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IMPROVED GEOTHERMAL WELL LOGGING TOOLS

by

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ABSTRACT

A geothermal well logging tool has been designed to operate at 275°C and 7000 psi. The logging tool will initially consist of a manometer, a gradiomanometer and a thermometer; the electrical and mechanical design is such that a flowmeter and a caliper can be added as a later development. A unique feature of the logging tool is that it contains no downhole active electronics. The manometer is a standard high temperature pressure gauge. The gradiomanometer consists of a differential pressure gauge which is coupled to ports separated vertically by 2 ft. The differential pressure gauge is a new development; it is designed to measure a differential pressure up to 2 psi at a line pressure of 10,000 psi. The thermometer is a platinum resistance thermometer previously developed for oil well logging. The pressure gauges are both strain gauge types which allows all three gauges to be connected in series and driven from a constant current supply. This arrangement makes it possible to use a standard seven-conductor cable with no downhole switching. The joints in the sonde are electron beam welded, thus eliminating any sealed joints in the sonde wall. The logging tool will be tested first in an autoclave and in a geothermal well later in the program.

1. INTRODUCTION

This is the Semi-Annual Technical Report under Contract No. E(04-3)-1315 to develop improved geothermal well logging tools. The logging sonde will initially combine a thermometer, a manometer, and a gradiomanometer, all to operate at a temperature of 275°C and a pressure of 7000 psi. The electrical and mechanical design of the sonde is such that a flowmeter and a caliper can be added as a later development.

A unique feature of the sonde design 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. The recent workshop on geophysical measurements in geothermal wells (Baker, et al., 1975) concluded that signal transmission (cables and their connections) and downhole electronics for signal processing, amplification, and other functions both limit the performance of available logging tools. Recommendations were made for circuit development using presently available high temperature ceramic tubes and for development of new higher temperature components. For those 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 sonde can be upgraded to the long-term objective of operation at 500°C.

The sonde will be useful in both cased and open geothermal wells to determine what fluids enter or leave the well, where, and in what quantities and thermodynamic states. The interpretation techniques previously published

by Schlumberger (Meunier, et al., 1971; Schlumberger, 1973) for a production combination tool (PCT) will apply directly to geothermal logging, except that changes of state between water and steam must be considered in addition to non-condensable gases entering and leaving solution. PCT usefulness in oil and gas production wells has already been demonstrated. The sonde will be useful in exploration geothermal wells in addition to its usefulness in production wells because of the importance of temperature in all geothermal wells and because of the requirement for very large fluid flows in commercial geothermal wells.

The five sensors were chosen for modification into a tool for high temperature operations because such a tool will be useful in all geothermal wells, regardless of the characteristics of the surrounding formations, and because all the measurement functions can be performed with no downhole active electronics. The logging tools will be so widely applicable because all of the measurements will be made on the borehole and its fluid content and not directly on characteristics of the surrounding formations. Geothermal reservoirs occur in an extreme variety of formations (Austin and Leonard, 1973) and different sets of formation evaluation measurements will be needed in different types of formations just as different measurements are currently made in sandstone and limestone oil reservoirs.

Temperature in borehole 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 measurements is not sufficient. Formation temperature is probably the single most important parameter in evaluation of a geothermal reservoir.

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 flowmeter, run inside casing, to detect flow in the annulus behind the casing by the discrepancy between the two flow rates. However, their methods can 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.

The gradient of pressure with depth is a direct measure of fluid density. Dench (1973) comments that, if the temperature is also known, reference to steam tables will show what fluid type is present. If other known gases and steam are present in the well outflow, temperature, pressure, and pressure gradient measurements can be used to

determine the origin of their production. For instance, since CO_2 and H_2S are considerably heavier than steam at the same temperature and pressure, a fluid of density between those of steam and water is either a steam-water mixture, if the measurements show saturation temperature/pressure conditions, or a gas plus water vapor if the temperature is below saturation for the pressure.

A gradiomanometer may also be used to make a flow analysis when flowmeter data are not available. Curtis (1967) shows that such analysis can determine flow rates of either a gas or a liquid but is in error when two-phase production is obtained from a single horizon. When multiphase flow is present in a well, flowmeter measurements are unreliable. At least in quick-look interpretations, when gradiomanometer data show a mixed-phase flow, flowmeter measurements are disregarded. Some attempts have been made to study multiphase fluid flow and the limitations of measurements in such flows (Nicolas and Witterholt, 1972).

When a flowmeter (and a caliper necessary in flowmeter interpretation) are added, 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 the information needed for reservoir evaluation. In addition, the measurements will be directly useful in optimizing geothermal fluid production so that, for instance, flashover to steam with resulting deposition of minerals will not occur at unwanted places in the formations or in the well.

In the following sections of this report descriptions will be given of the work that has been done to date on the selection of transducers, on the design of the measurement and recording circuits, and on the design of the sonde. During the remainder of the program the sonde will be constructed, the transducers will be tested and mounted in the sonde, and the complete sonde will be tested at full pressure and temperature in an autoclave. Following the autoclave tests the sonde will be tested in a geothermal well to be chosen by ERDA.

2. GAUGES

In order to use the constant current circuit described in the next section, it is necessary that all gauges in the logging tool be of a variable resistance type. For this reason, the gauges for both the manometer and the gradiometer are strain gauge types and the thermometer is a platinum resistance thermometer.

The gauge selected for the manometer is a standard high temperature pressure gauge manufactured by Precise Sensors, Inc. of Monrovia, California. The only modification to their standard gauge is that the gauge bodies are to be made from Inconel 625. Other specifications for this gauge are as follows:

Pressure range:	0 - 10,000 psi
Temperature range:	Up to 343°C (650°F)
Bridge:	Four active arms, 350 ohms
Repeatability:	Less than 0.2% of FS
Pressure limit:	110% FS
Thermal zero shift:	Less than 0.01% FS/°F
Thermal sensitivity shift:	Less than 0.01% FS/°F
Full scale output:	2.0 MV/V nominal

The thermometer that has been selected is a modification of a platinum resistance thermometer manufactured by Celesco Industries, Inc. of Conoga Park, California for use in oil well logging. An outline drawing of this gauge is given in Figure 10. The body of this gauge is also to be made of Inconel 625. Other specifications are as follows:

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 seconds to reach 63% of a step temperature change
Insulation resistance:	Greater than 100 megohms at room temperature

The gradiomanometer is a differential pressure gauge that will measure the pressure difference between two ports separated vertically by 2 feet (61 cm). If the geothermal fluid is water this pressure difference will be about 1 psi and if the fluid is steam the differential pressure will be considerably less. The main purpose of the gradiomanometer is to determine whether the geothermal fluid is water or steam. To do this requires a differential pressure gauge capable of measuring a differential pressure of 1 psi at a line pressure as high as 7,000 psi and at temperatures up to 275°C . A differential pressure gauge to meet these specifications was not available, thus requiring the development of a new gauge. Since the main purpose of the gradiomanometer is to distinguish between water and steam, an accuracy of $\pm 10\%$ in the differential pressure measurement is deemed adequate.

The development of a differential pressure gauge was discussed with ten gauge manufacturers, five of whom submitted proposals for gauge development. From these proposals Precise Senors, Inc. was selected to develop the gauge. This decision was based on both their technical proposal and on their cost, which was the lowest of any proposal received.

It was originally planned to couple the differential pressure gauge to ports on the side of the sonde by means

of fluid coupling, the ports being covered with flexible diaphragms. A high temperature silicone fluid might be used for this purpose. The main problem in designing such a fluid couple system is the thermal expansion of the fluid at the operating temperature of the logging tool, the diaphragms having to expand to allow for the expansion of the fluid. It is difficult to design a diaphragm that will allow for the fluid expansion and also remain flexible enough to measure a differential pressure of 1 psi. After starting the development of such a fluid coupled system, Precise Sensors, Inc. proposed a system in which the gauge is coupled to the diaphragms by solid metal bars rather than by a fluid column. Such a system has the important advantage that the thermal expansion of the metal bars is much less than that of high temperature fluids. They had previously built absolute pressure gauges using a similar arrangement. After considering their proposal for a solid coupled system it was decided that the development of the fluid coupled system should be discontinued and the solid coupled system be developed instead.

The complete gradiomanometer consisting of the differential pressure gauge coupled to ports separated by 2 feet is shown in a section drawing in Figure 9. The gradiomanometer is being developed as an integral part of the sonde, so that sections of the sonde below and above the gradiomanometer can be welded directly to it. The gradiomanometer is currently being built and tested by Precise Sensors, Inc. The specifications for the gradiomanometer are as follows:

Pressure range:

Differential 2 psid
Line 10,000 psi

Temperature range: To 316°C (600°F) continuous

Sensitivity:

Minimum 2 MV/V
Design goal 3 to 4 MV/V

Accuracy:

Minimum 10% of differential pressure range
Design goal 3% of differential pressure range

3. MEASUREMENT CIRCUITRY

3.1 DESIGN CONSIDERATIONS

A requirement of the logging tool is that the measurements be made with a standard 7-conductor logging cable. Each of the three gauges (manometer, gradiomanometer and thermometer) to be initially installed in the sonde is a variable resistance type, the basic circuitry for which is a four-wire circuit for each gauge. To use four-wire circuits with a 7-conductor cable would require downhole switching. Such downhole switching can be avoided by powering the three gauges in series from a constant current DC source, using the cable sheath for the return current as shown in Figure 1. This circuit leaves two leads for measuring the signal from each of the three gauges.

It is anticipated that pickup (mainly 60 Hz) and noise on the cable will be important factors limiting the accuracy with which downhole measurements can be made. The gauges will be at the end of a 10,000 foot long cable and with no downhole electronics to condition the signals from the gauges, 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 lead-to-lead capacity.

The use of a constant current source to power the gauges automatically compensates for any change 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 lead resistances do not affect the measurement. The use of DC excitation eliminates any effects due to changes in lead-to-lead capacity.

Lock-in amplifiers are phase sensitive detectors that are very effective in eliminating noise from the measurement of signal amplitude in many situations. Such an amplifier was considered and tested for use in the logging tool. It was very effective in eliminating induced noise when tested with a system consisting of 2,000 feet of four-conductor shielding 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 changes 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 amplifiers is only about 2%, they were deemed unsuitable for this application and the DC circuit with a constant current power supply was chosen for use with the logging tool.

3.2 CONSTANT CURRENT CIRCUIT

The circuit using a constant current source with the gauges in series shown in Figure 1 is the basic circuit that will be used with the logging tool. This circuit is capable of high measurement accuracy because of the availability of constant current supplies which are very accurately regulated. The constant current supply to be used with the logging tool is Kepco Model CC100-0.2M, 0 to 200ma and 0 to 100 volts. This power supply has a specification of $\pm 0.005\%$ on current variation.

The basic constant current circuit shown in Figure 1 can be modified to allow switching of downhole calibration

Figure 1. Measurement circuit using a constant current DC power supply.

resistors. Such a modified circuit is shown in Figure 2 in which calibration resistors are switched across one arm of the bridge circuits of the pressure gauges and across the resistance element of the thermometer by using a downhole relay. When the reversing switch 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 which switch in the calibration resistors. When the reversing switch is in the other position the relay coil is simply in the voltage lead to the thermometer.

This circuit requires the use of a three-pole, single throw downhole relay capable of withstanding temperatures of at least 275°C . Such a relay is not readily available but can be made by modifying a standard magnetic reed relay. In this 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 reeds of such a relay have been tested at temperatures up to 400°C with no adverse effects. The coils on standard relays limit their operation to temperatures much lower than this. The coil will be replaced with one wound on a metal or ceramic form with aluminum oxide insulated aluminum wire. This wire is usable up to the melting point of aluminum. Although we do not plan to use the circuit of Figure 2 in the initial version of the logging tool, a complete high temperature relay will be assembled and tested at high temperature for possible future use for downhole calibration or with the addition of a flowmeter and caliper.

In the constant current circuit of Figure 1 the excitation current is necessarily the same in all three gauges. However, the current (20 to 30 milliamps) required for the pressure gauges is considerably more than required for the platinum resistance thermometer. The maximum

Figure 2 Measurement circuit with downhole calibration.

current that can be used with the thermometer without degrading its accuracy is not yet known but will be determined after the thermometers are received from the supplier. It is expected that the current will be in the range of 5 to 10 milliamps. To reduce the current in the thermometer to this value, it is planned to install two thermometers in the sonde and connect them in parallel. If further reduction in the current is required, an additional resistor will be connected in parallel with the thermometers. For this purpose, resistors wound with wire having a very low temperature coefficient of resistance are being obtained.

In summary, the use of a constant current supply to power variable resistance gauges eliminates effects caused by changes in lead resistance and lead-to-lead capacity, resulting from changes in temperature and pressure. High measurement accuracy is also possible because of the availability of precisely controlled constant current power supplies.

3.3 SIGNAL MEASUREMENT AND RECORDING

As noted earlier, pickup and noise on the logging cable are expected to interfere with the measurement of signals from the gauges. Digital voltmeters that are currently available are very effective in rejecting pickup and noise when measuring DC voltages. For example, the Hewlett-Packard Model 3455A Digital Voltmeter has a common-mode rejection ratio >160 db at 60 Hz and a normal-mode rejection ratio >60 db at 60 Hz. Tests were conducted with a simulated circuit consisting of two thousand feet of four-conductor shielded cable terminated with a wheatstone bridge. The circuit was powered with a 20 milliamp constant current supply (Kepco Model CC15-1.5M) and the unbalance of the bridge was measured with a digital volt-

meter (Fluke Model 8300A with a resolution of 1 microvolt and an accuracy of 0.005% on the 100 millivolt range). When 400 millivolts of high frequency, wide band noise were impressed on a bridge signal of about 14 millivolts, there was no measurable change in the output signal from the bridge as measured with the digital voltmeter. Digital voltmeters are thus capable of both high noise rejection and high measurement accuracy. For these reasons, a digital voltmeter will be used for measuring the signals from the gauges in the logging tool. A complete data gathering system that would be suitable for use with the logging tool is the Hewlett-Packard Data Logger Model 3051-A, consisting of a Model 3455A Digital Voltmeter, a Model 31495A Scanner and a Model 9815A Programmable Calculator. A system similar to this is currently used in the LASL logging rig and would be available if the logging tool were tested in the LASL geothermal well. (Recent information from LASL indicates that this will be the case.)

4. 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, operating pressure of 7000 psi, hole diameter of 3.5 inches and downhole fluid containing salts and acid gas. These operating conditions limit the use of elastomers for effecting seals. The commercially available elastomers with high temperature ratings can operate only for short periods of time at 275°C. Also seals made of elastomers require zero-clearance fitup to withstand 7000-psi pressure differentials without extrusion.

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

4.2 MATERIAL SELECTION

The requirement for corrosion resistance in the presence of chlorine 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 which were unaffected by exposure to various combinations of chlorides and acids at temperatures to 500°F and pressures to 20,000 psi. Thirty-five highly alloyed metals were investigated in their study. The five unaffected materials are:

Hastelloy Alloy* C-276

Inconel Alloy** 625

* Trademark Cabot Corp.

** Trademark Huntington Alloys, Inc.

MP 35N[†]
MP 159[†]
Titanium

After considering availability of sizes and such properties as machinability, weldability, strength and ductility, in addition to resistance to corrosion and stress cracking, we chose annealed Inconel alloy No. 625 for the structural container for the downhole instruments. The pressure and temperature requirements on the sonde so seriously restrict the utility of elastomeric gaskets that their use has been eliminated in the sonde design.

Glass-to-metal (or ceramic/metal) seals are planned for the electric connector at the cable terminator. The joints of the sonde metal shell are to be welded, using an electron beam technique. The terminator will be bolted or screwed to the sonde and the pressure seal made with a gold plated Inconel X750 O-rings.

4.3 CABLE HEAD (TERMINATOR)

The electrical connector between the cable terminator and the sonde is to be compatible with Los Alamos Scientific Laboratories cable systems. Should the LASL cable head be judged unsatisfactory at temperatures above 250°C for reasons yet unknown, S³ has developed, in part, a head which should work at the higher temperatures. However, further development is required to optimize sonde/head parting load and water blocking, as well as between-test water drainage if this proves to be important.

[†] Trademark Standard Pressed Steel Co.

4.3.1 DESIGN OF S³ 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 3. 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 will be made of spring temper material, probably Inconel X718. The shells will be Inconel 625 with individual holes for each pin. The glass which seals the pins in place and insulate them from the shell is a proprietary mixture* which will provide an electrical resistance of 50 megohms at 300°C and withstand

* Hemetic Seal Corporation, Rosemead, California.

500 V. The shells will be electron beam welded to Inconel 625 end plates as indicated in Figures 3 and 4.

4.3.2 TESTS OF CABLE HEAD

Three types of tests have been conducted on different parts of the cable head. One type consists 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 3. 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 ERDA/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).

Figure 3 . S³ cable head.

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Figure 4. High temperature sonde with no down-hole electronics.

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 ERDA/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 our discussions with C. Hickam of Sandia Labs and Bert Dennis of LASL, we have 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 will be used in the connector cavity to insulate the cable conductors and feedthrough pins from each other and from ground. This volume will be 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 5. The minimum dimension across the surface of the glass was 0.045 inch. Figure 6 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

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

Figure 5. Glass/metal seal potted in high temperature epoxy for insulation resistance measurements.

Figure 6. Resistance dependence on temperature of Duralco 700 ultra-high temperature epoxy.

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.

Metal O-rings Tests

Two metal O-rings are planned 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 7. 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

Figure 7. Metal O-ring test fixture.

water flashes 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 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 size and to sealing surface finish. During those times when the tool is not connected to the cable head, maintenance of these critical surfaces is accomplished by proper protective covers.

4.4 DESIGN AND CONSTRUCTION

The design of the sonde is complete except for questions which remain with reference to the cable head interface. Design considerations indicate the need to avoid elastomeric gaskets and the use of metal-to-metal gaskets only in those applications where strong bolting forces clamp face seals. Cylindrical or radial type seals are to be avoided because clearance tolerances required for metal gaskets are not practical to attain. Small diameter metal gaskets have been successfully used to seal screw-in type transducers to chamber walls and plates.

4.4.1 STRUCTURAL DESIGN

The contractual design requirements are for the sonde to operate in a fluid at 275°C and 7000 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 (given in Figure 8) for boiler and pressure vessel construction with this material. The sonde will never be subjected to pressure when people are nearby and therefore it need not be built with the safety factors required for pressure vessels. The thinnest wall will be in the gradiomanometer section of the sonde, shown in the section drawing of the sonde in Figure 4 and in larger detail in Figure 9. Pressure induced stresses in the case wall of the gradiomanometer are determined by the method of Roark and Young (1975). Circumferential stress σ_2 and longitudinal stress σ_1 are given by

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

Figure 8. Maximum allowable design stresses for boiler and pressure vessel construction for Inconel alloy 625 annealed grade 1 ASTM B443, B444, B446, welded construction.

Figure 9. Sectional view of the Gradiomanometer.

where q is the external pressure in psi, and a and b are the outside and inside radii of the pressure case. For $q = 7000$ psi, $a = 1.5$ in. and $b = 1.0$ in.

$$\sigma_1 = -12,600 \text{ psi and}$$

$$\sigma_{2,\text{max}} = -25,200 \text{ psi.}$$

The certification data for the case material specifies the tensile strength of the material obtained for the sonde shell to be 124,500 psi. This results in a safety factor of 4.9 for 20°C (70°F) operation. If we reduce this safety factor by 5% as suggested by Figure 8, at 275°C the safety factor is 4.7. From the shell stress standpoint, therefore, the sonde should be capable of operating in fluid pressure up to 20,000 psi at temperatures up to 275°C.

4.4.2 SONDE ASSEMBLY

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 downhole test. The tolerance required for metal seals limit their use to strongly bolted face sealing arrangements. The loss of the option for field repair is clearly offset by the reliability of an all welded system.

The sonde shell design provides for electron beam welding of all joints. The joint design further provides for ease of parting by a simple lathe operation and reassembly by rewelding. The rewelding operation should preferably also be by the electron beam technique; however, the more common tungsten electrode inert gas welding technique could be used if care were exercised to prevent overheating certain critical areas. Figure 4 shows where welded pressure seals

are made in the sonde assembly. The electrical feedthrough at the head of the sonde may also be welded to the sonde using the electron beam process.

4.4.3 K-SEALS FOR GAUGES

The manometer pressure gauge is designed to use a metal gasket between its sealing shoulder and its mounting plate. The gasket to be used is a Harrison K-type seal No. 24107-875.

The thermometer is actually two platinum resistance thermometers, each of which is built into a special housing as shown in Figure 10. These thermometers are screwed into the same mounting plate as the manometer pressure gauge. The seals (Harrison K-type No. 24107-625) are of smaller diameter than required for the pressure transducer. The transducer plate is welded to the sonde and a ventilated lead point is screwed to the transducer plate as shown in Figure 4.

4.4.4 ELECTRICAL

Seven insulated conductors and a ground (or eight insulated conductors) are required to operate the three measuring sensors and record the signals. For use with the LASL cable head, the sonde will be fitted with a 22-conductor pressure feedthrough which is specified to match the LASL head. Should the sonde be used with the LASL 7-conductor cable, an adaptor "sub" is available at LASL to permit use of either cable head.

Within the sonde the hookup wire will be No. 26 Inconel X750 wire insulated with No. 24 woven fiberglass sleeving. The Inconel wire will be welded at each end to its terminator. Stress relief will be accomplished by filling the void space with a high temperature, low density casting material to be

Figure 10. Thermometer envelope.

selected from a variety available from several suppliers. Figure 4 shows the general arrangement of hookup wiring and feedthrough installation.

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