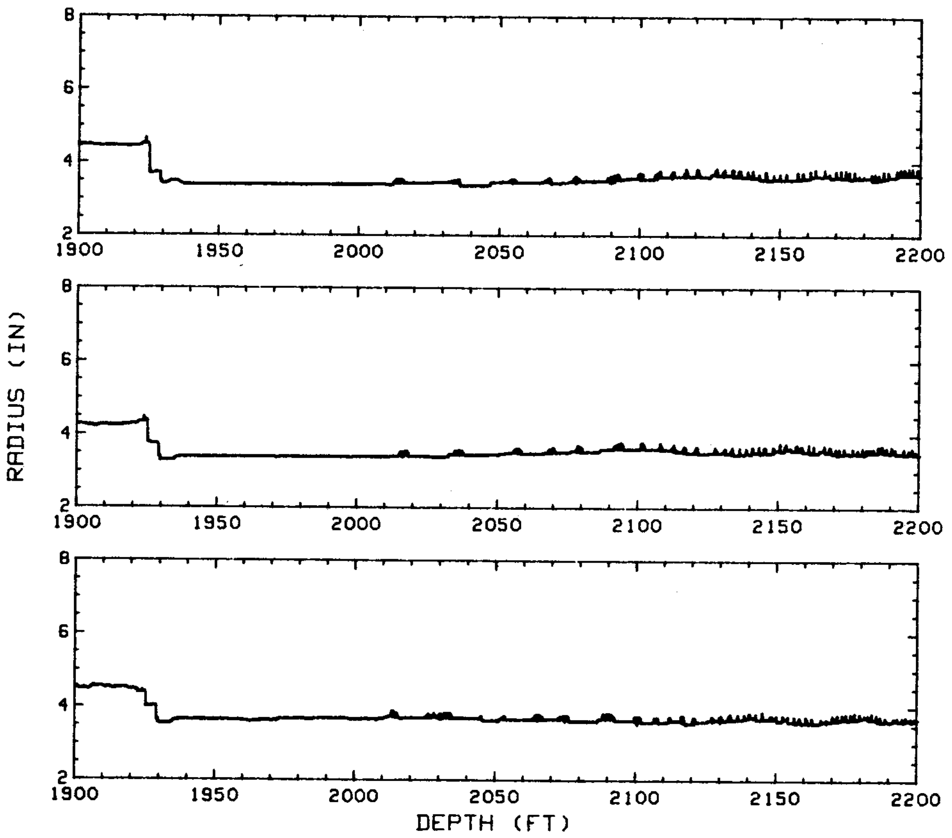

Fig. 5. Caliper data from Well PGM-3.

E. TP Tool

To record all functions of the STP tool on a 7-conductor logging cable, a potentiometric pressure transducer was used. An alternate pressure measurement was also used in Costa Rica with a temperature-pressure tool, or TP tool. The components in this tool include a thermistor and a strain gage-type pressure transducer rather than potentiometric.

Figure 8 is a plot of a temperature/pressure survey in Well PGM-10 from 0 to 1200 m under dynamic or flowing conditions. The top trace is pressure in bars, and the bottom trace is temperature in degree centigrade. Again, we can define a boiling point at 850 m by the break in both the pressure and temperature curves.

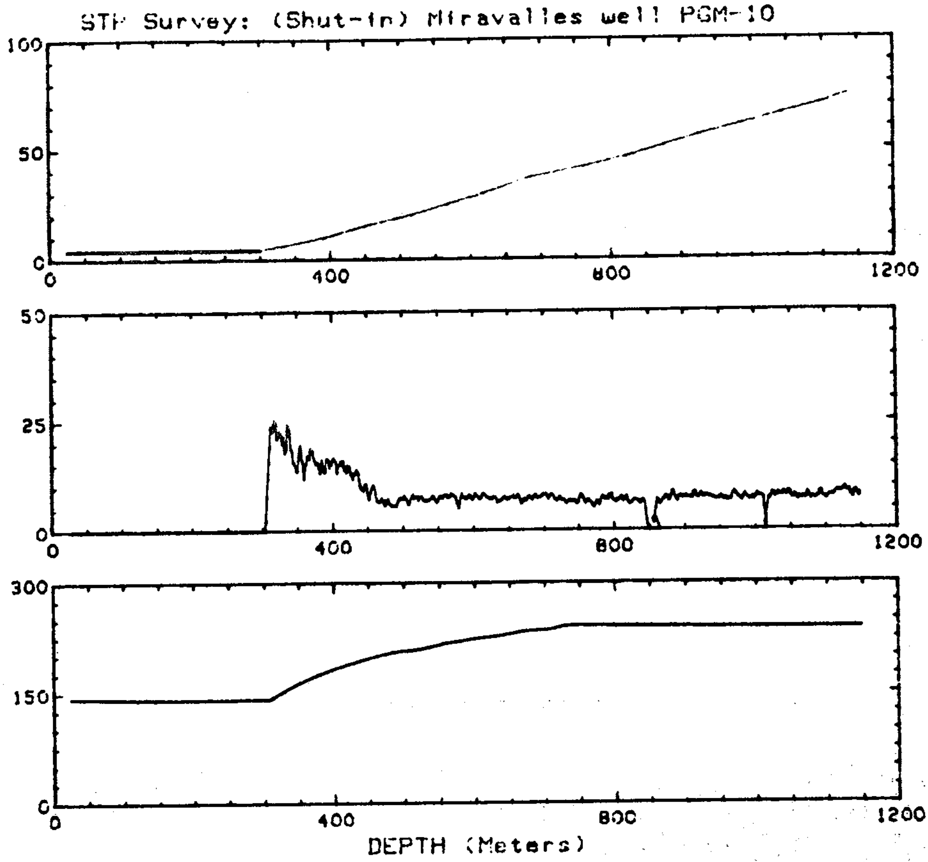

Fig. 6. Plot of an STP survey in Well PGM-10.

IV. SUMMARY

In summary, the recent logging operations in Costa Rica have demonstrated the use of several high-temperature components and transducers for use in geothermal well logging.

Transducers, components, seals, insulating materials, etc., used in the high-temperature logging operations in Costa Rica were purchased from the following manufacturers: Rochester Corporation; Kemlon Products; Gulton Industries; E.I. DuPont Company; American Electronics, Inc.; Dow Corning; Parker Seal; Bal-Seal; Allen Bradley; Multicore Solder; Boyd Industrial Rubber; Gearhart; Sparton Southwest; CEC Instruments; Litton Potentiometer; Conax Corporation; Standard Wire and Cable; Hot Hole Instruments; and Hamlin.

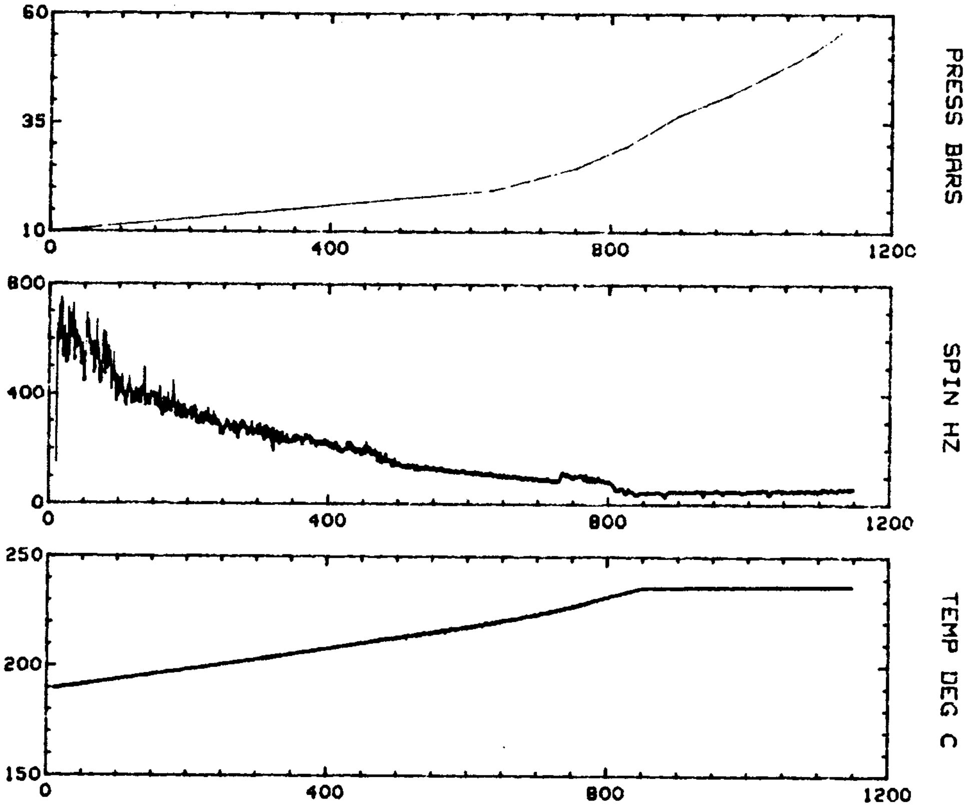

Fig. 7. Plot of an STP survey in Well PGM-10.

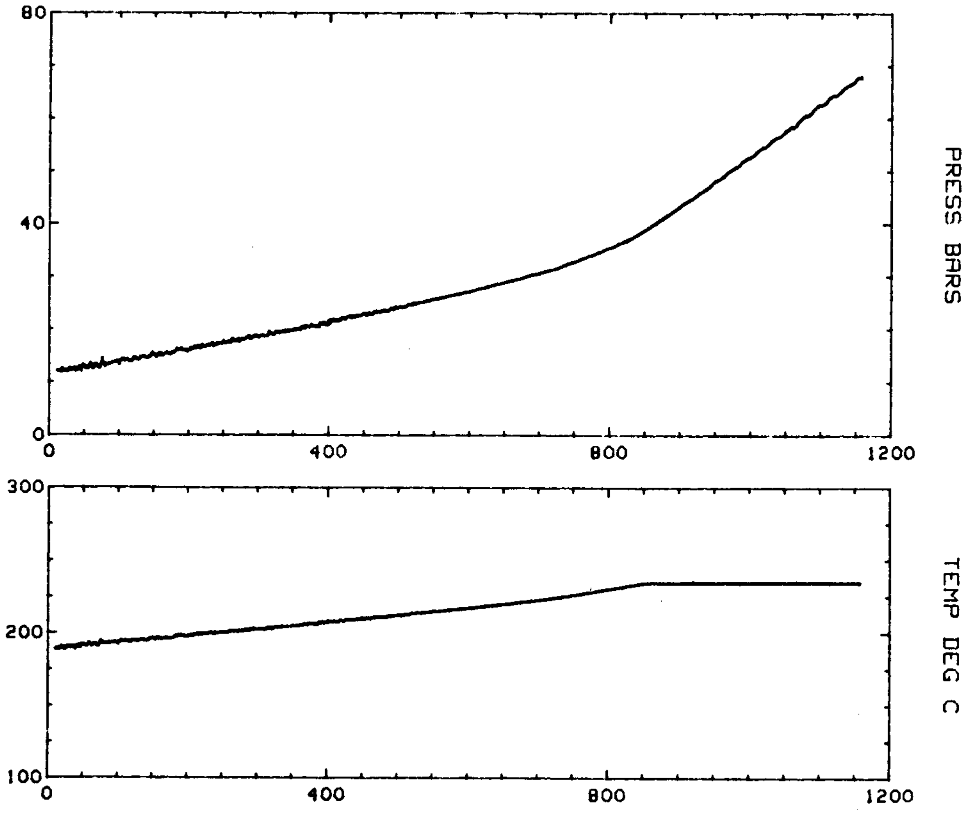

Fig. 8. Plot of a temperature/pressure survey in Well PGM-10.

HIGH-TEMPERATURE VELOCITY TRANSDUCERS

by

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ABSTRACT

The high-temperature transducers discussed in this paper are a modification of the moving-coil, velocity-sensitive, motion transducer widely used in seismic exploration in the oil business. They are commonly called geophones or seismometers. In this service they are expected to operate satisfactorily at any ambient temperature found from the north slope of Alaska to the Sahara desert. These conditions range from -40°F to 130°F.

Increasing usage of these transducers as a component in bottom-hole well-logging instruments at greater depths has raised the service temperature requirements for these components.

Two areas of interest are affected when the transducers are subjected to temperatures much above 200°F. These are

1) mechanical integrity due to changes in physical properties of materials in their construction, and

2) changes in electrical characteristics.

The materials used in the normal transducer and their substitutes for high-temperature applications will be discussed. Changes in electrical characteristics can be predicted fairly accurately by computer. Some verification has been made by test but not much over 200°F. We considered temperatures to 500°F, which is about the upper limit for materials presently being used in this application.

I. INTRODUCTION

The transducer discussed in this paper is basically a very simple device consisting of a moving coil in a magnetic field. Its sensitivity is proportional to the velocity of the coil with respect to its case and the product of the length of wire in the magnetic field and the flux density of the magnetic field. The length of coil winding is constant as is the flux density at a given temperature. Thus, it is a velocity-sensitive transducer.

Its coil form has two windings, each on aluminum bobbins or forms separated by an insulating plastic center section. This coil form is supported within two magnetic fields of opposite polarity by a pair of three-arm springs, one at each end of the coil form. The coils are wound in opposite directions and connected in series. Their outputs are thus additive. The opposite polarity of the two magnetic fields has a canceling effect on any external magnetic field. This type of construction is called "Hum Bucking." Transducer output that is due to power transmission lines or other strong fields is eliminated.

The materials normally used in the transducers's construction are such that their mechanical integrity is not compromised nor are their electrical characteristics much altered over the temperature range from -40°F through 200°F. However, if service temperatures much higher are to be expected for any period of time, changes must be made.

In this discussion, high temperature is considered to be continuous service at 500°F and short-time exposure of a few hours in the range of 525 to 550°F but never to exceed 550°F.

We examined the changes in the materials used in each part of the assembly that are needed to meet these service temperature requirements.

A. Outer Case

Cadmium-plated steel is normally used. This is satisfactory for well over 550°F.

B. Case Top and Bottom

A zinc die casting of Zamak 2 is normally used. Unsatisfactory. Part is machined from free machining yellow brass for high-temperature service.

C. Tubular Hermetic Seals

Hot tin-dipped Kovar/glass seals are normally used. Unsatisfactory. All tin is chemically removed and both flange and tubular portion of seal are gold electroplated. This is done to eliminate leaching of tin into high-temperature solder during termination. Contamination of high-temperature solder by the tin will lower its melting point to an intolerable level. Ersin HMP solder with a liquidus of 565°Fto 574°F is used both when soldering the hermetic seals and terminating the coil winding internally.

D. Coil Form Assembly

This part is normally a molded assembly consisting of two 2011-T3 aluminum alloy bobbins joined by an insulating plastic band of 33% glass-filled nylon. This is unsatisfactory over 200°F. For high-temperature service, the two bobbins are joined with a central band machined from DuPont Vespel SP-1. Its service temperature is over 650°F when in an inert atmosphere. All our transducers are evacuated and filled with an atmosphere of dry nitrogen and hermetically sealed. The aluminum bobbins are attached to the Vespel center section using gold-plated brass 00-90 machine screws.

E. Coil Windings

Normally soldereze-insulated copper magnet wire is used. This insulation is obviously not satisfactory for this service. Here we use Teflon-insulated wire good for 500°F continuous and much higher for short periods of time. Ersin HMP solder is used for termination to the gold-plated screws. The bobbins are insulated from each other by the Vespel section, and the bobbins themselves are used for coil termination. Output is brought out through the support springs on each end of the coil. The windings are insulated from the bobbins by a layer of 0.003-in.-thick Teflon tape.

F. Support Springs

These springs for all service temperatures are the same. They are made of BeCu Alloy 25 rolled to 1/2 hard temper. They are chemically etched to correct outline using techniques similar to those used in printed circuit board manufacture. Dimensions are held to closer than 0.0005 in. After the springs are etched to size, they are precipitation hardened to maximum properties by heat treating in a special fixture for 2 h at 600°F. This fixture performs the spring to a raised or offset condition when it is not supporting the coil mass to an amount equal to the sag when the coil mass is applied. Thus, the springs are flat when the unit is assembled. This flat spring condition produces a transducer with an output of a high degree of linearity and a distortion of less than 0.2% at high-output levels.

Temperatures much above 500°F will partially anneal the spring material, and the springs will sag until the coil rests on the case bottom and the transducer is inoperative. We have yet to encounter this failure in service and cannot predict life span at any particular temperature.

G. Magnets

The magnets used are made of Cast Alnico 8 and ground to size. Temperatures within the desired range have no irreversible effects on their magnetic properties. However, their magnetic strength or flux density does fall off by about 3.5% at 550°F. This is a small amount and is fairly predictable.

H. Pole Pieces

These are made of gold-plated screw machine steel and are not affected within the desired temperature range.

I. Other Internal Parts

There are three other insulating mechanical parts made of Vespel SP-1. As noted earlier, these are satisfactory to over 650°F in the atmosphere present. Two 0.010-in.-thick insulating washers of G-7 are also used to prevent ends of coil assembly from contacting the metal case top and bottom. This material has been satisfactory.

J. O-Rings

The O-rings used for hermetic sealing of the case top and bottom are of Parker E962-85 special ethylene propylene rubber compound for steam service over 500°F.

K. Changes in Electrical Characteristics

The electrical characteristics of the transducer are altered to various degrees by increase in operating temperature. These changes are predictable and easily calculated with a simple computer program. Most of these are most easily shown by response curves for the desired temperature. A series of these curves for a typical high-temperature transducer is included with this paper.

The natural frequency of the transducer does not change with temperature as long as it remains operable.

The open circuit sensitivity drops about 3.5% at 550°F. In most applications this can probably be neglected.

The change in resistance of the shunt resistor is only 0.5%/100° and can also be neglected in most cases.

The resistance of the aluminum portion of the coil form assembly increases markedly with temperature. The open circuit damping of the unit varies inversely with this resistance. Hence, open circuit damping drops considerably with temperature in the order of 7%/100°.

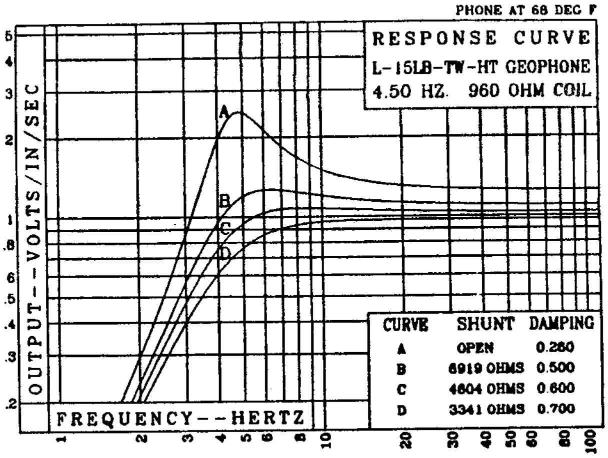
The total damping of the unit is the sum of the open circuit damping plus the damping caused by the shunt resistor. This will be materially affected by temperature.

The resistance of the copper winding increases markedly with temperature yet is easily calculable.

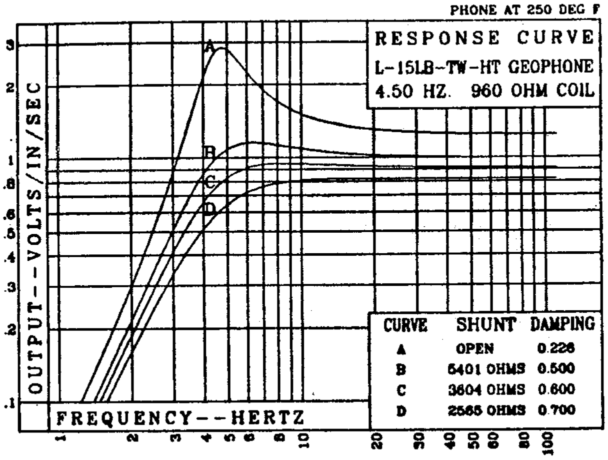
The damped output of the unit is equal to the undamped output times the value of the shunt resistor divided by the sum of the coil resistance plus the value of the shunt resistor. In that the coil resistance increases markedly with temperature, the damped output will fall off greatly with temperature at higher values of total damping. Since most transducers are shunted to give a total damping of 60 to 70% of critical, the damped output of the unit will be greatly reduced at higher temperatures. This is quite evident on the family of curves presented with this paper. These curves take into consideration all variations, however small.

It will be noted on the 8-Hz curves for 350°F and higher that no 70% is shown. It is not possible to dampen this phone to that degree at those temperatures with a resistive shunt.

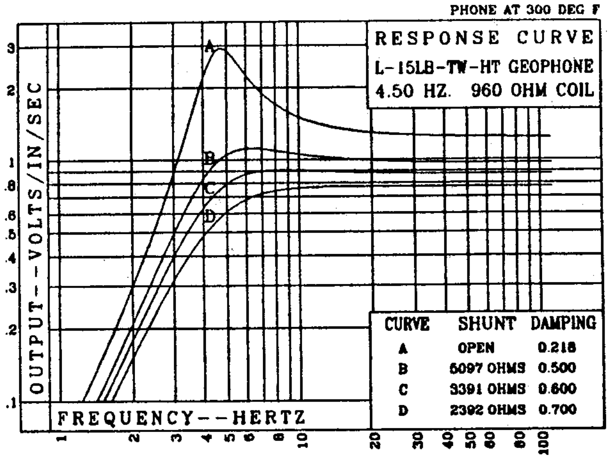
I hope I have given you an overview of the construction problems involved in the modification of seismic velocity-sensitive transducers for downhole application and the evaluation of their electrical characteristics at elevated temperatures.



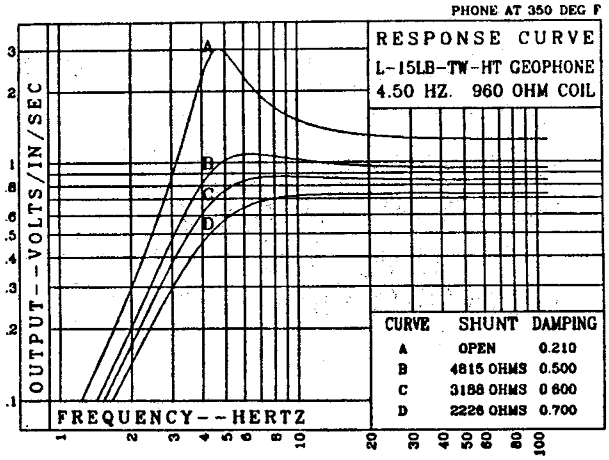
CURVE	SHUNT	DAMPING
A	OPEN	0.260
B	6919 OHMS	0.500
C	4604 OHMS	0.600
D	3341 OHMS	0.700



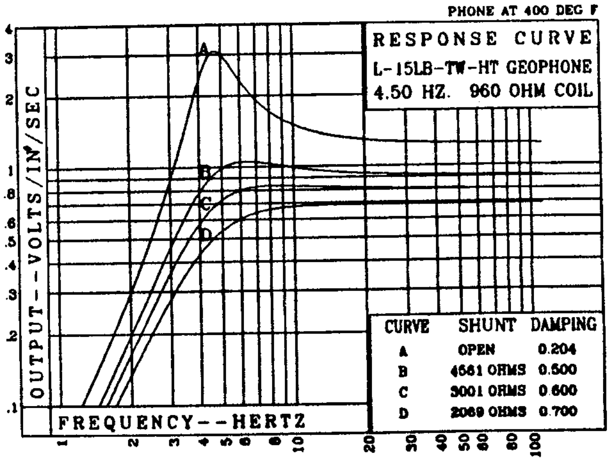
CURVE	SHUNT	DAMPING
A	OPEN	0.226
B	5401 OHMS	0.500
C	3604 OHMS	0.600
D	2565 OHMS	0.700



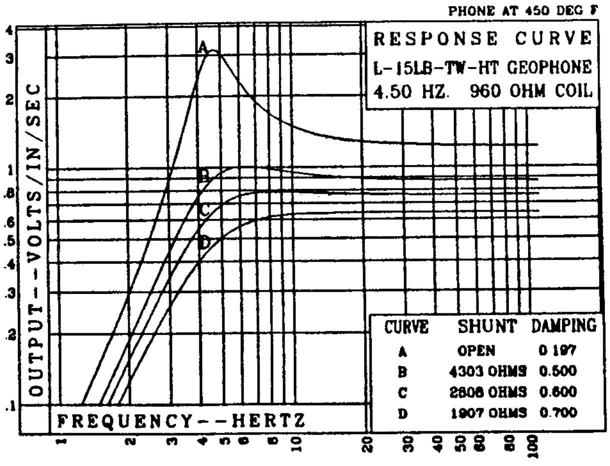
CURVE	SHUNT	DAMPING
A	OPEN	0.218
B	5097 OHMS	0.500
C	3391 OHMS	0.600
D	2392 OHMS	0.700



CURVE	SHUNT	DAMPING
A	OPEN	0.210
B	4815 OHMS	0.500
C	3188 OHMS	0 600
D	2226 OHMS	0.700

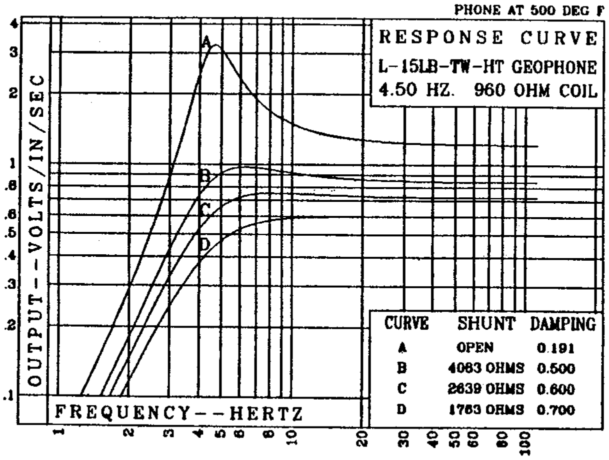


CURVE	SHUNT	DAMPING
A	OPEN	0.204
B	4561 OHMS	0.500
C	3001 OHMS	0.600
D	2069 OHMS	0.700



CURVE	SHUNT	DAMPING
A	OPEN	0 197
B	4303 OHMS	0.500
C	2806 OHMS	0.600
D	1907 OHMS	0.700

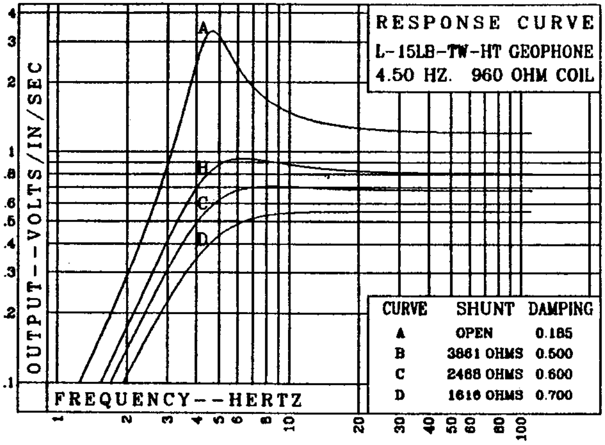
PHONE AT 500 DEG F



RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
4.50 HZ. 960 OHM COIL

CURVE	SHUNT	DAMPING
A	OPEN	0.191
B	4083 OHMS	0.500
C	2639 OHMS	0.600
D	1763 OHMS	0.700

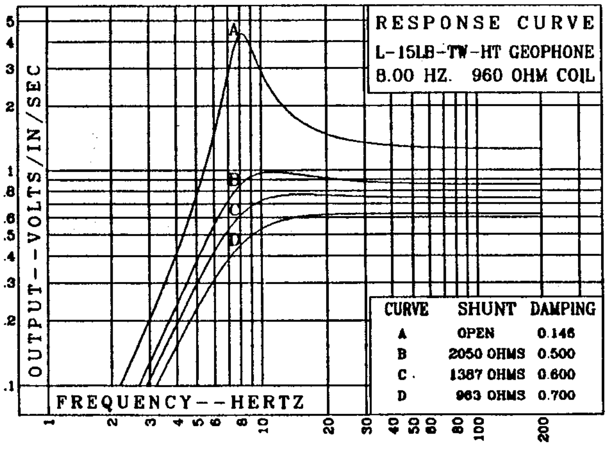
PHONE AT 550 DEG F



RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
4.50 HZ. 960 OHM COIL

CURVE	SHUNT	DAMPING
A	OPEN	0.165
B	3861 OHMS	0.500
C	2468 OHMS	0.600
D	1616 OHMS	0.700

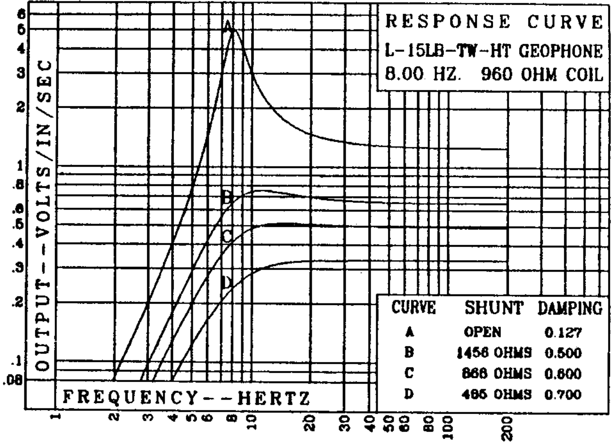
PHONE AT 68 DEG F



RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL

CURVE	SHUNT	DAMPING
A	OPEN	0.146
B	2050 OHMS	0.500
C	1387 OHMS	0.600
D	963 OHMS	0.700

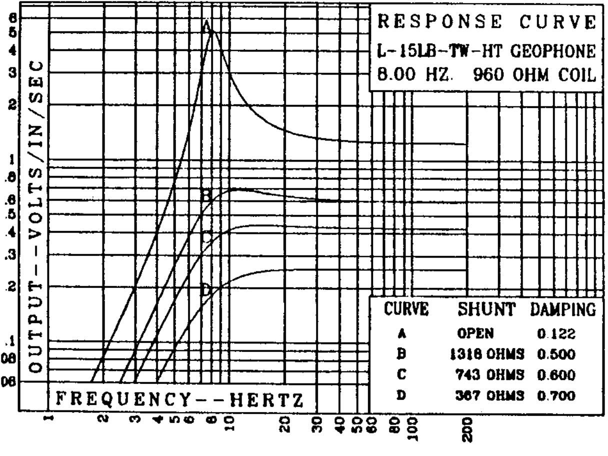
PHONE AT 250 DEG F



RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL

CURVE	SHUNT	DAMPING
A	OPEN	0.127
B	1456 OHMS	0.500
C	866 OHMS	0.600
D	466 OHMS	0.700

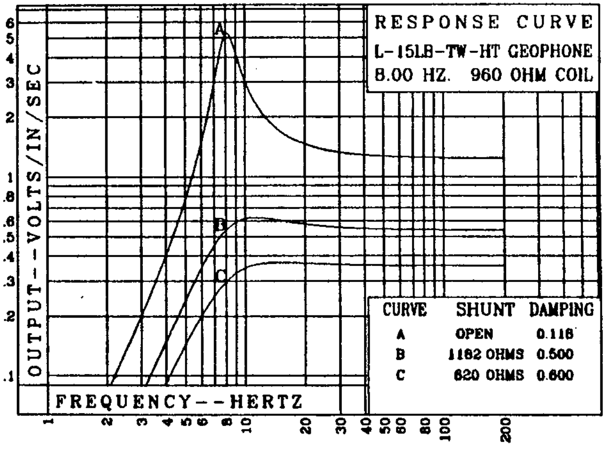
PHONE AT 300 DEG F



RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL

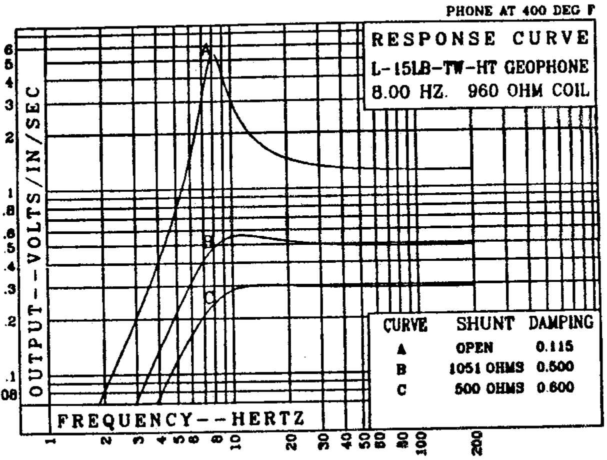
CURVE	SHUNT	DAMPING
A	OPEN	0.122
B	1318 OHMS	0.500
C	743 OHMS	0.600
D	367 OHMS	0.700

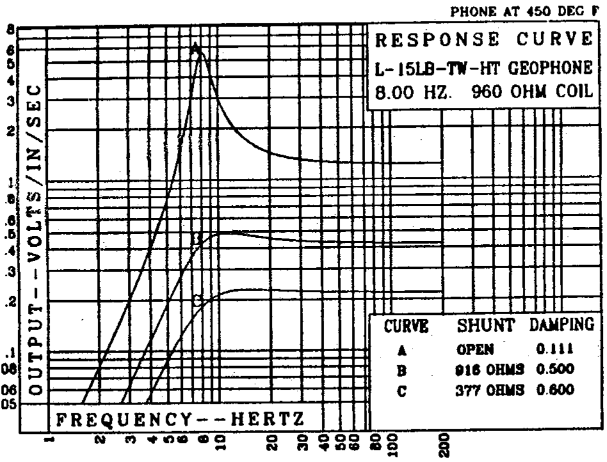
PHONE AT 350 DEG F

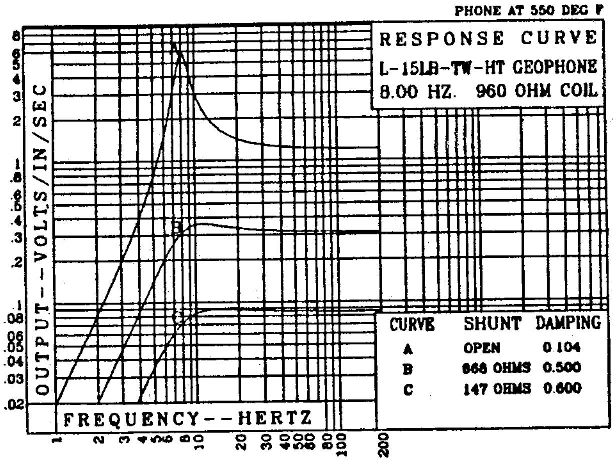


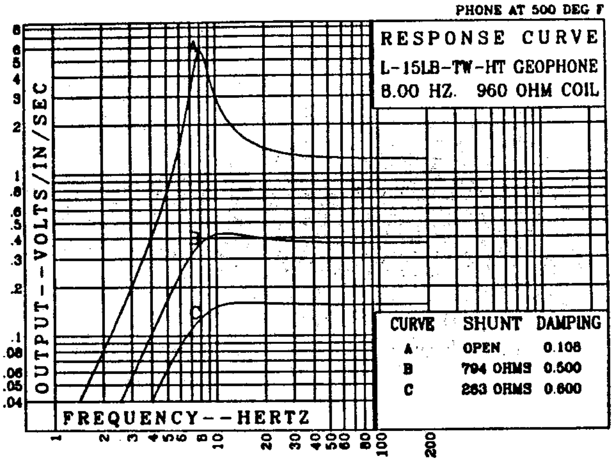
RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL

CURVE	SHUNT	DAMPING
A	OPEN	0.116
B	1162 OHMS	0.500
C	620 OHMS	0.600


PHONE AT 400 DEG F
RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL
OUTPUT--VOLTS/IN/SEC
FREQUENCY--HERTZ
A
B
C
6
5
4
3
2
1
.8
.6
.5
.4
.3
.2
.1
.08
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
200
CURVE SHUNT DAMPING
A OPEN 0.115
B 1051 OHMS 0.500
C 500 OHMS 0.600


PHONE AT 450 DEG F
RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL
OUTPUT--VOLTS/IN/SEC
FREQUENCY--HERTZ
A
B
C
8
6
5
4
3
2
1
.8
.6
.5
.4
.3
.2
.1
.08
.06
.05
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
200
CURVE SHUNT DAMPING
A OPEN 0.111
B 916 OHMS 0.500
C 377 OHMS 0.600


PHONE AT 550 DEG F
RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL
OUTPUT--VOLTS/IN/SEC
FREQUENCY--HERTZ
A
B
C
8
6
5
4
3
2
1
.8
.6
.5
.4
.3
.2
.1
.08
.06
.05
.04
.03
.02
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
200
CURVE SHUNT DAMPING
A OPEN 0.104
B 868 OHMS 0.500
C 147 OHMS 0.600


PHONE AT 500 DEG F
RESPONSE CURVE
L-15LB-TW-HT GEOPHONE
8.00 HZ. 960 OHM COIL
OUTPUT--VOLTS/IN/SEC
FREQUENCY--HERTZ
A
B
C
8
6
5
4
3
2
1
.8
.6
.5
.4
.3
.2
.1
.08
.06
.05
.04
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
200
CURVE SHUNT DAMPING
A OPEN 0.108
B 794 OHMS 0.500
C 263 OHMS 0.600

A HIGH-TEMPERATURE TRANSDUCER FOR MEASURING LOW-LEVEL DIFFERENTIAL PRESSURES IN A HIGH-STATIC PRESSURE FIELD

by

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ABSTRACT

A new pressure transducer has been designed utilizing state-of-the-art silicon micromachining processes. This transducer has been primarily designed for use as a low-level pressure sensor and, in some instances, a high-intensity microphone. Manufactured solely from single crystal silicon, the sensing element provides excellent linearity and low hysteresis. This paper contains a description of this sensor and its use in a downhole application for fluid density measurement.

I. INTRODUCTION

A classical pressure measurement problem has been to accurately sense differential pressure in the presence of high common-mode pressure. The most frequent application is differential pressure measurement across an orifice plate to determine flow rate ($V^2 \propto \Delta p$). Another application is the measurement of liquid density. This is determined by measuring the pressure difference between two points in a known column of liquid ($\gamma = P/h$). An example of such an application is fluid density measurement in a deep well at static pressures of over 700 bar. Assuming the well contains a liquid mixture with a density close to that of water, the need is to measure differential pressure below 0.1

bar in a 700-bar static field, assuming the column height is approximately 0.5 to 1 m.

One of the difficulties in making these measurements is caused by the common-mode pressure sensitivity of most transducers. This means that the output of the transducer, with no differential pressure across it, changes as the common pressure to both pressure ports increases. When the ratio of the common-mode pressure to differential pressure is as high as in the above example, measurements are usually not feasible. The zero shift errors are excessive.

II. SUMMARY

As shown in Figs. 1 and 2, the silicon-sensing element is three dimensional. The cross section in Fig. 2 shows a photomicrograph of the pressure diaphragm. One can easily see that a distributed load or pressure on one side results in stress concentrations at Points A, B, and C where all the bending occurs. Stress-sensitive materials are diffused in these areas, providing the highest possible sensitivity to pressure.

One version of this transducer is being used for measurement in hydrostatic pressure approaching 1000 bar. This is achieved by exposing the entire transducer to the pressure and connecting the front-end pressure port to a line which is less than 1 m above the transducer. A known liquid is contained in the column between the two pressure inlets.

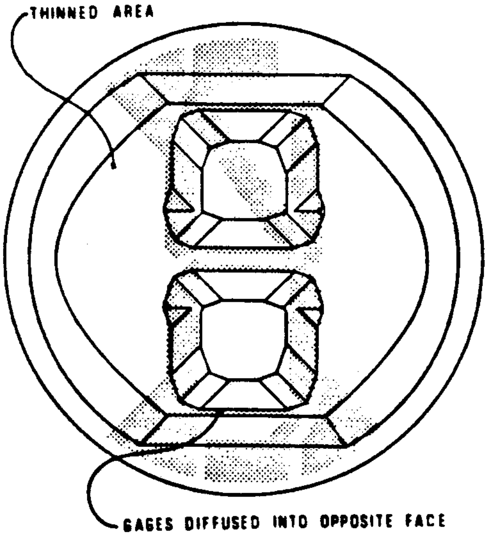

Fig. 1. Diffused, etch-contoured pressure sensor.

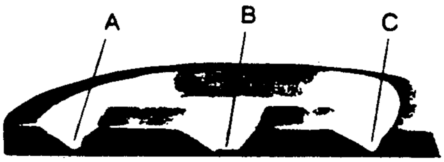

Fig. 2. Photomicrograph of diaphragm section through notches and islands.

In fact, this liquid, which is a dielectric fluid, also completely surrounds the miniature transducer and provides a media barrier to the hostile fluids in the well.

With the 8510B-style transducer used in this manner, the zero output change with 700-bar hydrostatic pressure surrounding it is less than 0.00 bar. This results in a small measurement error. The performance of this transducer has proved to be exemplary in this type of application.

In this type of application it would also be extremely difficult to use one of the rather large differential pressure transmitters as used in the process industry for flow measurements. In addition, the shock and vibration would likely destroy a larger and more flexible transducer.

With such a high common-mode pressure and such a low differential pressure, one risk is that the pressure to both ports does not track and the difference exceeds the range of the transducer. The over-range specification of 40 psi for the 8510B 2-psi full-scale transducer greatly assists in making this a practical measurement.

The performance characteristics of this new transducer make it an ideal choice for measuring low-level pressures amidst a high common-mode environment.

PASSIVE ACOUSTIC MEASUREMENTS IN GEOTHERMAL WELLS

by

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Detection of fracture dimensions and orientation of a geothermal reservoir is important for creating and understanding the operation of a dry, hot rock energy extraction system. The development of downhole instrumentation capable of characterization of hydraulic fracture systems in high-temperature and high-pressure borehole environments provides methods of measuring the location, orientation, and shape of the fracture. The downhole instrumentation must emphasize reliability of measuring devices and electromechanical components to function properly at borehole temperatures of 250°C and pressures of 10 000 psi.

A passive method by which acoustic signals are detected and used to "map" fractures has been under intense development for the Hot Dry Rock Geothermal Energy Program. This method uses downhole triaxial geophone instruments to detect acoustic signals generated during pressurization or inflation of the hydraulic fracture systems.

The geophones selected and utilized are manufactured by Mark Products (Model Nos. L15AHT-4.5Hz and L15AHT-30Hz). The first model is a 12° vertical geophone whose natural frequency is 4.5 Hz; the other detector has a natural frequency of 30 Hz and is used in both the vertical and horizontal axis. These geophones were tested to 280°C for several hours in the laboratory, were downhole for 30 continuous hours at borehole temperatures of 240°C, and showed no significant sign of signal degradation. The geophones are incorporated in three distinct downhole acoustic packages: the triaxial acoustic detector, the slimline triaxial acoustic detector, and the Precambrian vertical acoustic detector.

The triaxial acoustic detector is 13 ft long, weighs 325 lbs, and has an outside diameter of 5.5 in. Four 30-Hz geophones are used in each axis tied in series. The detector employs either a downhole multiplex or FM multiplex instrument system. The electronics are housed in a thermal- protection system, which is composed of a controlled-environment enclosure (dewar) used in conjunction with a heat sink containing cerrobend. This system greatly increases downhole operating time and allows the use of low-temperature electronics which enhances the capability of the instrument system.

The multiplex system allows monitoring of additional pertinent data other than the geophone signals, i.e., the internal dewar temperature, geophone orientation, and power-pack voltages (batteries). Borehole slant angle is measured and referenced to previous wellbore surveys to provide geophone orientation.

The downhole multiplex is controlled from the surface data acquisition and control system. The program is designed to step the downhole multiplexer by operator initiation of keyboard command allowing the measurement of auxiliary downhole data. Upon completion of this cycle, the computer will return the multiplex to continuously monitor the geophone outputs.

The FM system not only provides a multiplex system but also enhances the signal-to-noise ratio and increases data frequency transmission. Higher frequencies can be transmitted uphole without loss of signal information because attenuation caused by the cable only affects the magnitude of the carrier frequency and not the data. The FM system is also ideal for use on coaxial cable.

The high-temperature slimline triaxial acoustic detector was primarily designed for use in a drill string. It is 10 ft long, weighs 150 lbs, and has an outside diameter of 3-1/4 in. Two 30-Hz geophones are utilized in each axis and tied in series. A high-temperature amplifier circuit is employed in this package. All components are thermally hardened, tested to 260°C in the laboratory, and have been used downhole for 30 h at temperatures of 240°C. There was no significant sign of signal degradation. Compensation adjustment is made uphole on the electronics, which are placed in an oven set for the temperatures they were expected to encounter.

Borehole coupling of the triaxial and slimline triaxial acoustic detectors is achieved by means of an arm-actuating device driven by a high-temperature (275°C) dc motor. The coupling system extends an arm to force the package against the borehole wall. The actuating linkage includes a shear pin to release the extended arm should the motor fail downhole to retract the arm. A balanced piston has been designed into the actuating mechanism to equalize loading in both directions. The total force of the arm against the borehole wall is about 325 lbs.

The Precambrian vertical acoustic detector is 22 in. long, weighs 20 lbs, and has an outside diameter of 2-1/2 in. Four 4.5-Hz geophones are utilized in this package; they are tied in series. The package is positioned approximately 2000 to 3000 ft below the surface in granite. Several of these detectors are utilized and form a Precambrian network.

Microearthquakes recorded during hydraulic stimulation experiments provide important information on the size and orientation of a growing hydraulic fracture at the Los Alamos National Laboratory's Fenton Hill Hot Dry Rock Site. Signals recorded from the oriented downhole acoustic packages are analyzed to determine the location of the microearthquakes or events producing the signal.

The acoustic signals generated by a seismic source consist of two types of body waves. The compressional waves (P-waves) propagate parallel to the direction of particle displacement throughout the media. The transverse or shear waves (S-waves) propagate in the shear mode or perpendicular to the direction of particle displacement. In any given solid medium, compressional waves travel at a higher velocity than the S-waves. By knowing the medium and measuring the time delay between the arrival of the compressional and shear waves, distance can be measured. The polarization direction of the initial (P) wave arrival determines direction. The polarization direction and S-P time give the direction and distance of the event relative to the detector.

FLUID SAMPLER

by

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ABSTRACT

This paper discusses the design changes and modifications incorporated into an existing fluid sampler. The new design utilizes all features proved successful in a 1975 sampler design and upgrades from a 200°C specification limit to permit operation at borehole temperatures of 300°C and 10 000-psi pressure.

A downhole fluid sampler is required in geothermal operations in obtaining in situ borehole fluids before they mix with other wellbore fluids. Fluid samples are obtained immediately upon entering the wellbore from a resident reservoir, thereby preserving gases and dissolved solids in solution. A sample that is obtained at the wellhead after flashing is impossible to reconstitute.

Evaluation of downhole samples obtained at Fenton Hill, Costa Rica, El Centro, The Geysers, and other geothermal fields indicates that these fluids are useful in investigation of geothermal systems. Chemistry analysis allows characterization of reservoirs, fluid-time studies, and assessment of maximum reservoir temperature and capacity of deposition or scaling.

The new high-temperature design requires that it

1) operates at 300°C and 10 000 psi in geothermal fluids,

2) is able to operate on a single-conductor wireline,

3) incorporates features to reseal bottle after taking sample,

4) obtains a 2-ℓ sample volume,

5) has less than a 3-5/8-in. tool diameter.

A fluid sample is obtained by opening a valve mounted on the sample bottle. A miniature high-temperature dc motor is utilized to operate the valve stem.

The design changes required to upgrade are as follows:

1) new high-temperature motor furnished by AEI, Inc., Fullerton, California;

2) double seals at all joints;

3) high-temperature EPDM O-rings and Bal-Seals obtained from Parker Industries and the Bal-Seal Engineering Company, respectively;

4) rugged, pressure-balanced valve stem;

5) new, all stainless steel extraction valves;

6) built-in temperature well in sample bottle;

7) quick and simple sample transfer disconnect;

8) simple uphole (surface) controls;

9) slickline operation mode, i.e., uses no wires.

The new sampler has been field tested at the Fenton Hill HDR boreholes and at a geothermal well in the El Centro valley.

INTERPRETATION OF WELL LOGS TO SELECT PACKER SEATS IN OPEN-HOLE SECTIONS OF GEOTHERMAL WELLS

by

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I. INTRODUCTION

A wireline and mud logging program has been conducted in conjunction with redrilling operations in Well EE-3 at the Fenton Hill Hot Dry Rock (HDR) Site near Valles Caldera, New Mexico. The trajectory for the new bore, EE-3A, penetrated a fractured zone stimulated from adjacent Well EE-2 and thereby established hydraulic communication. To test and stimulate selected zones in EE-3A, inflatable open-hole packers designed for high-temperature service were used. Proper identification and selection of packer seats were crucial to the success of the project. The logging program successfully identified five competent packer seats in six attempts. Wireline temperature, caliper, and natural gamma-ray logs were used in conjunction with mud logs, drill cuttings, and drilling parameter data to locate fractures, out-of-gage holes, temperature anomalies and mineralized zones, which were avoided in selection of the packer seats.

The Los Alamos National Laboratory has been engaged for the past decade in developing technology for energy extraction from hot dry rock reservoirs. As a part of the development of a second, deeper, hotter reservoir (Phase II), field experiments are in progress at the HDR test site. The primary objective of the field operations has been to achieve hydraulic communication between Wells EE-2 and EE-3 at depths ranging from 11 500 to 13 200 ft. Thus cold water can be injected down one well and hot water produced at the other well. The rock mass surrounding the two wells was stimulated with the injection of large volumes of water. Subsurface microseismic detectors were used to map the microearthquakes during and after the massive injections. After failing to establish a connection, EE-3 was sidetracked and redrilled (EE-3A) on a lower trajectory to intersect a high density region in the cloud of microseismic events surrounding EE-2 resulting from the largest injection, which used five million gallons of fresh water.

A number of reservoir stimulation tests were conducted at various depths during redrilling operations. Due to the existence of a low-pressure region at 10 250 ft, the lower intervals had to be isolated from this zone and open-hole packers were selected as the only practical method to effectively stimulate and interrogate the wellbore. This was accomplished with the use of a recently improved, open-hole, inflatable packer. The high initial temperature, large thermal cycles, high differential pressures, and abrasive open-hole environment created an extremely challenging environment for open-hole packer operations. Packer seats had to be selected to avoid enlarged, fractured, incompetent, or mechanically weak boreholes. A reliable logging program was essential for successful packer operations and the reservoir development and testing program.

II. LOGGING PROGRAM

The logging program included in the EE-3A drilling plan sought to identify and locate effective packer seats. Most of the wellbore was assumed to be unsuitable due to one or more of the following conditions: oversized, irregular broken-out or washed-out bore; open fractures intersecting the bore; mineral-filled fractures; and jointed or weak rock more susceptible to fracturing than the targeted injection zone. Potential packer seats were located by using mud logs, temperature logs, and caliper logs. Open-hole and through-drill-pipe gamma-ray/collar-locator logs were used to correlate drill pipe and open-hole wireline depths.

III. WIRELINE LOGGING AND PROCEDURES

A 7-conductor, tetrafluoroethylene (TFE) Teflon-insulated logging cable and cablehead rated for continuous service at 320°C were used to run the Los Alamos project logging sondes. Pressure control equipment for the high-temperature logging cable was limited to 1000 psig. A casing collar locator was run in conjunction with other sondes for depth calibration.

A commercial "slim hole" gamma-ray/collar locator provided a through-drill-pipe log in a drill string cooled with low flow rate circulation.

The temperature sonde uses a thermistor probe with high accuracy and resolution. It is readily fielded, reliable, and more easily replaced than other sondes. Therefore, it was run before running other logging sondes. Cable tension and tool turnaround were monitored carefully to assure hole conditions were suitable for the caliper logging to follow. Surveys were run at 60 to 150 ft/min both into and out of the well. Depths were corrected for thermal lag time and cable stretch (turnaround).

Temperature surveys were run in Well EE-3A preceding and following each packer experiment. Anomalies and variations from the background temperature gradient were used to infer fracture inlets/outlets within ±10 ft. More precise location of fractures was often precluded by the high pressures that prevented logging during injection or early shut-in. The packer configuration prevented logging below it. Venting and circulation of the well was required before removal, and this resulted in a smearing of fluid entrances and made it difficult to determine the fracture locations.

The Los Alamos caliper tool is a 3-independent-arm tool configured to measure hole diameters from 5 to 14 in. Mechanical linkage, magnetic couplings, and high-temperature rotary potentiometers are used to convert borehole radius to an electronically measured output. The sonde was run with the arms retracted. They were extended to log out over the interval of interest and then retracted for removal. Logging speeds varied from 20 to 40 ft/min. Pre-log and post-log calibrations were made to calculate corrections for the caliper pad wear, which was significant on runs of over 2000 ft. The tool was run with two bow centralizers straddling the measuring arms. A slip and stick movement of the tool was indicated by caliper log quality below 12 600 ft.

Accurate caliper logs were required to select packer seats. Over-extension of the high-temperature design inflatable packer element (in the range of 9.5-in. diam) made the element susceptible to rupture. Washouts, breakouts, or ledges which could easily go undetected using a single or dual-arm caliper can also rupture the element.

A Geiger detector, gamma-ray sonde was run in the open hole of EE-3A to tie the natural gamma-ray depth signature to the project's wireline depths. The electronics for the tool are thermally protected in a dewar housing with a cerrobend heat sink. The tool operates at temperatures of 300°C for more than 6 h. The gamma-ray signature obtained was readily correlated with signatures obtained with the commercial through-drill-pipe log. Most logs were run at 60 to 80 ft/min. Logging speeds as low as 40 ft/min were required to obtain a good repeat signature with the dewared tool.

IV. RESULTS OF THE LOGGING PROGRAM

The logging program provided input to the successful packer operations and also added significantly to the reservoir description process, complementing injection and tracer data. Results that contributed to the reservoir description included depth correlation of drilling data with wireline data, location of active fractures, mineral-filled fractures, and foliation and formation changes.

Depth measurements made on various runs using the same wireline varied less than 4 ft. Depths measured using different wirelines varied as much as 20 ft. When working within 600 ft of the bottom of the hole, tag bottom depths were used successfully to make the drill pipe/wireline depth correction.

A logging run was required for each sonde run since multiplexing equipment for the Los Alamos open-hole logging tools (now under development) was not available. Where accurate packer depths were required, an open-hole gamma-ray log was run on the wireline currently in use to correlate with a through-drill-pipe gamma-ray log.

The EE-3A logging program was crucial in selection of packer seats for the reservoir testing program. The mud logging program provided well site input to focus the caliper logging on regions with good potential packer seats. The 3-arm caliper log was needed to eliminate sections of bore that were too large for the high-temperature packer element. Temperature logs provided sufficiently accurate location of fractures to select packer seats. The logging program has also contributed to the understanding of reservoir structure, which at this point is in good agreement with other reservoir data.

The importance of multiple arm caliper logging and good wireline depth corrections was demonstrated during these operations. High-temperature wireline logging has been shown to be a useful investigative tool in granitic rock. A 6-arm hot-hole caliper, a high-temperature multiplexing system, and high-pressure well control equipment for large-diameter hot-hole wirelines are needed to make the techniques described commercially viable. A method to eliminate the severe stick-slip movement of the caliper and other sondes in the inclined, abrasive wellbores at Fenton Hill would make the caliper and open-hole packers a powerful and complementary wellbore evaluation system.

HIGH-TEMPERATURE COMPONENTS

Description	Manufacturer	Type	Temp Rate (°C)
Acoustic Window	Los Alamos	TFE Teflon	>300
Amplifier Operational	Harris Electronics	2600-1	290
Amplifier Operational	Burr-Brown	OPA 11 HT	250
Cable Armored Wireline	Rochester Corporation	TFE Teflon	>300
Cable Armored Wireline	Vector Corporation	PFE Teflon	260
Cablehead	Los Alamos	81Y210200	>300
Cablehead Boot	Kemlon Products	KN-34	>300
Connector	Gulton Industries	BL06-20-16-UHR	300
Connector--Microminiature	ITT Cannon	MT B1	290
Connector--Cablehead	Reynolds Industries	178-7439	>300
Capacitor	American Technical Ceramics	100B510KAW500	290
Capacitor	Corning Glass Works	CHT-2A3258SP	200
Dewar	Vacuum Barrier	C-14286A	275
Detonator	Reynolds Industries	RP84	275
Firing Module	Reynolds Industries	FS20	200
High-Temperature Grease	E.I. DuPont Company, Inc.	Krytox	260
Geiger-Muller Tube	Harshaw/Filtrol	G1000-17TL	200
Heat Pipe	Los Alamos	Methanol	100
Heat Sink	Los Alamos	81Y210297	80
Motor--dc	American Electronics, Inc.	AEI17DG2	275
Motor--ac	American Electronics, Inc.	AE17JG2	260
Oil	Dow Corning	710	275
Oil	E.I. DuPont Company, Inc.	Krytox	260
O-Ring	Parker Seal	E962-85-SIZE	>300
O-Ring	Bal Seal	IS-55-SIZE	>300
Printed Circuit Board	Circuit Shop	Polyomit GIN 139497	300
Printed Circuit Connector	AMP	3-330808-8	300
Relay DPDT	Teledyne	412H	275
Relief Valve	Lee Company	PRRA-1875040L	275
Resistor	Allen Bradley	Metal Film	300
Rotary Transformer	Ceramic Magnetics	C2050	275
Slip Ring	Corning Glass Works	MaCor Ceramic	>300
Slip Ring Assembly	Los Alamos	81Y210418	300
High-Temperature Solder	Multicore Solder	HMP Alloy 22 Gage	300
High-Temperature Tape	Boyd Industrial Rubber	Kapton/Teflon	260
Transducers			
Accelerometer	BBN Instruments	BK424	300
Accelerometer	Endevco	7705-200	260
Accelerometer Cable	BBN Instruments	070905	300
Acoustic Crystal	Channel Industries	C5500	200
Acoustic Crystal	Specialties Engineering	Lithium Niobate	260
Acoustic Crystal	Keramos, Inc.	K-350	220
Collar Locator	Gearhart	05-2010	250
Geophone	Mark Products	L15AHT	260
Magnetometer	Humphrey	FD17-0201-1	275
Potentiometer	Litton Potentiometer	6119	260
Pressure Transducer	Bell & Howell/CEC Division	CEC-1000-09	>300
Reed Relay	Hamlin	MSRR-2CD	300
Thermistor	Conax Corporation	T3	>300
Voltage Regulator	White Technology	C8000-15	290
Wire Hookup	Standard Wire and Cable	TFE Teflon	>300

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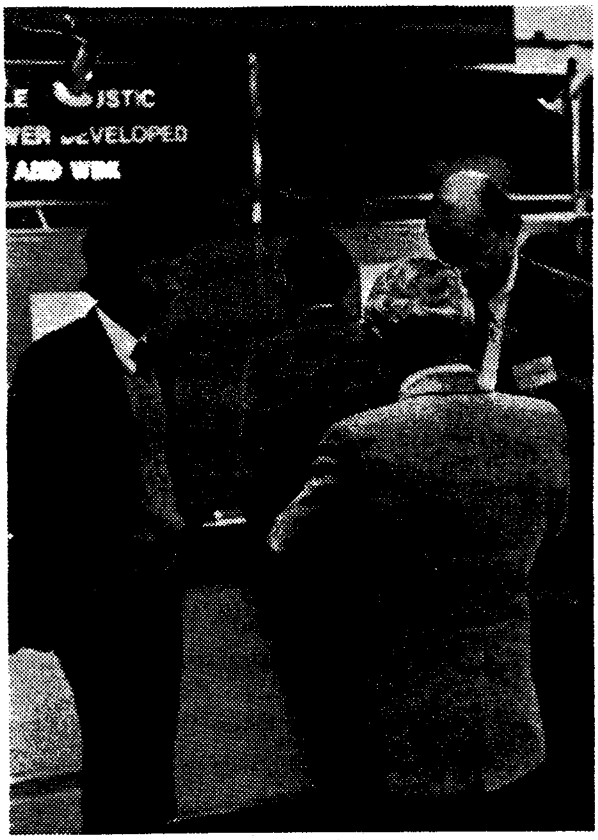

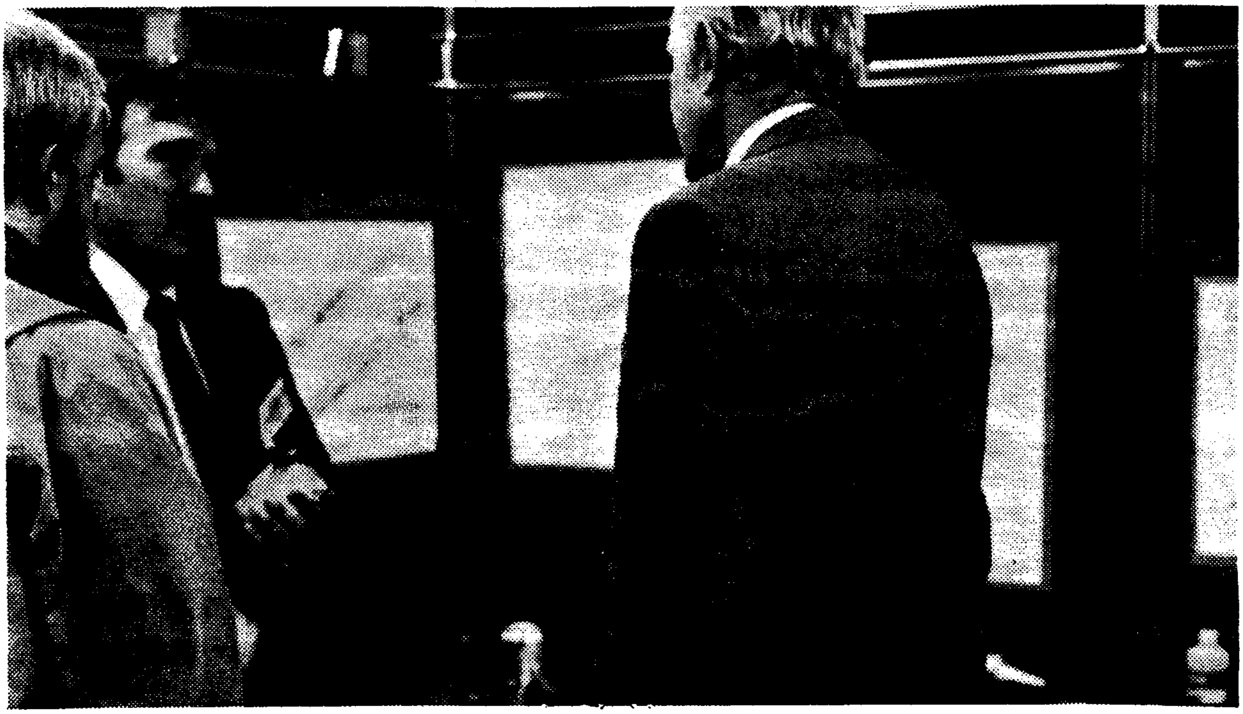

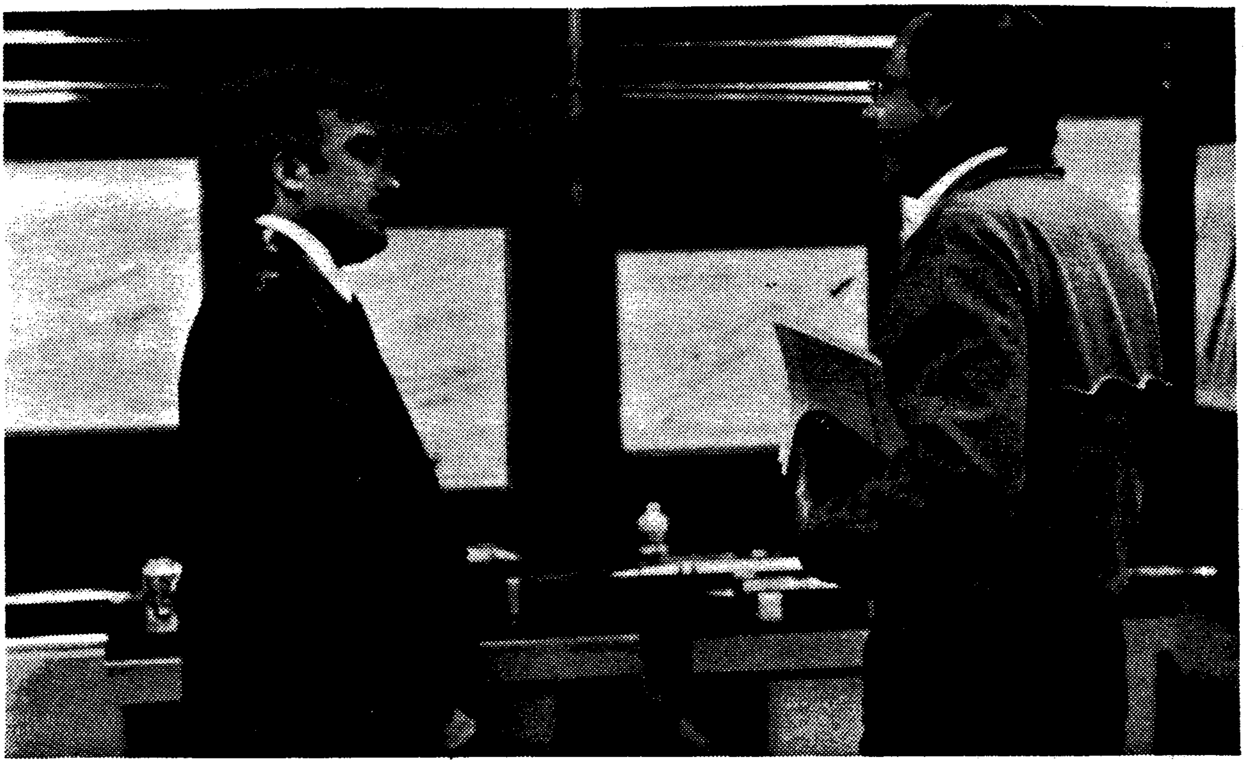

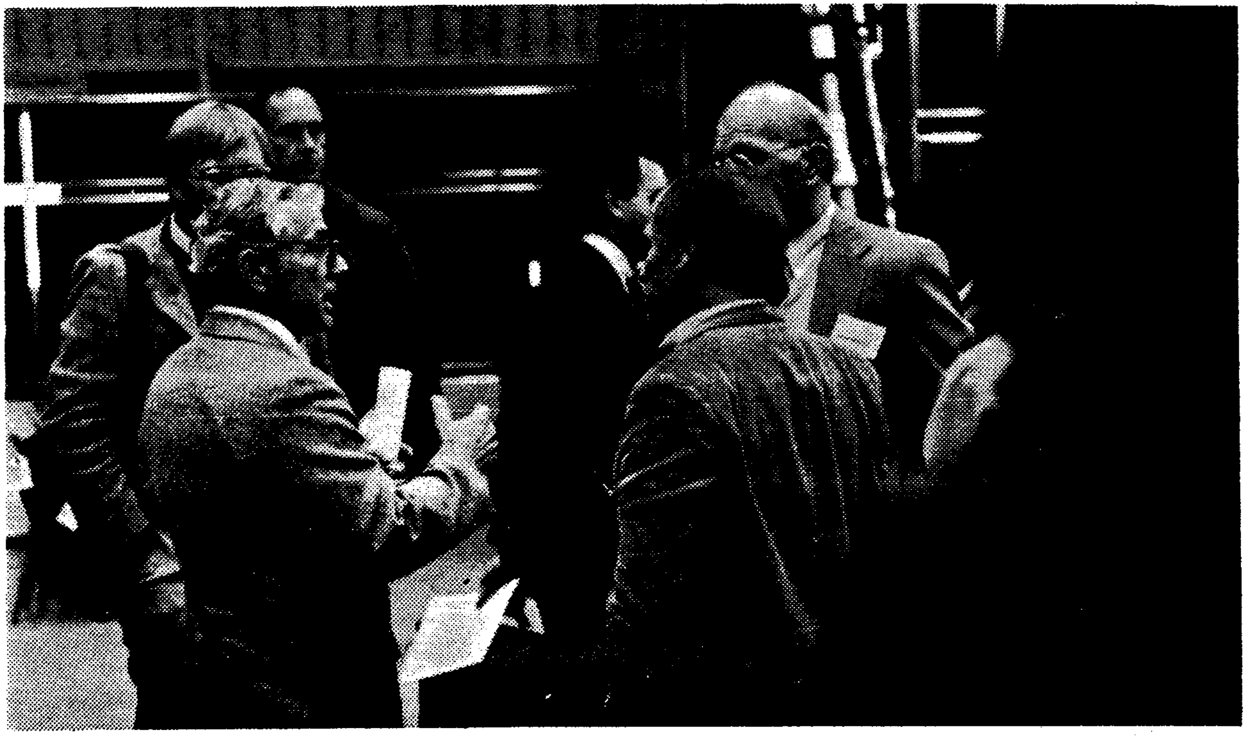

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