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**IMPROVED GEOTHERMAL WELL LOGGING TOOLS
USING NO DOWNHOLE ELECTRONICS**

Final Report

By
H. R. Kratz
E. A. Day
W. G. Ginn

July 1979

Work Performed Under Contract No. EY-76-C-03-1315

Systems, Science and Software
La Jolla, California

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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H. R. KRATZ
E. A. DAY
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JULY 1979

UNDER CONTRACT ET-76-C-03-1315

PREPARED FOR THE
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
DIVISION OF GEOTHERMAL ENERGY

SYSTEMS, SCIENCE AND SOFTWARE
P. O. Box 1620
LA JOLLA, CALIFORNIA 92038

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ABSTRACT

A geothermal sonde for measuring temperature and pressure using no downhole electronics was designed and tested for operation at temperatures up to 275°C (527°F) and pressures of at least 10,000 psi. The measurement system uses variable resistance transducers which are powered in series by an up-hole constant current supply. The output signals from the transducers are measured with a digital voltmeter having very high common mode and normal mode rejection ratios. The high rejection ratios of the digital voltmeter virtually eliminate any noise or pickup introduced into the measurement system. The system was tested in a hydroclave at temperatures up to 288°C (550°F) and at pressures up to 8,000 psi. The sonde was also tested in the Los Alamos geothermal well at temperatures up to 186°C (366°F) and pressures up to 4100 psi. The main problems encountered were associated with pressure transducers and the logging cable or the cable head and connector. The results of this project indicate that this is a feasible method of making geothermal measurements without the use of downhole electronics and that with further development the technique could be extended to higher temperatures and pressures.

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1. INTRODUCTION

This is the final report under Contract No. ET-76-C-03-1315 to develop improved geothermal logging tools. The initial objective of this project was to develop a logging sonde that combined a thermometer, a manometer, and a gradiomanometer, all to operate at a temperature of 275°C and at a pressure of 7000 psi. The sonde was to be designed to operate with a standard seven conductor logging cable. The design of the sonde was to be such that a flowmeter and a caliper could be added as a later development. As discussed in Section 2, inclusion of the gradiomanometer required the development of a new differential pressure gauge capable of measuring a differential pressure of 2 psi at a line pressure of 7000 psi. After considerable effort, the gauge manufacturer who was selected to develop this gauge was unable to design a gauge to these specifications and this portion of the sonde development was discontinued. The sonde that was developed contained a thermometer and a manometer and was designed to operate at a temperature of at least 300°C and at a pressure of 10,000 psi.

A unique feature of the sonde developed on this project is that it contains no downhole active electronics. The elimination of downhole electronics is important because it eliminates one of the two main problem areas identified in upgrading logging tools for high temperature use. A workshop on geophysical measurements in geothermal wells held in 1975 (Baker, et al., 1975) concluded that both signal transmission (cables and their connections) and downhole electronics for signal processing, amplification, and other functions limit the performance of available logging tools. Recommendations were made at that time for development of new higher temperature components. Since the workshop, much has been done in developing high temperature electronic components and circuits. However, for those logging tools for which it can be

done, elimination of downhole electronics permits the development of a sonde to meet the near term requirement of operation at 275°C relatively quickly and cheaply. In addition, if and when better cables and connectors become available, the present sonde could be upgraded to the long term objective of operation at 350°C. The operating temperature of the sonde is presently limited by the transducers and the cable; upgrading the sonde to higher operating temperatures will require developments in both of these components.

The basic circuitry of the sonde utilizes variable resistance transducers and an uphole constant current power supply. The transducers are connected in series and driven with a single power supply. An important advantage of driving the transducers with a constant current is that the power supply can be located uphole and there is automatic compensation for temperature variations in the resistance of the cable. The availability of two modern developments in electronics has made this circuit feasible for well logging; (1) extremely stable constant current power supplies and (2) digital voltmeters with very high common mode and normal mode rejection ratios. Using a digital voltmeter to read the output of the transducers eliminates virtually all the noise induced and generated in the logging cable, resulting in accurate measurements even at low signal levels. The constant current circuit and its components are discussed in detail in Section 3.

The sonde as developed to date will be useful in both cased and open geothermal wells to determine what fluids enter or leave the well, where, and in what quantities. Temperature in bore hole fluids, logged during different flow conditions, can be used to estimate static formation temperature (Dowdle and Cobb, 1975). Multiple temperature measurements at various times after shut-in are required; a single peak reading of bottom hole temperature is not sufficient. Formation temperature is probably the single most important parameter in evaluation of geothermal

reservoirs.

Curtis and Witterholt (1973) show how a continuous temperature log can also be used to compute mass flow rate from various producing zones in a well. They intend the method to be used in combination with a flow meter, run inside casing, to detect flow in the annulus behind the casing by the discrepancy between the two flow rates. However, their methods can also be used with temperature and pressure tools to calculate flow rates into a geothermal well from producing horizons or out of the well into thief horizons. Smith and Steffensen (1975) conclude that temperature logs can be used to detect injection zones as thin as six feet. The temperature log thus will also be useful in wells used to reinject water into geothermal fields.

Downhole pressure measurements are needed for pressure drawdown and buildup tests from which permeability of the various producing horizons can be evaluated. Rice (1976) shows how a computer simulation of reservoir behavior during multiphase flow can be used together with downhole pressure measurements to interpret reservoir behavior. Downhole temperature and pressure measurements can also be used to distinguish between various models of multiphase flow in hot water geothermal wells. Quite different models for such flow have been proposed by Gould (1974) and by Nathenson (1974). Nathenson comments that very few data are available on temperature and pressure distribution in flowing geothermal wells and that what are available must be interpreted with care.

When a flowmeter (and a caliber necessary in flow meter interpretation) are added to the sonde, the complete set of interpretation techniques already developed for such a combination tool in oil wells will apply. With the theories of multiphase fluid flow currently being worked out, it should be possible to determine how much of what is coming from where. Such determinations, made at different surface

flow conditions and matched with adequate computational reservoir simulations, will provide information needed for reservoir evaluation. In addition, the measurement will be directly useful in optimizing geothermal fluid production so that, for instance, flashover to steam with resulting deposition of minerals will not occur in unwanted places in the formations or in the well.

In the following sections of this report the development of the sonde is described in some detail, including the selection and testing of transducers, the design of the measurement and recording circuits, the design of the sonde itself, and the testing of the completed sonde in both a hydroclave and a geothermal well.

Engineering drawings of the sonde are assembled in Volume II.

SECTION 2 GAUGES

In order to use the constant current circuit described in section 3, it was necessary that all gauges in the sonde be of a variable resistance type. Our contract specified that the gauges were to be commercially available or that they were to be developed by a commercial manufacturer so that they would be available in the future.

2.1 TEMPERATURE GAUGE

Because past experience has shown that platinum resistance thermometers are both highly accurate and reliable, this type of gauge was chosen for measuring temperature. The thermometer that was selected was a modification of a platinum resistance thermometer manufactured by Celesco Industries Inc. of Canoga Park, California, for use in oil well logging. An outline drawing of this gauge is given in Figure 1. For reasons discussed in Section 4, the body of the gauge was machined from Inconel 625. Other specifications for the thermometer are as follows:

Table I. Specifications for Celesco Platinum Resistance Thermometer

Element	Platinum wire, reference grade, non-inductive wound
Range	To 343°C (650°F)
Operating Pressure:	20,000 psi
Resistance	100 ohms at 32°F
Output	Nominal $\alpha = 0.00390 \Omega/\Omega/^{\circ}\text{C}$
Linearity	$\pm 0.5\%$ FS
Response	Less than 1.0 second to reach 63% of a step temperature change
Insulation resistance	Greater than 100 megohms at room temperature

Figure 1. Thermometer envelope.

In general, the platinum resistance thermometers performed according to specifications. The only problem encountered in their use was that one of the thermometers developed a low insulation resistance and had to be replaced. We have discussed this problem with the manufacturer who indicated that they would investigate the use of some high temperature insulating material other than their current proprietary insulation to seal the thermometer.

2.2 PRESSURE GAUGES

During the course of this program three different types of pressure gauges, all of the strain gauge variety, were used. The first two types of gauges that were tested were not satisfactory. The first gauge was a standard high temperature pressure gauge manufactured by Precise Sensors Inc., of Monrovia, California. The only modification made to their standard gauge was that the body was machined from Inconel 625. This gauge had a specified pressure range of 0-10,000 psi and a temperature range up to 343°C (650°F). Two of these gauges were purchased. During testing and calibration of these gauges by the manufacturer they were pressure and temperature cycled many times to their maximum specified values, during which the insulation resistance of the gauges remained high. However, during our first test of the sonde in a hydroclave (see Section 5), the insulation resistance of the gauge decreased to an unacceptably low value. During the hydroclave test, in which the temperature was raised to 274°C (525°F) and the pressure to 2000 psi, the insulation resistance of the pressure gauge gradually decreased from 1.2 megohms to 18,000 ohms. After returning to our laboratory in San Diego, the gauge was removed from the sonde and tested at ambient pressure. The insulation resistance had increased to 0.5 megohms and remained at this value when heated to 260°C (500°F). The other Precise Sensors gauge was then also tested at ambient pressure by heating it to 260°C, during which the insulation resistance decreased from 1.2 megohms to 0.82 megohms.

This decrease in insulation resistance, especially that of the first gauge, would have markedly reduced the accuracy of pressure measurements and the gauges were therefore judged to be unsuitable for this application.

The second type of pressure gauge used was an unbonded strain gauge variety (type 4-317-0001) supplied by the CEC Instruments Division of Bell and Howell Company, Pasadena, California. This gauge was pressure rated to 8000 psi and was calibrated at constant current up to a temperature of 315°C (600°F). Before installation in the sonde, the gauge was temperature cycled between room temperature and 280°C (540°F) once every five hours for a period of two days. In hydroclave tests at temperatures up to 277°C (530°F) the gauge performed according to specifications. The only problem encountered in these tests was the time for the pressure gauge to come to temperature equilibrium when the temperature of the hydroclave was changed. This was probably because the gauge had unbonded strain gauge elements which were in poor thermal contact with the gauge body. In a later test in a geothermal well at Los Alamos (see Section 5), in regions of the well in which the temperature was changing rapidly with depth a delay of the pressure gauge in coming to temperature equilibrium resulted in inaccurate pressure measurements. For this reason this gauge was also judged to be unsatisfactory for this application.

The third type of pressure gauge was a sputtered strain gauge pressure transducer (Type CEC 1000) which was also supplied by the CEC Division of Bell and Howell Company. This is a new type of gauge that is in the developmental stage and delivery times are several months. Consequently, only one of these gauges was procured in time for testing on this program. The gauge is specified and calibrated by the manufacturer to temperatures of only 204°C (400°F). However, it is the opinion of the manufacturer that the gauge is stable to considerably higher temperatures. The gauge installed in the sonde was

calibrated in a hydroclave up to a temperature of 276°C (530°F) with no evidence of gauge deterioration. During the hydroclave test the gauge showed much less sensitivity to changes in temperatures than the previously unbonded strain gauge transducer. This is because the sputtered strain gauge elements are in much better thermal contact with the gauge body than are the wire elements in the unbonded strain gauges. The specifications for the CEC 1000 pressure gauge are given in Table II.

Table II. Specifications For Type CEC 1000-04
Sputtered Strain Gauge Pressure Transducers

Pressure range	10,000 psi
Full range output	30.765 mv
Compensated temperature range	80°F to 430°F
Input resistance	415 ohms
Output resistance	365 ohms
Rated excitation	10.0 Vdc
Zero shift	+0.001%FR/°F
Sensitivity shift	+0.001%FR/°F
Combined non-linearity hysteresis and non-repeatability	±0.25%FR

This pressure transducer is temperature compensated by using two platinum resistors in series with the bridge circuit and they are designed to provide compensation with constant voltage excitation. However, with constant current excitation the temperature compensation is not as good. The small effect of temperature on the gauge calibration using constant current excitation was determined in hydroclave tests and used in data reduction of logging runs. The gauge could be specifically temperature compensated for constant current excitation, but such a gauge is not currently available.

2.3 GRADIOMANOMETER

As stated in the introduction, it was initially planned that a gradiomanometer, to measure fluid density, would also be included in the sonde. The gradiomanometer was to measure the pressure difference between two ports on the side of the sonde which were separated a distance of two feet. The gradiomanometer would require a differential pressure gauge to measure 2 psi differential pressure at a line pressure of 7000 psi and at a temperature of 275°C (527°F). This is a very stringent requirement for a differential pressure gauge and no such gauge is presently available commercially. We discussed the development of such a differential pressure gauge and requested proposals from ten different gauge manufacturers, five of whom submitted proposals. From these proposals we selected Precise Sensors Inc., Monrovia, California to develop the gauge. This decision was based on both their technical proposal and on their cost proposal. The gauge design that they proposed was judged to be the most suitable for the gradiomanometer.

Precise Sensors spent a full year trying to develop a differential pressure gauge to these specifications, but then concluded that they were unable to develop such a gauge in a reasonable time. At that time, in consultation with representatives of the DOE, it was decided to proceed with the development and testing of the sonde, both in hydroclave and in geothermal wells, without the differential gauge. For this reason, the sonde developed on this program included only a thermometer and a manometer.

3. MEASUREMENT CIRCUITRY

3.1 DESIGN CONSIDERATIONS

A requirement of the logging tool is that the measurements are to be made with a standard seven-conductor logging cable. Each of the gauges installed in the sonde is a variable resistance type, the basic circuitry for which is a four wire circuit for each gauge. Since it was initially planned to install three gauges (manometer, gradiomanometer and thermometer), the use of four wire circuits with a seven-conductor cable would require downhole switching. Such downhole switching can be avoided by powering all of the gauges in series with a constant current source, which is the arrangement that is used. It was anticipated that the main sources of noise in the signal would be cable-induced noise (due to its mechanical motion) and pickup in the cable from extraneous sources. Three methods of making measurements to minimize the effect of noise were considered and tested. These methods were: (1) with lock-in amplifiers (2) with box-car amplifiers and (3) with dc digital voltmeters. The first two methods require pulsing the circuit at a reasonable repetition rate (perhaps 100 per second) whereas the third method uses a dc current.

Lock-in amplifiers are phase sensitive detectors that are very effective in eliminating noise from the measurement of signal amplitude in many situations. It was very effective in eliminating induced noise when tested with a system consisting of 200 feet of four-conductor shielded cable terminated with a Wheatstone bridge. However, lock-in amplifiers rectify and filter signal pulses to obtain an average value of the signal. If the rise time of the pulses change as the cable temperature increases (due to an increase in cable resistance) the average value of the signal changes. Calculations of the response of such a system to changes in cable resistance indicated that the change in the rise time of current pulses to

the gauge circuits would be sufficient to introduce appreciable errors in lock-in amplifier measurements. Because of this problem and the fact that the overall accuracy of lock-in and box-car amplifiers is only about 2%, they were deemed unsuitable for this application and the dc circuit with a constant current supply was chosen for use with the logging tool.

With the gauges at the end of a cable 10,000 feet long and with no downhole electronics to condition the signals, changes in the characteristics of the cable with temperature and pressure are important considerations in designing the measurement circuitry. The most important characteristics of the cable to be considered are changes in lead resistance and changes in lead-to-lead capacity. The use of a constant current source to power the gauges automatically compensates for any changes in resistance of the leads carrying the excitation current. If the signals are measured with a high impedance device, such as a digital voltmeter, changes in the resistances of the signal leads also do not affect the measurements. In addition, the use of dc excitation also eliminates any effects due to changes in lead-to-lead capacity.

3.2 BASIC CIRCUITRY

The schematic circuit shown in Figure 2, using a constant dc current source with gauges connected in series, is the basic circuit that is used with the logging tool. This circuit is capable of high measurement accuracy because of availability of constant current power supplies which are very accurately regulated. The constant current supply used with the logging tool is Kepco Model CC100-0.2M, 0 to 200 mA and 0 to 100 V. This power supply has a specification of $\pm .005\%$ on current variation. The output current is determined by measuring the voltage across a 50 ohm precision resistor (CVR) in series with the power supply.

However, during a test of the constant current circuit at Los Alamos with a full length logging cable, one of the main sources of error was found to be variation in the current from the constant current power supply resulting from temperature changes of resistors used to regulate the current. In subsequent discussions with the manufacturer of the power supply it was learned that there are also other components that are temperature sensitive. It was therefore decided that in order to achieve the highest degree of stability, the entire power supply should be housed in a temperature controlled chamber. Initial tests in a temporary chamber did indeed show that thermostatic control of the power supply greatly improved its stability. Subsequently the power supply was permanently mounted in the thermostatically controlled cabinet. In tests conducted over three hour periods while drawing 30 mA, the current remained constant to within about 1 part in 100,000.

In the constant current circuit of Figure 2 the excitation current is necessarily the same in both the pressure gauge and the thermometer. However, the current (20 to 30 mA) required for the pressure gauge is considerably more than the current (1 mA) for which the platinum resistance thermometer is

Figure 2. Schematic of basic constant current circuit.

designed. The Celesco thermometers were calibrated at 1 mA and 20 mA and showed only a small difference due to self heating. However, to minimize the effect of self heating in the thermometer, two thermometers connected in parallel are used in the sonde so that only half the current flows in each.

3.3 CIRCUIT WITH SHUNT CALIBRATION

The basic constant current circuit shown in Figure 2 can be modified to allow switching of downhole shunt calibration resistors. Such a modified circuit is shown in Figure 3 in which shunt resistors are switched across one arm of the bridge circuit of the pressure gauge and across the resistance element of the thermometer by using a downhole relay. When the reversing switch shown in Figure 3 (which is uphole) is in one position, the coil of the relay is in series with the gauges so that the excitation current also flows through it and closes the contacts, thus switching in the downhole calibration resistors. When the reversing switch is in the other position the relay coil is simply in the voltage lead to the thermometer and there is not sufficient current to activate the relay.

This circuit requires the use of a multi-pole, single throw downhole relay capable of withstanding temperatures of at least 275°C that will operate on a current of 20 to 30 mA. Such a relay is not readily available but can be made by modifying a standard magnetic reed relay. A relay of this type was developed and tested on this program and is described in Appendix A.

3.4 CIRCUIT FOR MEASURING CABLE INSULATION RESISTANCE

Although using shunt resistors as shown in Figure 3 is a standard method of calibration bridge circuits, their use does not necessarily calibrate a circuit at the end of a long cable if the insulation resistance between pairs of conductors in the cable decreases to a sufficiently low value. Such a

Figure 3. Schematic of constant current circuit with downhole calibration.

decrease in insulation resistance may result, for example, from heating of the cable or from water leakage into the cable connector. In that case, the signal from the bridge circuit may be partially the result of low insulation resistance between two leads across one arm of the bridge. For example, if the insulation resistance across one arm of the bridge circuit of the pressure transducer in the sonde decreased to one megohm, the output signal would be changed by an amount equivalent to 7% of the gauge signal at 4000 psi. Using a shunt calibration resistor across one arm of the bridge would not detect the effect due to the low insulation resistance. Under these conditions a shunt resistor merely serves to calibrate the sensitivity of the gauge and not the absolute accuracy of the measured signal.

We had originally planned to use shunt calibration in our final geothermal well test. However, with the realization of the effect of insulation resistance on bridge balance we decided that it would be better to actually measure the insulation resistance between pairs of conductors to determine whether the resistance decreased sufficiently to produce an appreciable error in the pressure gauge readings. If the insulation resistance were to decrease, having measured the resistance between the various pairs of conductors would allow the gauge readings to be corrected for the effect of changes in cable insulation resistance. The circuit that was designed for this purpose is given in Figure 4.

The circuit of Figure 4 requires two double-pole down-hole relays to disconnect the gauges from the cable while the cable resistances are being measured. However, these relays do not have to operate on the 20 to 30 mA current from the constant current supply and are operated by an auxiliary power supply. The high temperature relays used with this circuit were manufactured by Babcock Electronics Corp., 3501 North Harbor Blvd., Costa Mesa California 92626. The manufacturer

Figure 4. Schematic of circuit used to measure cable insulation resistance during a logging run.

rates these relays for operation at 200°C (392°F), but we tested the relays at 288°C (550°F) for several hours with no apparent deterioration. The relays also worked well in the geothermal tests in which the circuit of Figure 4 was used. In using these relays it is necessary to connect the terminals of the two contactors in each relay in such a way that the thermal emf's are in opposition; when this is done, the resulting thermal emf at 288°C is only about 6 microvolts. The H.P. 3495A scanner with three sets of relays shown in Figure 4 is part of the data acquisition system (see Section 3.5) used in the well logging tests. The circuit of Figure 4 was designed to measure the insulation resistance between each pair of conductors in a seven conductor cable and between one of the conductors and the cable shield.

3.5 SIGNAL MEASUREMENT AND RECORDING

One of the modern instruments that makes the constant dc current measurement system feasible is the dc digital voltmeter used to measure the output signals of the downhole transducers. The high rejection ratios of these voltmeters for noise and ac signals virtually eliminate these unwanted signals from the dc outputs of the transducers. The voltmeter that was used in testing the sonde was the Hewlett-Packard 3455A digital voltmeter. This voltmeter has a normal mode rejection ratio greater than 60 dB at 60 Hz and an effective common mode rejection ratio greater than 160 dB at 60 Hz. This characteristic together with its high accuracy and sensitivity make it an ideal instrument for this application.

In the early stages of this program when lock-in amplifiers were being compared with the constant dc current system, a test of the two systems was made using 2000 ft of four conductor shielded cable terminated in a Wheatstone bridge. In this test, 400 mV of high frequency, wide band noise was impressed on a bridge signal of about 13 mV. With the lock-in amplifier the change in the measured signal was about 100 μ V,

whereas with the constant dc current circuit and a digital voltmeter with a resolution of $1 \mu\text{V}$ the change in the output signal was undetectable. Later in the program, a similar test was conducted at Los Alamos using 13,000 ft of seven-conductor logging cable. A one-half horsepower electric drill running close to the transducer circuitry induced several volts of noise in the circuit. Again, the noise induced in the circuit was not detectable in the voltmeter readings, indicating that the noise changed the voltmeter readings by less than one part 10^5 . These tests showed how effective digital voltmeters are in rejecting noise induced in the system.

In hydroclave tests of the sonde the outputs of the transducers were measured with a digital voltmeter and recorded manually. However, during logging runs in the geothermal well at Los Alamos the data was automatically recorded by their Hewlett-Packard modified 3050 automatic data acquisition system. This system consists of a digital voltmeter, a scanner and a programable calculator. It was programmed to automatically take readings every 10 or 20 feet of sonde depth, including the reading of the insulation resistance of each of the conductor pairs as indicated in the circuit of Figure 4. The relays in the scanner of the data acquisition system were used to switch from one pair of conductors to another.

IV. SONDE

4.1 DESIGN CONSIDERATIONS

The operating conditions established by contract set the limits for the design of the sonde. These specifications are an operating temperature of 275°C (527°F), an operating pressure of 7,000 psi, a diameter not greater than 3.0 inches and downhole fluid containing salts and acid gas. These operating conditions limit the use of elastomers for making seals. The commercially available elastomers with high temperature ratings can operate only for short periods at a temperature of 275°C. In addition, seals made of elastomers require zero-clearance fit to withstand 7,000 psi pressure differentials without extrusion.

All materials exposed to the geothermal fluids must be resistant to hydrogen embrittlement, chloride-enhanced stress corrosion cracking and acid corrosion.

The body of the sonde was actually designed to withstand temperatures of at least 300°C (572°F) and pressures in excess of 10,000 psi.

4.2 MATERIAL SELECTION

The requirement for corrosion resistance in the presence of chloride precludes the use of conventional stainless steel for exposed parts of the sonde. In a pertinent study, Watkins and Greer (1976) found four high nickel alloys and a titanium material that were unaffected by exposure to various combinations of chlorides and acids at temperatures up to 260°C (500°F) and pressures up to 2,000 psi. Thirty-five highly alloyed metals were investigated in their study. The five unaffected materials are:

Hastelloy Alloy* C-276

Inconel Alloy** 625

MP 35N†

MP 159†

Titanium

After considering availability of sizes and such properties as machineability, weldability, strength and ductility, in addition to resistance to corrosion and stress cracking, we chose Inconel Alloy No. 625 for the body of the sonde. The pressure and temperature requirements for the sonde so seriously restrict the utility of elastomeric gaskets that their use was completely eliminated in the sonde design.

Ceramic-to-metal seals were used for the electrical feedthroughs at the cable termination. The joints of the sonde body were all made by electron beam welding. The gauges were initially sealed to the sonde body with metal gaskets, but when two of them leaked during the first hydro-clave test the gauges were also sealed by electron beam welding.

4.3 DESIGN AND CONSTRUCTION

By the time the sonde was actually constructed it had been decided that it would be tested in the Los Alamos geothermal well. The sonde was therefore designed to be compatible with the Los Alamos cable head. However before it was decided that the sonde would be tested in the Los Alamos well and because the Los Alamos cable head may not withstand temperatures above 250°C (482°F), S³ started developing a cable head to meet the design temperature of 275°C (527°F). A description of the development of this cable head is included as Appendix B of this report. In hopes that we would

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* Trademark Cabot Corp.

** Trademark Huntington Alloys, Inc.

† Trademark Standard Pressed Steel Co.

also be able to test the sonde in a higher temperature well, a sonde compatible with the Sandia cable head was also designed but not constructed.

The initial design of the sonde also made provisions for the inclusion of the gradiometer, but after the development of the differential pressure gauge was discontinued, the sonde was redesigned to eliminate the gradiometer.

4.3.1 Structural Design

The design requirements for the sonde were to operate in a fluid at a temperature of 275°C (527°F) and at a pressure of 7,000 psi. Inconel 625, the selected sonde material, in the annealed state has tensile properties which degrade relatively little over the design temperature range as indicated by the maximum allowable design stresses (see Figure 5) for boiler and pressure vessel construction from this material. Since the sonde would never be subjected to pressure when people are nearby, it was not necessary to build the sonde with the safety factors required for pressure vessels. The outside diameter of the sonde is 3 inches and the thinnest wall section is one-half inch (see detailed engineering drawing in Volume II. Pressure induced stresses in the wall of the sonde were determined by the method of Roark and Young (1975). Circumferential stress σ_2 and longitudinal stress σ_1 are given by

$$\sigma_1 = \frac{-qa^2}{a^2-b^2} \quad \text{and} \quad \sigma_{2\max} = \frac{-2qa^2}{a^2-b^2}$$

where q is the external pressure in psi, and a and b are the outside and inside radii of the sonde body. For

$$\begin{aligned} q &= 7,000 \text{ psi, } a = 1.5 \text{ inches and } b = 1.0 \text{ inch,} \\ \sigma_1 &= -12,600 \text{ psi} \\ \sigma_2 &= -25,200 \text{ psi.} \end{aligned}$$

Figure 5. Maximum allowable design stresses for boiler and pressure vessel construction for Inconel alloy 625 annealed grade 1 ASTM B443, B444, B446 welded construction.

The certification data for the material from which the sonde body was machined specified the tensile strength of the material to be 124,500 psi. The yield strength should be greater than 60,000 psi; this results in a safety factor of 2.4 for 20°C (70°F) operation. If this safety factor is reduced by 5 percent as suggested by Figure (5), at 275°C (527°F) the safety factor is 2.3. From a stress standpoint, therefore, the sonde body should be capable of operating in fluid pressure up to 16,000 psi at temperatures up to 275°C.

4.3.2 Sonde Assembly

An assembly drawing of the complete sonde is given in Figure 6 and a detailed engineering drawing of the assembly is given in Volume II of this report. Photographs of the sonde and various parts are shown in Figures 7, 8, 9 and 10. Before finalizing the design, studies were made to determine the most practical method of joining the various sections of the sonde. The pressure and temperature requirements limit available elastomers for gaskets to very short exposure periods, probably requiring the replacement of all such seals after each down-hole test. The tolerance required for metal seals limit their use to strongly bolted face seal arrangements. It was our opinion, therefore, that the loss of the option for field repair was clearly offset by the reliability of an all welded system. The sonde design, therefore, provides for electron beam welding of all joints and seals.

The design of the joints in the sonde body provides for ease of parting by a simple lathe operation and reassembly by rewelding. (Parting and rewelding of the sonde joints was accomplished several times during the testing phase of this program.) The rewelding operation should preferably also be by electron beam welding; however, the more common tungsten electrode inert gas welding technique could be used if care were exercised to prevent overheating certain areas.* In

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* The electron beam welding was done by Southern California Metals Joining, 17751 Sky Park East, Irvine, California

Figure 6. Sectional drawing of temperature and pressure measuring sonde.

Figure 7. Expanded view showing various sections of the sonde. Electrical feedthroughs and gauges are also shown.

Figure 8. Photograph of assembled sonde before welding and without centralizers.

Figure 9. Photograph of thermometers and pressure gauge mounted in end plate.

Figure 10. Photograph of electrical feed-throughs mounted in header plate.

Figure 6 are shown the places where the welded joints and seals are made in the sonde assembly. The electrical feedthroughs in the header of the sonde were also welded to the head using the electron beam technique.

As noted earlier in this report, in the initial design of the sonde the gauges were sealed with metal gaskets. The gaskets used were Harrison K-Seals No. 24107-875 and No. 24107-625. During the first hydroclave test two of these seals leaked. This does not necessarily mean that these seals are unreliable because the leaks may have been the result of defects or scratches in the gasket seats on either the sonde or the gauges. Nevertheless, it was decided that welded seals for the gauges would be more reliable. The gauge mountings were, therefore, redesigned and the mounting with electron beam welded seals shown in Figure 11 was used in all subsequent gauge installations.

A verification of the validity of the decision to use all welded construction was made evident by the fact that no electron beam weld leak was found in the hydroclave and down-hole tests.

4.3.3 Electrical

Seven electrical feedthroughs were mounted in the head of the sonde to accommodate the seven conductors in the logging cable. (See Figure 10). These feedthroughs are a ceramic-to-metal type (Alberox feed-thru #A1107 sold by H & W Products, Dallas, Texas). An insulation test of one of these seals after it had been welded to a base plate gave a value for the insulation resistance greater than 300 megohms at 500°C (930°F).

In order to minimize the generation of thermal emf's, it was initially planned to make all hookups to the gauges with Inconel X750 wire insulated with woven fiberglass sleeving. The first pressure gauges were provided with such leads

Figure 11. Method of mounting gauges to the sonde using electron beam welded seals.

by the manufacturer. The leads were made long enough to extend from the gauge to the feedthroughs at the head of the sonde and were used during testing and calibration of the gauges at high temperature (up to 315°C) by the manufacturer. However, it was found in assembling the sonde that these leads had become very brittle and were easily broken when bent sharply. Further testing of samples of wire by heating in an oven at 315°C for a period of three hours resulted in similar embrittlement of the wire. Such embrittlement had not been indicated in the specifications published by the manufacturer of the wire. However, subsequent discussions with metallurgists of the manufacturer revealed that the wire is work hardened when drawn and subsequent heating to even the relatively low temperature of 315°C produces an aging effect which further hardens the material. Because of this embrittlement problem, the Inconel leads were replaced with copper leads which were brazed to the gauge terminals and the feedthroughs. The electrical leads inside the sonde were supported and strain relieved as shown in the detail engineering drawing in Volume II.

5. SONDE TESTING

Two types of tests were conducted with the sonde:

(1) tests in a hydroclave at Southwest Research Institute (SwRI), San Antonio, Texas, which also served to calibrate pressure gauges, and (2) tests in the Los Alamos Fenton Hill geothermal well (Injection Borehole: EE-1).

5.1 HYDROCLAVE TESTS

The hydroclave at SwRI can be pressurized to 10,000 psi and heated to 288°C (550°F). It is large enough to accommodate the entire sonde, is filled with high temperature transformer oil and is provided with electrical feedthroughs for measurement leads to the sonde. Pressure in the hydroclave was measured with a precision gauge that had been calibrated with a dead weight tester. Temperature in the hydroclave was measured with a thermocouple at a location near the thermometer on the sonde. Temperature measurements with the thermocouple were not so sensitive as those with the platinum resistance thermometer in the sonde and therefore could not be used to check the calibration of the resistance thermometer, which had been calibrated by the manufacturer against NBS standards. However, there was generally good agreement between the thermocouple and resistance thermometer measurements.

The first hydroclave tests were conducted with the Precise Sensors pressure gauge installed in the sonde. During these tests the gauge developed a low resistance to ground and was therefore unusable.

The next hydroclave tests were with a Bell and Howell type 4-317-0001 unbonded strain gauge pressure transducer installed in the sonde. Tests were conducted with pressures ranging between 0 and 8,000 psi at temperatures of 27°C (80°F), 110°C (230°F), 210°C (410°F) and 277°C (530°F). During these tests pressure readings were taken at various settings both

going up and coming down in pressure. The pressure calibration determined from these tests was a few percent different from that determined by the manufacturer and the temperature dependence of the pressure calibration was somewhat greater than given by the manufacturer. In other respects, especially in regard to non-linearity, hysteresis and non-repeatability, the pressure calibration in the hydroclave tests was within manufacturers specifications for this gauge. The calibration determined in these tests was used in reducing the data from the well logging runs with this gauge.

Because of difficulties with the unbonded strain gauge pressure transducer in geothermal well tests, the gauge was replaced with a Bell and Howell type CEC 1000 sputtered strain gauge pressure transducer. With this gauge installed, the sonde was again tested in the SwRI hydroclave at temperatures of 27°C (80°F), 102°C (215°F), 149°C (300°F), 204°C (400°F) and 288°C (550°F) and at pressures varying by 1000 psi increments between 0 and 8000 psi. This gauge was calibrated by the manufacturer with a constant voltage supply and, as expected, the calibration was somewhat different with a constant current supply. Also, the gauge is temperature compensated for a constant voltage supply and consequently there was a small but appreciable temperature effect on the pressure calibrations. However, at any given temperature the output of the gauge was linear with applied pressure. In other respects the performance of the gauge was within manufacturers specifications.

The calibration of the CEC 1000 pressure transducer is accurately represented by the following equations:

$$P = \frac{1.0^6 E_p - 0.640 (T-80)}{3.109 [1 + 0.262 \times 10^{-3} (T-80)]} \text{ psi.} \quad (1)$$

Where E_p (in volts) is the output (at $I_o = 24 \text{ mA}$) of the pressure gauge (corrected for zero shift)

I_o (in amperes) is the constant current in the circuit.

T (in °F) is the temperature.

For the platinum resistance thermometers, a quadratic equation was fit to the three calibration points (32°F, 250°F, and 500°F) given by the manufacturer, considering the two thermometers in parallel. The following equation accurately represents the calibration of these thermometers:

$$T = 5292.25 \left[1 - (1.15784 - .003387 E_t/I_o)^2 \right] ^{\frac{1}{2}} \text{ } ^\circ\text{F} \quad (2)$$

Where E_t (in volts) is the output voltage across the thermometers in parallel.

Equations 1 and 2 were used in reducing the data recorded on the final geothermal well logging test (see Section 5.2).

In considering the calibration and accuracy of the pressure gauge in relation to the manufacturers specifications for the gauge, it is important to understand the implication of those specifications, especially the specification for combined hysteresis and non-repeatability. The specification for combined non-linearity, hysteresis and non-repeatability for the CEC 1000 pressure gauge is $\pm 0.25\%$ of full range output. This means, for example, that if an 8000 psi gauge is cycled from low to high pressure and back to low pressure, such as in going down and coming up a geothermal well, the readings at 2000 psi going down and coming up may differ by $\pm 1.0\%$ and at 1000 psi they may differ by $\pm 2.0\%$. These differences are largely due to hysteresis and non-repeatability and are the main effects that limit the absolute accuracy of pressure measurement at a given pressure level. However, hysteresis and non-repeatability do not appreciably effect the sensitivity of the gauge to small changes in pressure which is frequently of more interest in well logging than the absolute accuracy of the gauge. In calibrating the CEC 1000 pressure transducer, the hysteresis and non-repeatability were well within the manufacturers specifications in most cases, but in a few cases approached the limits of this specification.

5.2 GEOTHERMAL WELL TESTS

Two well logging tests were run in the injection borehole (EE-1) of the Los Alamos Fenton Hill geothermal well site. The first test was run on 24 August 1978 using the unbonded strain gauge pressure transducer and the second was run on 21 December 1978 using the CEC 1000 sputtered strain gauge pressure transducer. These logs were run to a depth of 10,000 feet and 9,740 feet respectively. The tests were run using the Los Alamos cable rig, their seven conductor logging cable and their cable head, which our sonde had been designed to accept. Los Alamos also supplied the recording system, auxiliary equipment and all necessary support people to prepare and run the tests. The temperature at a depth of 10,000 feet in the Los Alamos well is 200°C (392°F) and the pressure is approximately 4100 psi. We had hoped to test the sonde in a geothermal well at a temperature more nearly approaching or even exceeding our contract design specification of 275°C. However, a well in which to test the sonde up to this temperature was not made available to us during this program.

The first test in the Los Alamos well was run at a rate which varied between 1 and 2 feet per second, with most of the run at a rate of approximately 1.6 feet per second. Readings of depth, time, pressure, temperature, and excitation current were recorded every 10 feet, both going down and coming up, with their Hewlett Packard automatic data acquisition system. The temperature data was reduced by using Equation 2 and the pressure data by using calibration curves from the hydroclave test. Plots of temperature and pressure versus depth are given in Figures 12 and 13 and in expanded form in Figures C.1 and C.2 of Appendix C. The differences in the temperature readings going down and coming up were too small to be distinguishable on this plot and therefore only the readings going down are plotted. This temperature log is similar to one that Los Alamos had obtained sometime before our test. The absolute accuracy of

Figure 12. Temperature versus depth.
Injection borehole of the Los Alamos
Fenton Hill Site Run - 21 December 1978

Figure 13. Pressure versus depth.
Injection borehole of the
Los Alamos Fenton Hill Site
Run - 24 August, 1978.

these temperature measurements is believed to be $\pm 0.5^{\circ}\text{F}$ except in the rapidly changing temperature region between 8800 feet and 9400 feet where the accuracy is $\pm 2^{\circ}\text{F}$. The accuracy of the temperature measurements in the rapidly changing region could be improved by logging this region more slowly to allow more time for the thermometers to come to equilibrium with the geothermal fluid.

In the pressure versus depth plots of Figures 13 and C.2 the measurements taken going down the well and coming up are not in good agreement and are in especially poor agreement in the rapidly changing temperature region below 8800 feet. The disagreement is the result of the long time lag for this gauge to come to temperature equilibrium. This is especially evident in the region between 8800 feet and 9000 feet where the rapidly changing temperature results in large and opposite effects on the pressure readings going down and coming up. As noted earlier in this report, the temperature lag of this gauge is the result of poor thermal contact of the unbonded strain gauge with the body of the gauge (and hence with the geothermal fluid). This data clearly shows that this gauge is unsuitable for geothermal well logging at even this moderate rate of between 1 and 2 feet per second.

In the second geothermal well test at Los Alamos, using the CEC 1000 sputtered strain gauge pressure transducer, the circuit of Figure 4 was used to measure the cable insulation resistance as well as the transducer outputs. (See Section 3.4). The reasons for this were to determine if at any time during the logging run the cable insulation resistance became low enough to affect the transducer reading and, if so, to correct the readings for the effects of low cable insulation resistance. As discussed in Section 3.4, low cable insulation resistance has a much greater effect on the output of the bridge circuit of the pressure gauge than on the thermometer.

The complete circuit for the CEC 1000 pressure transducer, including the strain gauge bridge, the temperature compensating resistors and cable insulation resistance across each leg of the bridge, is given in the schematic circuit of Figure 14. The resistances R_1 , R_2 , R_3 and R_4 represent the insulation resistances between cable leads connected to the gauge, the R_0 's are the temperature compensating resistors and the R 's are the nearly equal resistances of the strain gauge bridge. R_1 , R_2 , R_3 and R_4 are the same resistances indicated in the circuit of Figure 4. The analysis of the circuit of Figure 14 to determine the effect of the insulation resistances on the bridge output is straightforward but tedious. The result of this analysis is given by the following equation:

$$e = 183 I_0 (183 + R_0) \left[\frac{1}{R_1} - \frac{1}{R_2} - \frac{1}{R_3} + \frac{1}{R_4} \right] \quad (3)$$

Where I_0 (in amperes) is the constant current through the circuit.

$R_0 = 25 [1 + .00218 (T-32)]$ ohms

T (in °F) is temperature

R_1 , R_2 , R_3 and R_4 (in ohms) are cable insulation resistances shown in Figure 14.

Equation 3 was used to correct the pressure data from the well logging run by subtracting the calculated value of e from the recorded output of the pressure gauge. Equation 1 was then used to reduce the pressure data.

The insulation resistance between the leads to the thermometer never became low enough to appreciably effect the output of the thermometer and the temperature data was reduced directly with Equation 2.

Figure 14. Schematic of CEC 1000 pressure gauge bridge circuit including cable insulation resistances.

During most of the logging run the cable insulation resistances remained high ($>20\text{ M}\Omega$) and the correction for their effect on the output of the pressure gauge was small ($<1\%$). Near the bottom of the well, especially coming up, the correction was greater, amounting to about 4% at 9700 feet. Whether the lower insulation resistance near the bottom of the well was a temperature effect on the cable or on the connector in the cable head or possibly even water leakage into the cable head could not be determined. The other location in the logging run where the insulation resistances dropped to low values ($1\text{-}10\text{ M}\Omega$) was near the top of the well coming up. When the cable head was removed from the sonde at the end of the run some water was found in the cable head. The source of this water is unknown; it may have leaked in at the Viton O-ring seals of the cable head or, as was also speculated, it may have come from the cable and condensed in the cable head when its temperature fell below the boiling point of water. In any event, it seems likely that the water found in the cable head was responsible for the low insulation resistances near the end of the run by creating low resistance paths in the cable connector rather than in the cable itself. The cable insulation resistance measurements also indicated occasional sudden drops in insulation resistance for short periods. These sudden drops in resistance were probably the result of mechanical effects on the cable during its removal from the cable reel and its passage over various sheaves in its passage to the well. The measurements of insulation resistance were therefore useful in the determining the behaviour of the cable and the cable connector during the logging run as well as providing the resistance values used to correct the output of the pressure gauge.

The temperature versus depth plot in the Los Alamos well from the logging run of 21 December 1978 is given in Figure 15 and in expanded form in Figure C.3 of Appendix C.

Figure 15. Temperature versus depth.
Injection borehole of the Los Alamos
Fenton Hill Site Run - 21 December 1978

In these figures, both the going down and coming up data are plotted, although the two sets of data are indistinguishable on the scales of these plots except in the rapidly varying temperature region below 8800 feet. The temperature plot of Figure 15 differs in detail from the logging run of 24 August 1978 in the same well (see Figure 12). The differences in the two runs are real and represent the changes in the temperature of the well during the interval between the two runs. A temperature log by Los Alamos about a week before our run of 21 December 1978 gave a temperature profile similar to that of Figure 15.

The plot of pressure versus depth in the Los Alamos well from the logging run of 21 December 1978 is given in Figure 16 and in expanded form in Figure C.4 of Appendix C. Again the data taken going down and coming up are both plotted. Throughout most of the run the agreement between the going down and coming up data is excellent and is nearly indistinguishable on these plots. This illustrates the marked difference in temperature response between the CEC 1000 sputtered strain gauge pressure transducer and the unbonded strain gauge transducer used in the previous run (see Figure 13). However, in the rapidly varying temperature region below 8800 feet there is still considerable disagreement between the going down and coming up data. This is a consequence of the short but non-zero lag of the pressure gauge to changes in temperature; in logging through a region such as that below 8800 feet the temperature varies too rapidly for the gauge to come to temperature equilibrium with the geothermal fluid. If this region had been logged more slowly the agreement between the going down and coming up data would have been much better. This is a problem associated with the pressure transducer and not with the method of making the measurements; if downhole electronics had been used to condition the signals before transmitting them uphole the results would have been the same. The

Figure 16. Pressure versus depth.
Injection borehole of the Los Alamos
Fenton Hill Site Run - 21 December 1978

temperature response of pressure gauges, therefore, represents an area which requires further development if accurate pressure measurements are to be made at high temperatures in regions with large temperature gradients.

The four or five points at and above 2000 feet in Figure 16 that are obviously off the pressure curve are spurious and are the result of sudden but short duration changes in insulation resistance. In setting up the data acquisition system at Los Alamos, it was found by trial and error that, in order to get an accurate reading, a period of approximately one second between switching and taking a reading was required. Since the time constant to charge the cable is only a few milliseconds, why a period as long as one second was required is not understood. When setting up the logging run, there was not sufficient time to look into this problem, but instead the data acquisition system was programmed to take each reading one second after the switching operation for that reading. As a consequence of this, the pressure readings were taken 12 seconds after the first insulation resistance measurements. Sudden changes in insulation resistance may not have persisted until the pressure reading was taken or, on the other hand, the insulation resistance may have changed between the time its reading was taken and the pressure reading was taken. The recorded data shows that the spurious points above 2000 feet in Figure 16 correspond to sudden but short duration changes in insulation resistance and therefore should be disregarded.

6. DISCUSSION AND RECOMMENDATIONS

The main objective of this program was to develop a high-temperature geothermal logging tool to operate with no downhole electronics by making use of modern electronic equipment that is now commercially available. The system chosen is a dc system in which the gauges are powered by a precisely regulated uphole constant current supply and the output signals from the gauges are read with a digital voltmeter having very high rejection ratios for both common mode and normal mode noise signals. This measurement system worked very well with almost no measureable interference with the output signals from the gauges by noise generated in the cable or elsewhere in the system. The main problems that were encountered were problems associated with the transducers themselves, with the cable or with the cable head that attaches the cable to the sonde. To a greater or lesser extent these problems are common to all measurement systems, including those with downhole electronics.

One of the main requirements for any transducer used in geothermal well logging is that it must quickly come to temperature equilibrium with the geothermal fluid or alternately that changes in temperature have no effect on its output. The rate at which a well can be logged with a given accuracy depends among other things on the rate at which the transducer comes to temperature equilibrium with the fluid, so the shorter the equilibration time constant is the faster the logging rate can be.

The platinum resistance thermometers used to measure temperature performed very well with only minor difficulties that can easily be corrected. Our experience at temperatures up to 300°C (572°F) indicates that this type of thermometer should be useful to considerably higher temperatures. The main problem is likely to be insulation of the electrical

leads. The time constant (equal to or less than one second) to come to equilibrium with a fluid was sufficiently short that only a small error was introduced by this effect when logging at the rate of one foot per second, even in the regions of the well where the temperature gradient was large.

Pressure gauges presented more problems than did thermometers. The main problems associated with pressure gauges were stability (and repeatability), insulation resistance and the time required to come to temperature equilibrium. By far the most reliable gauge that we tested was the CEC 1000 sputtered strain gauge pressure transducer manufactured by Bell and Howell Company, Pasadena, California. The stability of this gauge was good, although improvements in this regard would lead to higher accuracy measurements. There were no problems with insulation resistance up to the highest temperature (300°C) at which it was tested. The main problem was the time required to come to equilibrium and this presented a problem only during the portion of the logging run in which the temperature gradient was very large. The gauge that we used was temperature compensated for use with a constant voltage supply; it is likely that a gauge of this type that is specifically temperature compensated for constant current would not be as greatly affected by temperature changes. It is recommended that if a constant current is used, such a temperature compensation be designated. The CEC 1000 gauge is a new gauge and the production problems are still being worked out and delivery times are consequently long. As the production problems are solved it is likely that the stability and quality of the gauge will further improve. We tested the gauge at temperatures higher than those rated by the manufacturer with no apparent deterioration in gauge performance. However, to use the gauge at still higher temperatures will probably require further development by the manufacturer.

The development of the gradiomanometer was not completed because the manufacturer was not successful in developing a high-temperature differential pressure gauge with the required sensitivity. A high-temperature gradiomanometer would be a useful addition to the sonde for measuring fluid density and its development should be continued. One of the problems in developing a gradiomanometer is thermal expansion of the columns (either fluid or solid) leading from the differential pressure gauge to ports in contact with the geothermal fluid. D. R. Grine has suggested that a possible solution to this problem would be to maintain the columns at a constant temperature equal to or higher than the maximum temperature anticipated in use, thus avoiding the problem of thermal expansion due to temperature changes. However, even using such a technique, a high temperature differential pressure gauge of sufficient sensitivity would still be required and its development is a major task.

In our logging runs it was found that the output signal from the platinum resistance thermometer was much less affected by changes in cable insulation resistance than was the output signal from the pressure transducer. The reason for this is that, in using a resistance thermometer, changes in the entire resistance of the thermometer are measured and low values of cable insulation resistance merely shunt part of the current that would ordinarily flow through the thermometer. For this reason, a cable insulation resistance as low as one megohm has a negligible effect on the output of the thermometer. On the other hand, in a pressure transducer of the strain gauge variety a bridge circuit is used and the output signal is the unbalance of the bridge circuit. Because the change in resistance of the strain gauges is small, the output of the bridge circuit is much more sensitive to changes in cable insulation resistance. For example, with the CEC 1000 pressure transducer, a cable insulation resistance as low as one megohm across one

arm of the bridge produces a bridge unbalance equivalent to 7% of the gauge signal at 4000 psi and even larger percentages at lower pressures. A pressure transducer that did not use a strain gauge bridge would be much less sensitive to this effect. One type of pressure gauge that does not use a bridge circuit and that could be used with a constant current circuit is a bourdon tube type pressure transducer driving a rheostat. No such gauges for use at high temperatures are currently commercially available although at least one gauge manufacturer has plans to undertake such a development. Ceramic type rheostats, which could probably be adapted to high temperature use, are currently available. These have an important advantage over wirewound rheostats for this application in that the change in resistance is continuous rather than in steps from wire to wire and therefore the sensitivity of the gauge to small changes in pressure can be made greater.

Even at temperatures up to 275°C the currently available logging cables continue to be a problem and the problems will become more severe at higher temperatures. The main electrical problem with the cables is the decrease in the insulation resistance. Techniques such as the ones used on our last logging run to measure the insulation resistance are useful both in determining the behaviour of the cable during a logging run and for making corrections to the data if the decrease in the insulation resistance is sufficient to warrant such corrections. But for the high temperatures contemplated in the future, new cables with better high temperature insulation will be required. Ceramic insulation, such as the magnesium oxide insulated cable currently being developed, is likely to be the type of cable that will be used. Furthermore, the first type of logging cable with ceramic insulation is likely to be monoconductor coaxial cable and high temperature logging tools will have to be developed that will operate with such a monocable.

Systems, Science and Software (S³) had independently devised and is currently testing a modified version of the constant current measurement system to operate with a monocable. This system appears to be a promising approach to high-temperature logging with a monocable because it still does not require the use of downhole electronics and all of the measurement techniques used on this program would apply.

The Hewlett Packard data acquisition system used to program and record data during our logging runs at Los Alamos was not used to full advantage. This system includes a programmable calculator that can be programmed to reduce the data to temperature and pressure as it is being logged and recorded. At the time of the logging runs at Los Alamos we were neither sufficiently familiar with the data acquisition system nor did we have enough time at Los Alamos to program the calculator to do this. However, since the data was reduced by programming it on the S³ computer after returning from Los Alamos, programming the data acquisition system to reduce the data as it was logged would have greatly lessened the amount of work involved. S³ has now acquired a data acquisition system similar to that used at Los Alamos and any future logging runs will be programmed on this system.

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APPENDIX A

HIGH TEMPERATURE RELAY

The circuit for downhole shunt calibration given in Figure 3 requires a two-pole, single-throw downhole relay. Such a relay is not available but can be made by modifying a standard magnetic reed relay for high temperature use and the development and testing of such a high temperature relay was undertaken as part of this program. In a magnetic reed relay, the reeds and contacts are encapsulated in a glass envelope and are actuated by a coil wound around the outside of the envelope. The glass envelope and the reeds were tested at 400°C with no adverse effects. In a preliminary version of a high temperature relay the magnetic coil was replaced with one wound with TFE insulated wire, which had previously been tested at 316°C (600°F) for several days with no apparent deterioration. During testing of this relay, the switch was actuated and monitored once a minute. Tests were run for 24 hours at 260°C (500°F) and for nine hours at 288°C (550°F) with no failures or apparent deterioration. The temperature was then raised to 316°C (600°F) and this caused the coil form to break due to thermal expansion of the coil windings. This resulted simply because the coil was originally wound too tightly.

The coil was rebuilt to accept three single-pole relays as shown in Figure A-1. The coil was wound by D. C. Harder Engineers of San Diego, on a brass form with Anaconda SX glass covered #33 copper wire and the winding coated with a high temperature ceramic as shown. During testing of this relay a current of 50 milliamperes was switched off and on by the activating it four times per minute over a period of eight hours on each of three days, for a total of over 5700 switchings. There were no failures or indications of deterioration in the performance of the relay during or after these tests.

Schematic of High Temperature Relay

Figure A-1. High temperature triple single-pole relay.

APPENDIX B

S³ CABLE HEAD

B. 1. DESIGN OF CABLE HEAD

No cable head, or terminator, which would operate under the conditions required for this phase of operation had been designed; therefore, S³ undertook the design of a backup cable head and made preliminary tests which indicate considerable promise for functional reliability.

The design of the cable head is indicated in Figure B-1. The cable armor is potted and anchored in a conical opening that surrounds a tubular protector for the cable conductors. Each conductor is welded or silver soldered to a pin of the multipin glass-to-metal feedthrough which becomes an integral part of the cable head when the connector void is pressure potted with high temperature epoxy. Pressure potting collapses gas bubbles in the epoxy, making the system less susceptible to fluid permeation. The armor anchor cone is machined into a bored rod which is designed to accept a fishing head in the event the sonde is lost.

The exposed electrical pins and the gasket sealing surfaces are to be protected by bolted-on covers when the head is removed from the sonde. It is likely that a new sealing ring (an O-ring in this design) will be required each time the head is attached to the sonde.

The glass-to-metal feedthrough is designed to permit interchangeable use of different sondes with a given cable head. The sockets and the pins would be made of spring temper material, probably Inconel X718. The shells would be Inconel 625 with individual holes for each pin. The glass which seals the pins in place and insulates them from the shell is a proprietary mixture* which provides an electrical resistance of 50 megohms at 300°C and withstands 500 V. The

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* Hemetic Seal Corporation, Rosemead, California

Figure B-1. S³ cable head.

shells are electron beam welded to Inconel 625 end plates as indicated in Figure B-1.

B. 2. TESTS OF CABLE HEAD

Three types of tests were conducted on different parts of the cable head. One type consisted of cold and hot tests of the armor anchor; others were dielectric tests of the epoxy potting material and tests of the metal O-ring seal.

Armor Anchor Tests

An ambient conditions test was made of the armor anchor of a full scale prototype cable head similar to that shown in Figure B-1. The parts were made of 4130 steel, an aluminum sleeve to protect the cable insulation from the armor wires, and a 3/8-inch cable with seven conductors rated at 300°F. The armor was anchored in the conical shell with Cotronics' Duralco 700 epoxy. The assembly was tested by pulling it in the DOE/S³ ambient pressure cable test facility. The male threaded part was not optimum because it was made from available steel tubing which left excessive clearance between the protection sleeve and the male part. This permitted epoxy to flow up the conductor bundle rather than being compressed around the armor wires when the parts were threaded together. Nevertheless, good filling was achieved and the wires were well-anchored.

The cable was slowly stretched with increasing tension (over a period of 20 minutes) until it failed. The cable failed mechanically about 3 feet from the connector at a force of 12,670 lbs (the rated breaking strength of the cable is 11,800 lbs).

The cable was then cut off, the conductors checked for continuity through the anchor assembly and the insulation resistance measured. All results were normal. The connector

was then sectioned by milling away material nearly to the centerline to reveal the condition of the anchor.

A second armor test was conducted at elevated temperature and atmospheric pressure. The cable used in this test was U. S. Steel, 7-conductor high temperature well logging cable Number 7J46RF. The assembly was heated in the DOE/S³ atmospheric pressure test stand at a temperature of 260°C (500°F) for three hours, after which tensile loading was applied. The load was progressively increased until the cable parted under a total load of 15,810 lbs at a position 12 inches from the connector. The nominal breaking strength of the cable given by the manufacturer is 17,000 lbs. The rated strength is usually given for the cable ends constrained against rotation; in our test no constraint against twisting was made. The conclusions are that the cable broke at its expected breaking strength and that the armor termination is as strong as the cable itself. The connector was sectioned to reveal the condition of the armor anchor and the conductors. No damage to any of the seven conductors was observed by post-test visual inspection of the connector region. There was some evidence that the armor wires had "pulled" about 0.08 inch to "set" the armor/epoxy in the conical region of the termination.

As a result of discussions with C. Hickam of Sandia Laboratories and Bert Dennis of LASL, we considered cable water blocking and terminal break strength control in the terminator design. All the conditions desired following a cable/sonde parting may not be practical to attain. When parted from the sonde, the cable should not have an enlarged end fitting which could be trapped in a cave-in. The break-away force at the cable sonde interface should be no more than 3000 lbs for a 17,000 lb breaking strength cable. This limit makes either a metal shear or a tension link very small and subject to damage by the shock loading that can be expected in normal

handling and hole traversing. A section of either a weakened cable or a smaller cable may be the only feasible solution to providing resistance to dynamic loading and yet breaking at a fraction of the main cable strength. After the cable is separated from the sonde, to facilitate recovery of the sonde it should present an upper end protrusion that will accept a fishing tool.

Epoxy Dielectric Test

The same high temperature epoxy* that was used to anchor the armor wires is used in the connector cavity to insulate the cable conductors and feedthrough pins from each other and from ground. This volume is pressure potted in order to minimize penetration of fluids into the insulation. No data were available on the high temperature resistance of this epoxy material which maintained such good mechanical properties at temperatures of interest to current geothermal well logging. To obtain resistance data, tests were conducted at temperatures up to 375°C (700°F) by making resistance measurements between pins of a two-pin glass-to-metal seal which had been potted in epoxy as shown in Figure B-2. The minimum dimension across the surface of the glass was 0.045 inch. Figure B-3 shows the resistance dependence on temperature for this geometry as indicated by the three data points. The resistance of the bare glass-to-metal seal was more than an order of magnitude higher in the temperature range shown, indicating that the conductance associated with the assembly was largely that of the epoxy. Nonetheless, the data shows that the resistivity of the epoxy remains high at temperatures up to 300°C.

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* Duralco 700 Ultra High Temperature (700°F) epoxy supplied by Cotronics Corp., 37 West 29th St., New York, NY 10018.

B-6

Figure B-2. Glass/metal seal potted in high temperature epoxy for insulation resistance measurements.

Figure B-3. Resistance dependence on temperature of Duralco 700 ultra-high temperature epoxy.

Metal O-rings Tests

Two metal O-rings are used in the S³ sonde at the cable head end. The larger of these is 1.750-in OD and becomes an integral part of the cable head when the termination space is pressure potted with epoxy. The other O-ring, which is 1.375-in OD, is active to keep well fluid from entering the region where the electrical connectors make contact. Both O-rings are United Aircraft Products, Inc. self-energizing hollow metal type for external pressure service. The O-ring material is Inconel X750 plated with .001 to .002 inch of gold. One of the larger size O-rings was tested in the fixture shown in Figure B-4. As indicated in the figure, the O-ring was externally pressurized with water through a high pressure line connected to an Enerpac hand-operated pump. A Viton O-ring was positioned outside the high pressure port to complete the pressurized water cavity. The leak detection port was connected to a U-tube manometer which served to indicate leakage past the metal O-ring.

The test fixture was placed in an oven and heated to the test temperature, with the water pressurized to prevent boiling (approximately 2500 psi at 525°F). A thermocouple was clamped to the fixture to indicate its temperature. The pump, pressure gauge and U-tube manometer were, of course, outside the oven. The manometer is rather insensitive to leakage of cold water, but is very sensitive to hot water leakage past the O-ring. (At 275°C any leakage water flashed to vapor having a volume 2500 times greater than water.)

The O-ring test fixture was heated to 275°C and held at temperature for a period of four hours. The pressure was raised to 3000 psi prior to heatup, and to 9500 psi, the upper limit of the pump, during the test. A total of three

Figure B-4. Metal O-ring test fixture.

tests were conducted. No indication of a leak was observed on the first test.

During the second test the manometer indicated a leak past the metal O-ring when the pressure was raised to 9000 psi and then dropped back to 2000 psi; upon repressurization the leak recurred. After sitting at temperature for about two hours, the pressure was again raised to 9500 psi and this time no leak was observed. The location of the leak was visually obvious by discoloration patterns on the faces of the test fixture. On closer inspection, a small depression was observed on the sealing surface. This depression was probably responsible for the temporary leak. The depression was smooth edged and apparently shallow enough to permit the resealing indicated during the later portion of the test. On the third test no pressure rise was attainable and when the system was taken apart the Viton O-ring was found to have been badly deteriorated.

From this limited test data and from discussion with Sandia Laboratories personnel, it appears that small-diameter metallic O-rings can make satisfactory all-metal seals provided proper attention is paid to tolerances and to sealing surface finish. During those times when the tool is not connected to the cable head, maintenance of these critical surfaces can be accomplished by proper protective covers.

Figure C-1. Temperature versus depth.
Injection borehole of the Los Alamos
Fenton Hill Site Run - 21 December 1978

Figure C-2. Pressure versus depth.
Injection borehole of the
Los Alamos Ferton Hill Site
Run - 24 August, 1978

Figure C-3. Temperature versus depth.
Injection borehole of the Los Alamos
Fenton Hill Site Run - 24 August 1978

Figure C-4. Pressure versus depth.
Injection borehole of the Los Alamos
Fenton Hill Site Run - 21 December 1978