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Closed-Loop Flow Test Miravalles Geothermal Field Well-Log Results

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CLOSED-LOOP FLOW TEST
MIRAVALLES GEOTHERMAL FIELD

WELL-LOG RESULTS

by

Bert Dennis, Guy Eden, and Robert Lawton

ABSTRACT

The Instituto Costarricense de Electricidad (ICE) conducted a closed-loop flow test in the Miravalles Geothermal Field. The closed-loop test was started in May and ran through August of 1990. The effluent from the production well PGM-11 was carried by a pipeline through a monitor station to the injection well PGM-2. Before starting the long-term flow test in May, cold-water injection experiments were performed in each well to determine the pressure and temperature response. A series of downhole measurements were made in each well to obtain background information. The downhole measurements were repeated in August just before terminating the flow test to evaluate the results.

I. INTRODUCTION

The Republic of Costa Rica is pursuing the development of a geothermal power plant located on the southern flank of the Miravalles Volcano in the Guanacaste Volcanic Range. The Instituto Costarricense de Electricidad (ICE) drilled eight production wells in the Miravalles Geothermal field that have penetrated a high-temperature geothermal brine reservoir at a depth of less than 2 km. The first three wells, PGM-1, PGM-2, and PGM-3, were drilled in 1979. From 1984 to 1986, six additional production wells were drilled and completed (Fig. 1). Fluid temperatures exceeded 240°C, and flow rates ranged from 40 to 100 kg/s. Initial flow testing of these wells revealed that calcite scaling could be a potential problem in the wellbores.

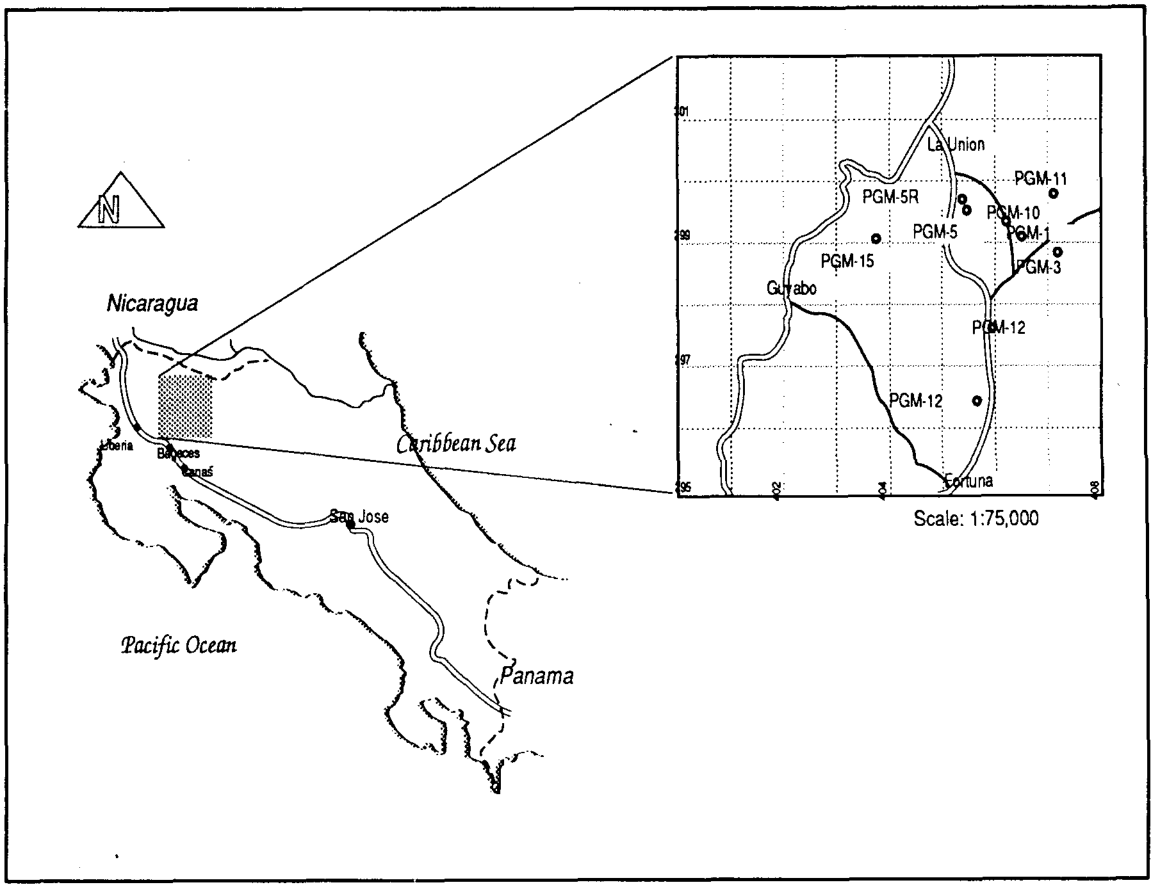

Fig. 1. Well locations in Miravalles geothermal field.

The Los Alamos National Laboratory had been involved in the development of specialized high-temperature well-logging instruments for the past 12 years (Dennis, et al., 1985). The downhole systems were designed to operate at temperatures up to 300°C and fluid pressures up to 103 MPa (15,000 psi). The measurement capability included the downhole well-logging tools, high-temperature armored cable, data-acquisition system and necessary equipment to perform the well logging operations in geothermal wells. A description of the high-temperature well-logging tools is given in the Appendix.

At the request of ICE, the Los Alamos National Laboratory conducted a series of downhole measurements in several selected wells in 1985 and again in 1986 (Dennis et al., 1989). The U.S. Agency for International Development (USAID) provided for the purchase and fabrication of a complete high-temperature logging system that would remain in Central America for the cooperative use by the countries developing geothermal energy. A special well-logging crew from several Central American countries were trained at Los Alamos to perform the well-logging operations under the guidance of the team from Los Alamos. Two members of this international team were from El Salvador, two from Costa Rica, one from Guatemala and one from Honduras.

During the summer of 1990, ICE planned a closed-loop flow test using well PGM-11 as the production well and well PGM-2 as the injection well. Prior to starting the 3-month closed-loop test, injection tests were performed in each well to determine the pressure and temperature response during and after cold-water injection. A series of downhole surveys, using the well-logging equipment provided by Los Alamos, was scheduled to provide background information and to monitor reservoir response. Another series of downhole logs would be performed in the flowing wells just before terminating the closed-loop test.

II. PREFLOW INJECTION TESTS AT PGM-11/PGM-2

Before starting the closed-loop flow test between PGM-11 and PGM-2, ICE had planned a cold-water injection test in each well. Well-completion information for both wells is given in Table I. Casing and liner sizes are listed for outside diameters.

First a three-arm caliper log was attempted in PGM-11, but the caliper tool would not enter the liner below 972 m because of chemical build-up (calcite) at the top of the liner and in the casing above the liner (Fig. 2). Caliper logs run previously in 1986 (Dennis et al., 1989) showed serious chemical build-up in this region of the well.

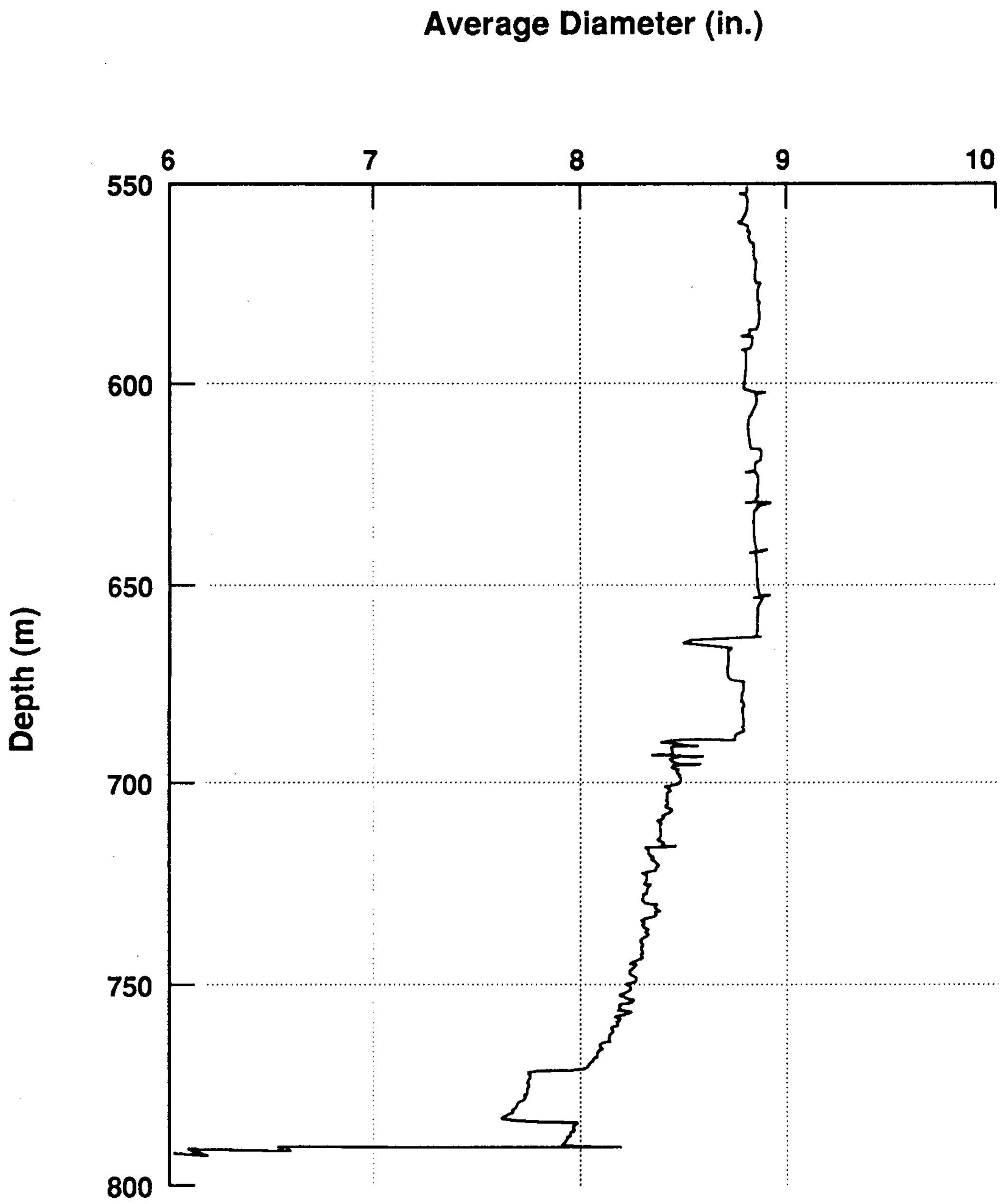

Fig. 2. Caliper survey in Miravalles well PGM-11.

Fluid velocity, temperature, and pressure were prime measurements requested by ICE during the injection tests. The sequence of measurements using the spinner/temperature/pressure (STP) tool were:

- First run a background log with the well shut in (static) from the surface to 1280 m.
- Then station the STP tool at 1000 m and inject cold water into the well for approximately 4 hours.
- Use the STP tool to log from 650 m to 1280 while continuing to inject cold water.
- Finally, return the tool to 1000 m, shut in the well, and continue to record recovery data for another 6 hours.

TABLE I

WELL-COMPLETION INFORMATION

Well Number	PGM-2	PGM-11
Casing size (mm)	244.5	244.5 (9 5/8 in)
Liner size (mm)	193.7	193.7 (7 5/8 in)
Bottom of casing (m)	759.6	787.0
Top of liner (m)	731.9	785.0
Bottom of liner (m)	1905.5	1304.0

The data recorded during the initial static log and the log after 4 hours of cold-water injection are shown in Fig. 3. The static borehole fluid level was found at about 400 m. Some boiling (two-phase) turbulence was recorded around the 400-m depth. The maximum temperature of 260°C appeared at 980 m dropping to 245°C at 1280 m. This data suggests a circulation zone with borehole fluid moving down the well. The spinner output during the static log shows significant fluid entering the well at 980 m.

The temperature data recorded during the interim log run following the 4 hours of injection (Fig. 3) describe a porous zone allowing the injected fluid to leave

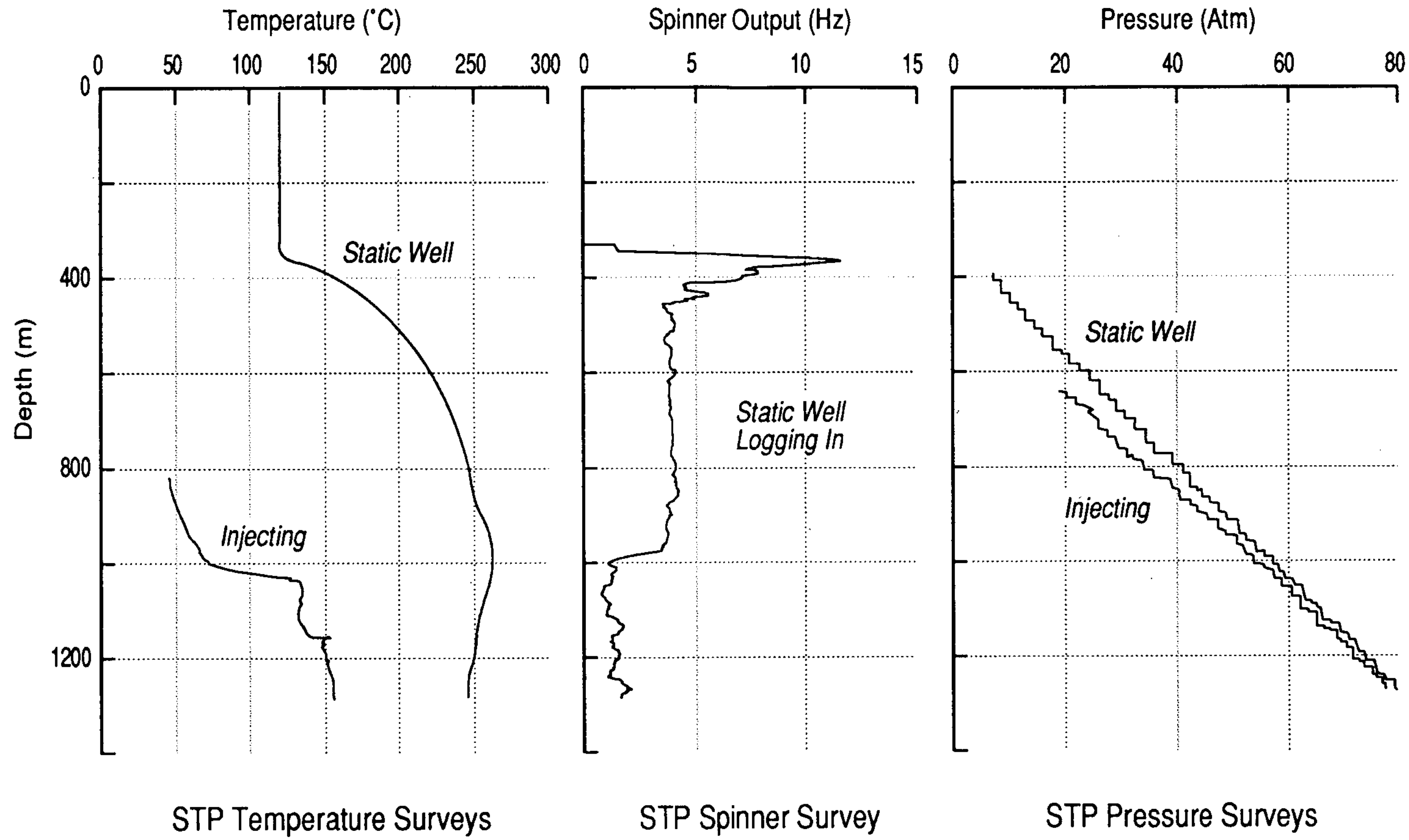

Fig. 3. STP static log and injection log for Miravalles well PGM-11.

the wellbore with little resistance. The pressure data recorded during this log confirms that the injected water has a higher density than the borehole fluid.

Data recorded during the cold-water injection and the recovery with the well shut in while the STP tool was parked at 1000 m is shown in Fig. 4. The gap in this data occurred while the tool was being used to run the interim log from 650 m to 1280 m. The pressure data show a significant decrease in fluid pressure, indicating the porous formation taking fluid. The original fluid level in the static well moved down the borehole until pressure equilibrium was established.

A similar cold-water injection test was conducted in PGM-2. This well was reported to have a high concentration of acids not found in the surrounding wells. The pH was determined to be in the range of 2.5 to 3. An abundance of brown scale was found in the STP tool external openings (spinner and temperature probe cages) when the tool was retrieved from this well. The initial STP log was run from the surface to 1470 m with the well shut in. The tool was then parked at 1000 m during the cold water injection that lasted for about 3 hours. The interim log was run from 540 m to 1470 m while continuing to inject cold water. The tool was again parked at 1000 m to monitor the recovery for another 3 hours.

Data recorded during the static (well shut in) and the interim log in PGM-2 are shown in Fig. 5. Static fluid level was detected at 400 m. The static spinner data show no evidence of significant reservoir fluid entering the wellbore nor does there appear to be a circulation zone in this well. Data obtained during the interim log again confirm that the density of the injected water was approximately 25% greater than that of the borehole fluid. These data also show that the injected water was leaving the well at 750 m. The temperature and pressure data recorded while the STP tool was stationed at 1000 m during injection and recovery are shown in Fig. 6. The significant decrease in pressure describes a condition similar to that observed in PGM-11, indicating a porous formation that allows the injected water to leave the well with little resistance.

Before starting the cold-water injection tests, downhole fluid samples were obtained from each well at depths specified by ICE. Two fluid samples of 4 liters each were obtained from PGM-11, one at 1012 m and one at 1250 m. Two 4-liter samples were also taken from PGM-2, one at 1450 m and one at 800 m. The chemical

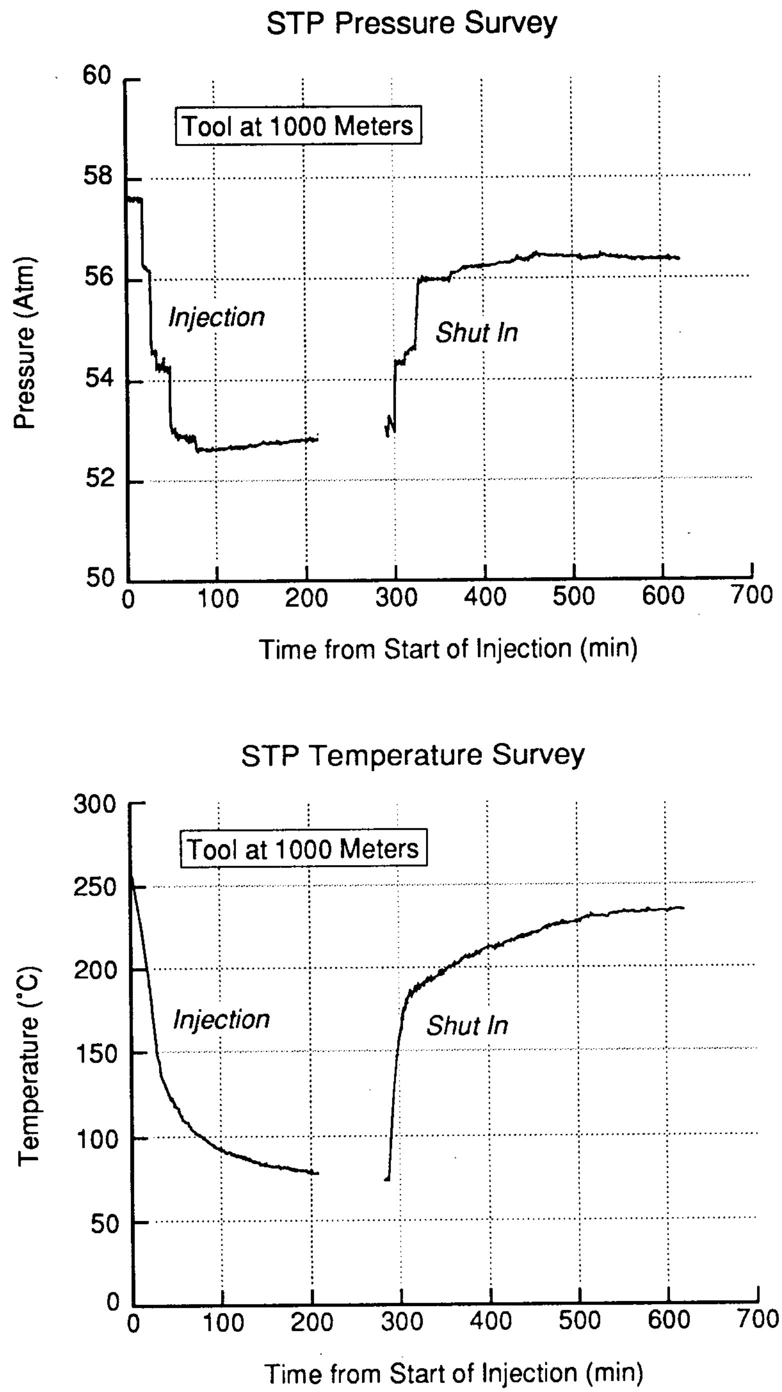

Fig. 4. Temperature/pressure data recorded during injection and shut in at the Miravalles well PGM-11 (1000 m depth).

analysis of the samples would be done by ICE personnel using equipment and procedures previously provided by Los Alamos (Grigsby et al., 1989).

III. CLOSED-LOOP FLOW TEST

Soon after the completion of the cold-water injection tests, ICE began a 2-month closed-loop flow test. Using PGM-11 as the production well, its effluent was carried by a pipeline through a monitor station to the injection well PGM-2. Then in August 1990, several downhole measurements were made in both wells using the STP tool with the system still under flowing conditions.

The spinner survey (Fig. 7) describes a throttling effect of the fluid between 750 and 900 m. The calcite build-up in this area is the most likely cause of this disturbance. The spinner data taken while logging in and out of the liquid region in the well are used to calibrate the spinner and establish a proportionality constant to compute fluid velocity (Dennis and VanEeckhout, 1990).

Pressure surveys compared flowing pressures and the earlier static log. The liquid/vapor interface moved down the well to about 810 m in the flowing well. The fluid pressure above 810 m was lower than the calculated saturation pressure, showing that the fluid was not in thermodynamic equilibrium. The vapor was in the superheated region. Using the thermodynamic properties of the fluid, the mass flow rate being extracted from PGM-11 was calculated to be approximately 60 kg/s (Dennis et al., 1987).

Figure 8 shows the temperature and pressure distributions in PGM-2 measured during the injection of the effluent from PGM-11 and compared to the logs that were run previously with the well shut in. The temperature of the effluent from PGM-11 has cooled to around 150°C as it passes through the pipeline.
Spinner data show an anomaly at 750 m. The impeller spinning in one direction with the injected fluid going down the wellbore suddenly reverses direction when the tool encounters the liquid below the fluid exit zone.

A 4-liter fluid sample is taken in PGM-2 at 1270 m while injecting the effluent from PGM-11.

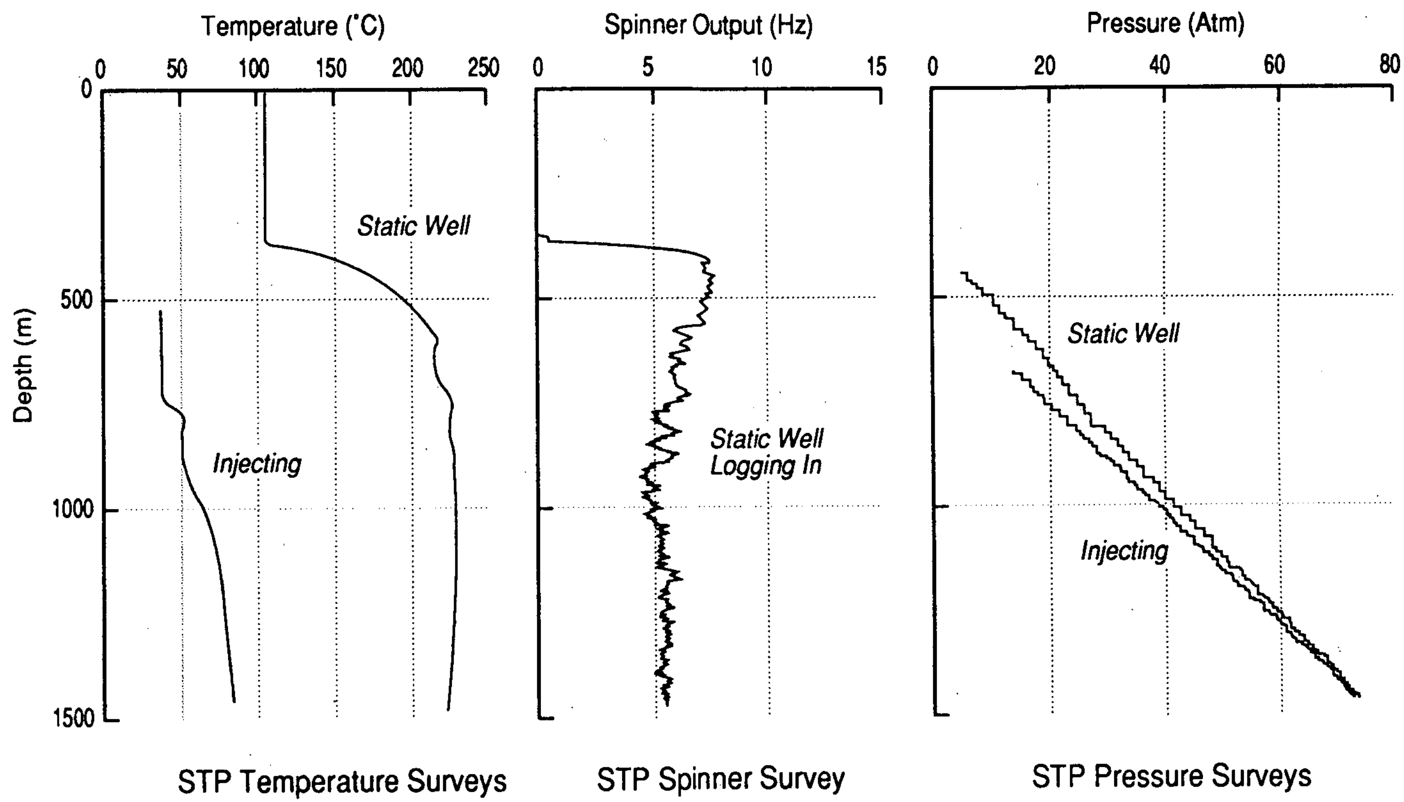

Fig. 5. STP static and injection log for Miravalles well PGM-2.

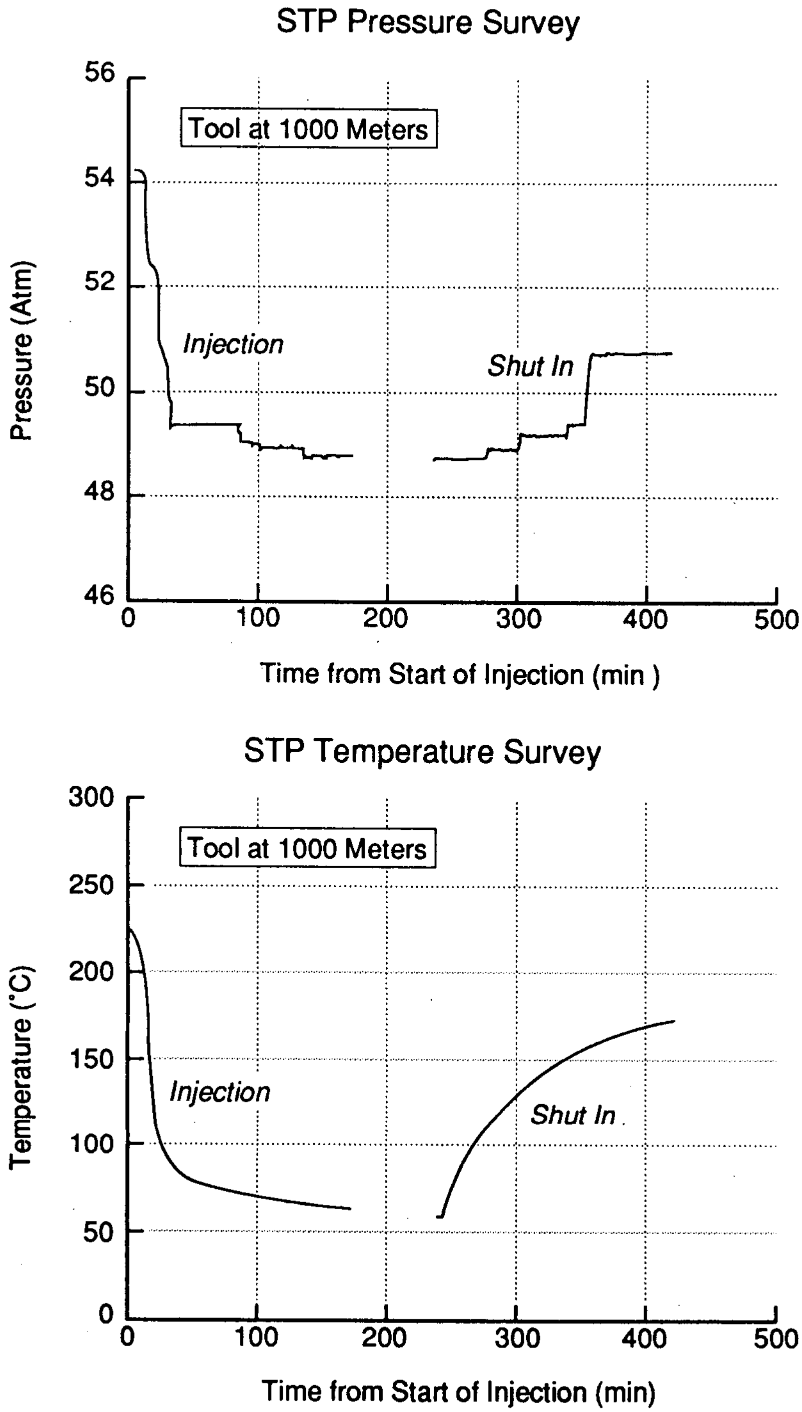

Fig. 6. Temperature pressure data recorded during injection and shut in at the Miravalles well PGM-2 (1000 m depth).

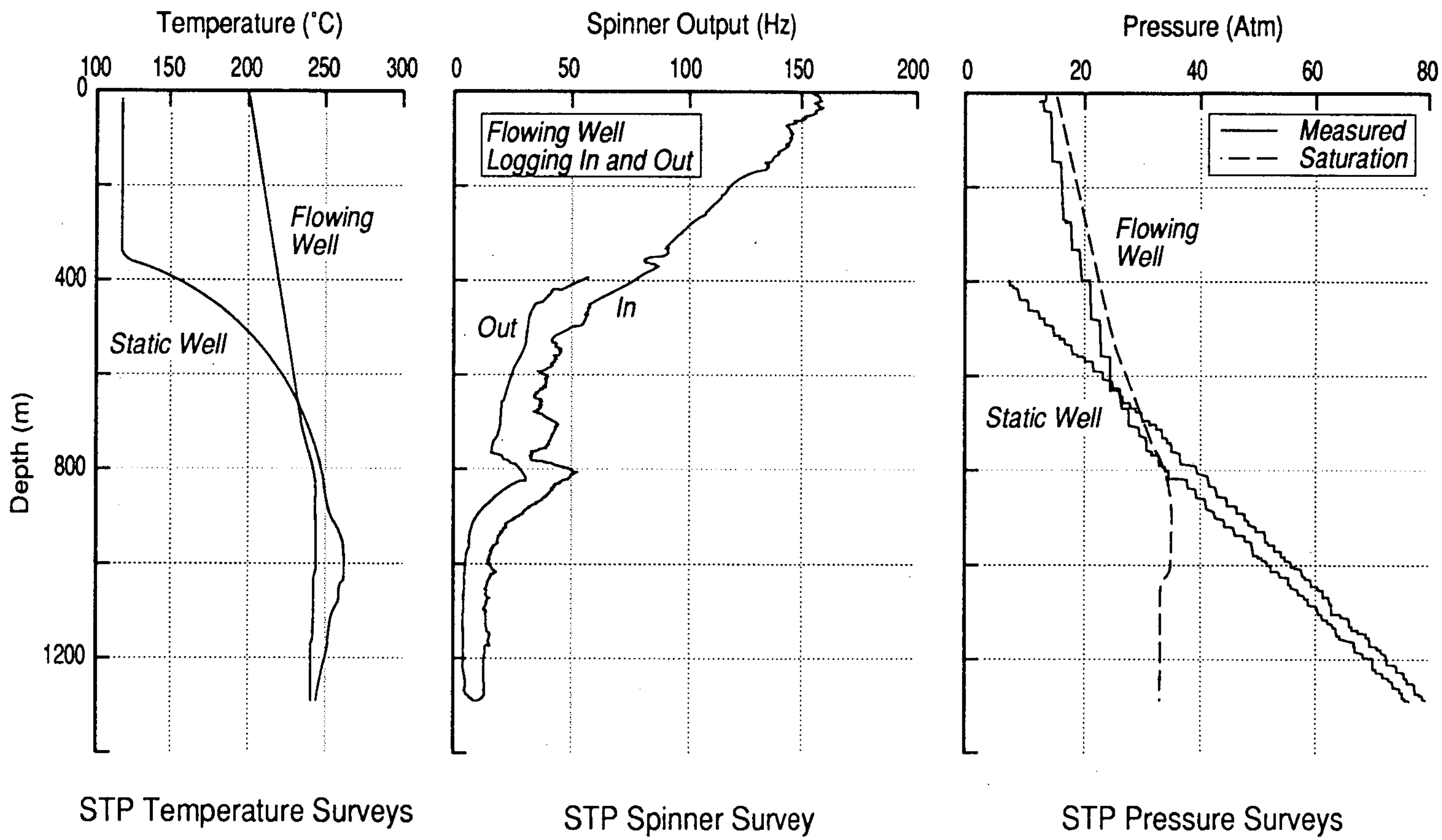

Fig. 7. STP data obtained in Miravalles well PGM-11.

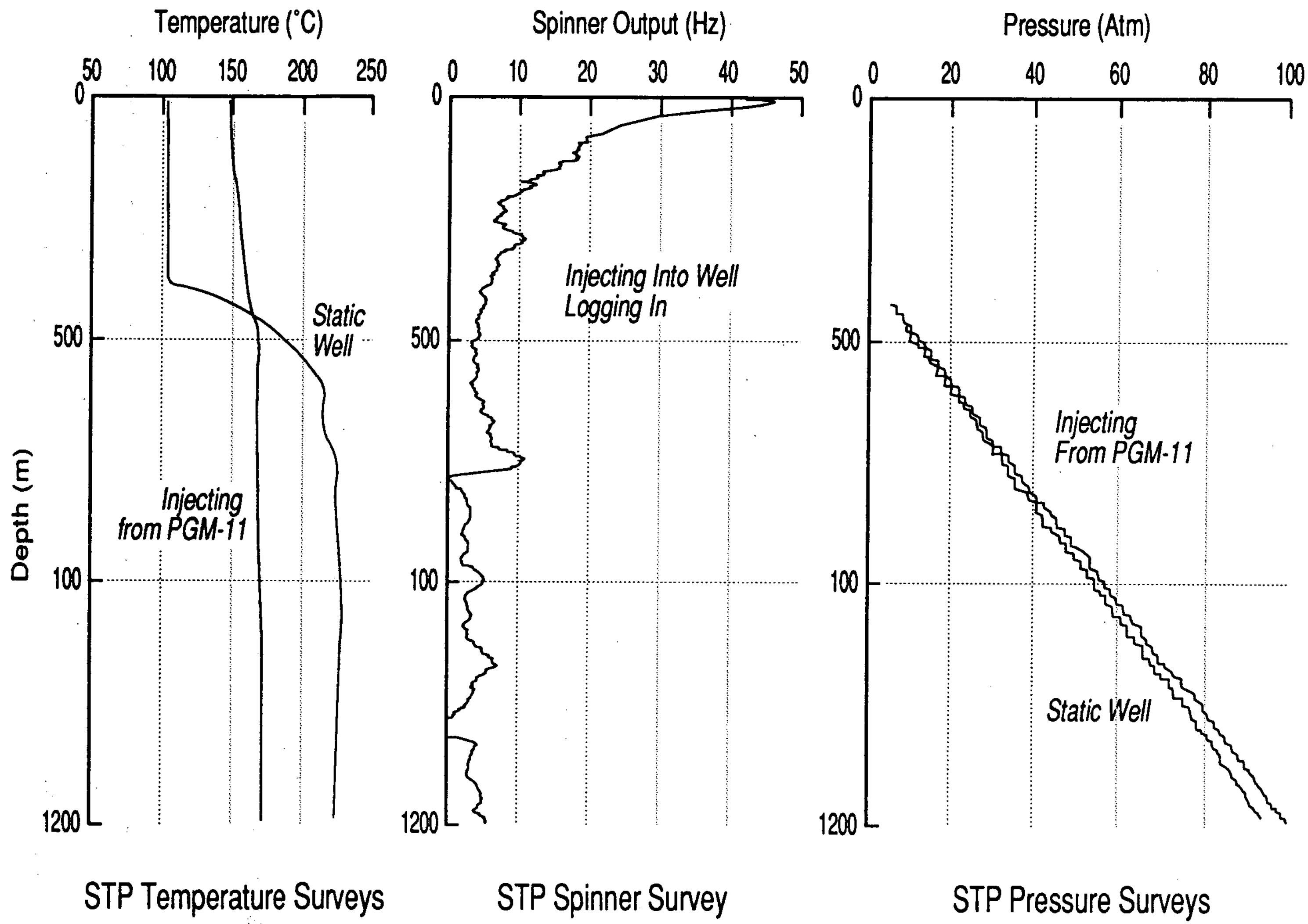

Fig. 8. STP data obtained in Miravalles well PGM-2.

IV. OTHER WELLS OF INTEREST

After conducting the logging operations in PGM-11 and PGM-2 during the closed-loop flow test, ICE requested downhole measurements in three other wells in the Miravalles field. PGM-12 and PGM-3 were considered production wells, but both required a gas lift to start the wells flowing. No attempt was made at this time to lift the wells. Downhole fluid samples were taken (4 liters each) from PGM-12 at 400 m and PGM-3 at 570 m.

PGM-5R was a shallow well drilled to only 240 m producing a relatively high vapor mass flow rate that prevented further drilling. The well contained only vapor, so no fluid sample was attempted.

Well-completion information for these three wells is given in Table II.

TABLE II
WELL-COMPLETION INFORMATION

Well Number	PGM-3	PGM-5R	PGM-11
Casing size (mm)	244.5	244.5	340.0
Liner size (mm)	193.7	NA	244.5
Bottom of casing (m)	643.0	240.0	530.0
Top of liner (m)	587.0	NA	530.0
Bottom of liner (m)	696.0	NA	1590.0

A caliper log was run in the liner of PGM-12 from 1160 m to 560 m (Fig. 9). The results show considerable calcite build-up, especially at the top of the liner. The large casing (340-mm) inside diameter was greater than the caliper arm extension, so no data were taken from 530 m to the surface. The STP tool was run from the surface to 1160 m. Temperature and pressure distributions and spinner output are shown in Fig. 10. The static fluid level in this well was found at 200 m. The spinner output indicates a circulation zone with fluid entering the wellbore at approximately 680 m and then moving downhole. This is also shown in the temperature data.

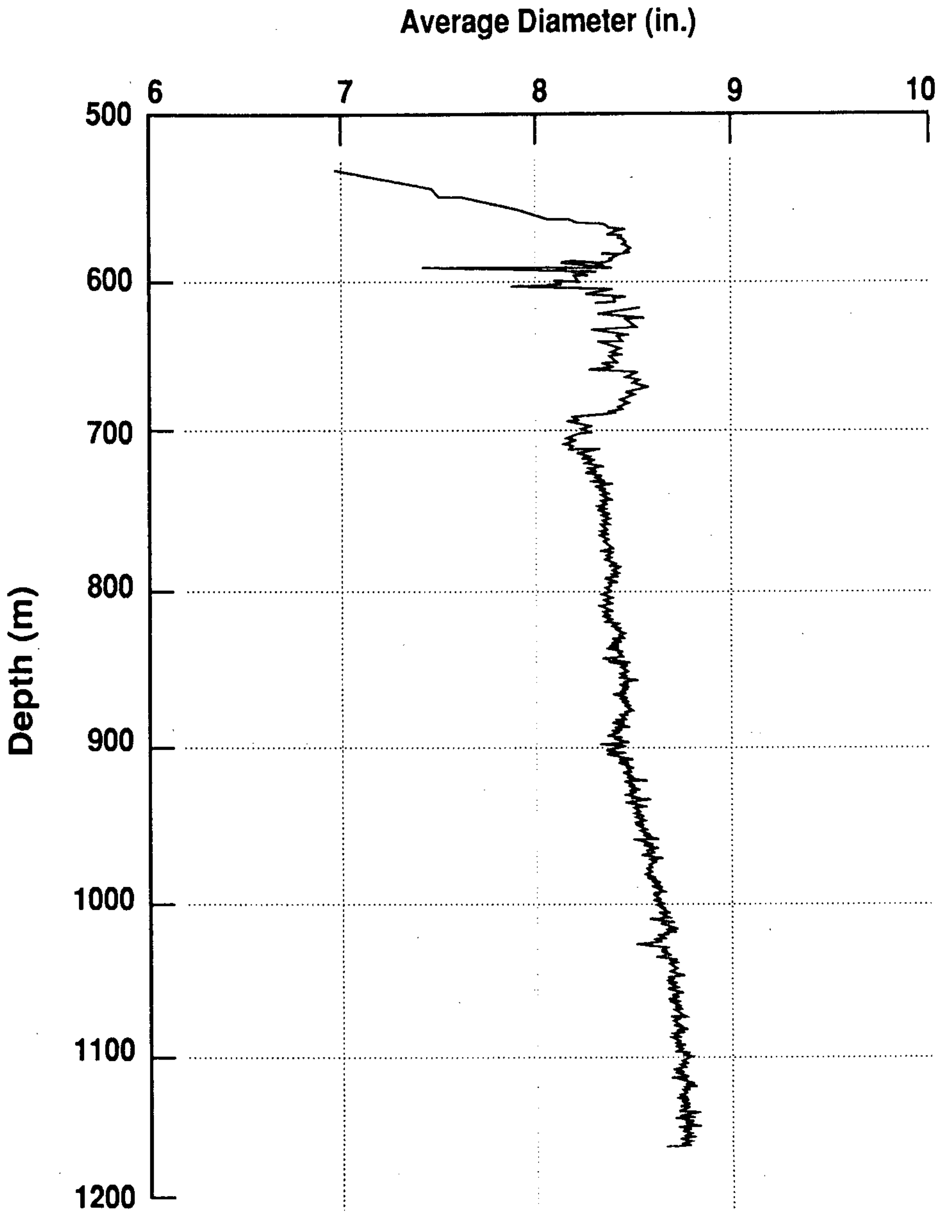

Fig. 9. Caliper survey in Miravalles well PGM-2.

The STP tool was run in PGM-3 under static conditions. Measured temperatures, pressures, and spinner output are shown in Fig. 11. The liquid level in PGM-3 was detected at 250 m, and the spinner output was essentially constant, showing no clear evidence of fluid entering the wellbore above 540 m.

An STP log was also run in PGM-5R from the surface to 240 m. The well contained only vapor with a constant temperature of 208°C and constant wellbore pressure of 18 atmospheres from the surface to the bottom of the well.

V. DISCUSSION

The cold-water injection tests performed in May 1990 provided evidence that the formation below the casing in PGM-11 and PGM-2 was quite porous. A significant amount of the injected water left the PGM-11 wellbore at 980 m, the same zone where reservoir fluids entered the well. A similar zone was found at 750 m in PGM-2. When the wells were shut in following the injection of cold water, recovery to original temperatures and pressures was quite rapid, confirming very little resistance to flow in the formation.

Simultaneous measurements of temperature and pressure in the flowing production wells can be used to determine the thermodynamic state of the fluid. The additional fluid-velocity measurements allow calculation of mass flow rates. The mass flow rate from PGM-11, during the closed-loop flow test, was found to be 60 kg/s. Another important result from the data shows that there was essentially no thermal drawdown during the 2-month flow test.

One significant problem that is prevalent in all the wells in the Miravalles geothermal field is the continuous build-up of calcite. The calcite accumulation is especially noticeable at the top of the liners. There was, however, no observed chemical build-up in PGM-2.

ACKNOWLEDGEMENTS

We again thank the well-logging team from Central America for their participation in these field operations: Noé Dubón, from Guatemala; Orlando Recarte, from Honduras; Miguel Monterrosa and Manuel Monterrosa from El Salvador; Victor Varela and Carlos Arley from Costa Rica. We would especially like to thank Ed Van Eeckhout for his exceptional support and encouragement for the well-logging operations.

APPENDIX

DESCRIPTION OF LOGGING TOOLS

The Los Alamos National Laboratory furnished a new logging truck for the Central American geothermal energy program, complete with auxiliary generators, a data-acquisition system, hydraulic-powered draw works, and associated controls (Fig. A-1). The draw works are equipped with 3,000 m (10,000 ft) of armored cable that contains seven electrical conductors with FTE Teflon insulation. The cable armor package is improved galvanized plow steel, and the cable is rated for continuous service at temperatures up to 320°C.

Los Alamos also equipped the logging truck with the wellhead apparatus required to “rig up” for deployment of the downhole instrument. (The downhole instrument is commonly referred to as the logging tool.) This apparatus includes the upper and lower sheaves, pressure lock with cooling jacket, Bowan control head (pack off), and cable cooling system. All downhole instrument systems were designed, fabricated, and tested at the Los Alamos National Laboratory. The set of logging tools consists of cable heads, a temperature probe with a casing collar locator (CCL) and ring gauge, a downhole fluid sampler, a three-arm caliper, and a fluid velocity STP tool.

The cable head (Fig. A-2) is designed specifically for long-term operation in a geothermal environment where fluid temperatures exceed 300°C. The cable head permits termination of the seven-conductor armored cable; it completes the transition of the logging tool while ensuring watertight integrity in the high-temperature and high-pressure geothermal fluids. The cable head can be disconnected from the armored cable, should the tool become stuck in the wellbore.

Fig. A-1. The well-logging truck.

CABLE HEAD

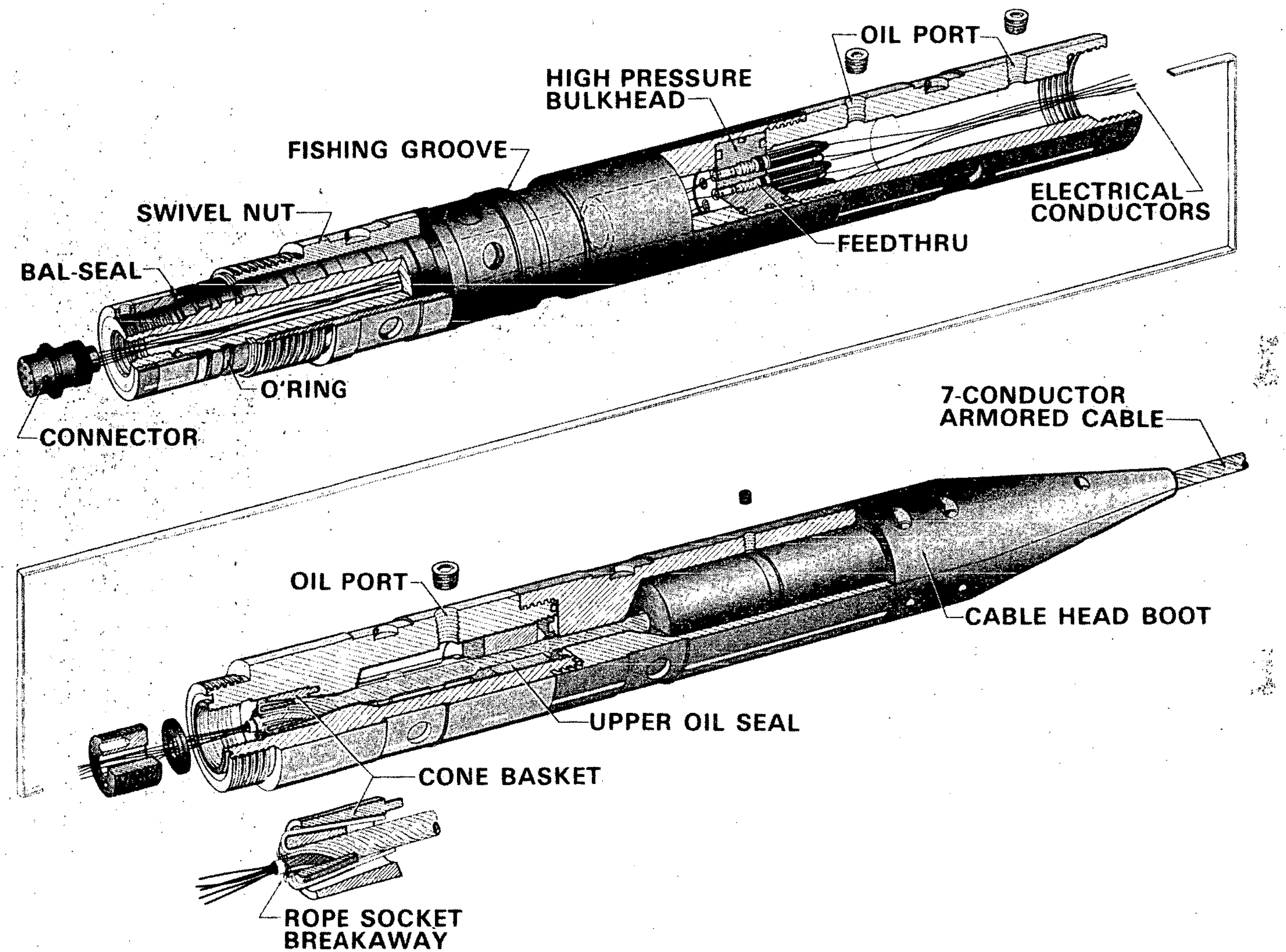

Fig. A-2. The cable-head assembly.

Borehole temperature surveys are used to determine thermal gradients along the borehole under both static and flowing conditions. Temperature anomalies in regions where fluid flows into or out of the borehole are easily detected, so that fracture intersections or perhaps damaged casing can be located. The temperature tool includes the CCL to detect casing signatures for correcting tool depth, which can be exaggerated by cable stretch. The ring gauge or "rabbit" is attached to the pressure housing to gauge the borehole diameter (Fig. A-3). The temperature probe with the CCL and rabbit is run first in every borehole before the borehole is logged with the more expensive, complex instrument packages.

The high-temperature borehole fluid sampler is operated by opening and closing a flow control valve on the 4-liter sample bottle. Once the fluid sampler is stationed at the desired depth in the wellbore, a downhole high-temperature motor is actuated to open and close the flow valves (Fig. A-4). The motor is energized upon command from the power supply in the logging truck. Before the fluid sampler is run into the borehole, a vacuum pump is used to evacuate the 4-liter sample bottle. When the tool is retrieved at the surface, the sample bottle is taken to a nearby facility where the gas and liquid fluids are preserved and prepared for further analysis.

Wellbore conditions, such as open-hole or casing diameters, contour, wear, scale accumulations, breakouts, etc., can be measured using the three-arm caliper tool. The three arms, which are spaced 120° apart on the circumference, operate independently. Normally the caliper tool is deployed in the wellbore, with the arms retracted, to the lowest depth of interest. The arms are then extended by applying current to the downhole dc motor and associated drive. When fully extended, the arms provide a moderate spring-activated force against the borehole or casing wall. The tool is then pulled up the wellbore, and the motion of each arm, as it follows the contour, is transformed to a rotational motion sensed by a cosine-type potentiometer as a function of the radius from the center line of the centralized tool to the tip of the arm (Fig. A-5). Caliper calibration is verified before each log.

To determine the thermodynamic state of a flowing wellbore, simultaneous measurements of temperature, pressure, and fluid velocity are necessary. A high-temperature (300°C) well-logging tool was developed specifically to measure these parameters in the production wells in Central America. This tool is referred to as the

STP tool (Fig. A-6). The fluid velocity transducer (spinner) incorporates a rotating impeller with hardened-steel pivot bearings. The rotation shaft operates a reed switch that transforms the rotational speed of the impeller to pulses recorded as frequency in hertz. The rotational speed in hertz is proportional to the velocity of the fluid relative to the logging tool. A proportionality constant is determined by logging in the liquid-filled region of the borehole.

The temperature sensor is a thermistor that has been calibrated to an accuracy of 0.10° up to 300°C. This temperature sensor is the same type as that used in t he temperature tool described above. The thermistor provides very fast response and exceptional resolution. The pressure transducer provides accurate pressure measurement in the geothermal fluids when meticulous calibration procedures are used. Pressure measurements are made in the STP tool using a 0 to 34.5 MPa (5000 psi) potentiometer-gauge pressure transducer. The constant current excitation is sensed at the pressure gauge so that the power supply at the surface can compensate for line losses over the 300-m armored cable.

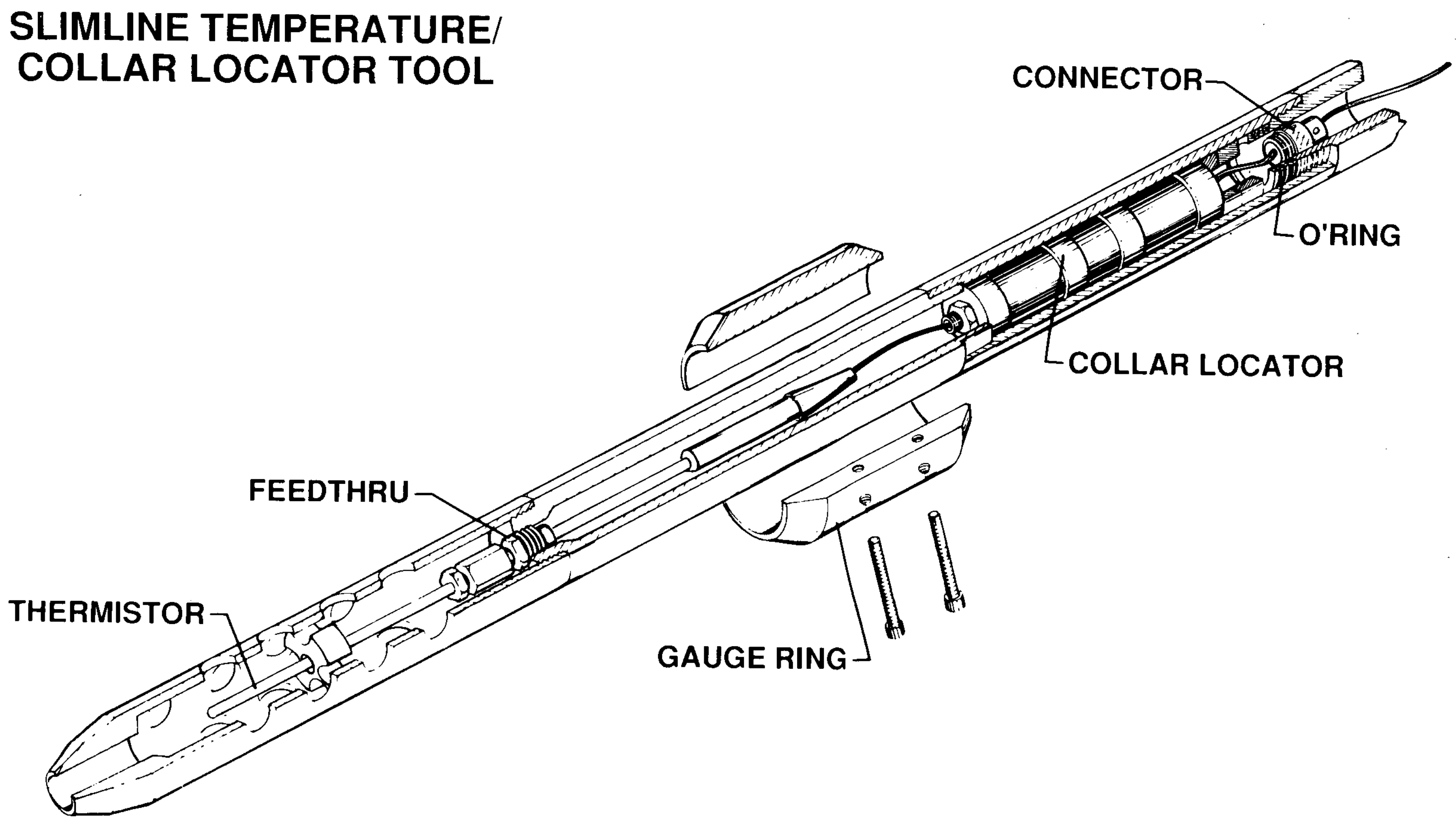

Fig. A-3. The temperature/rabbit tool.

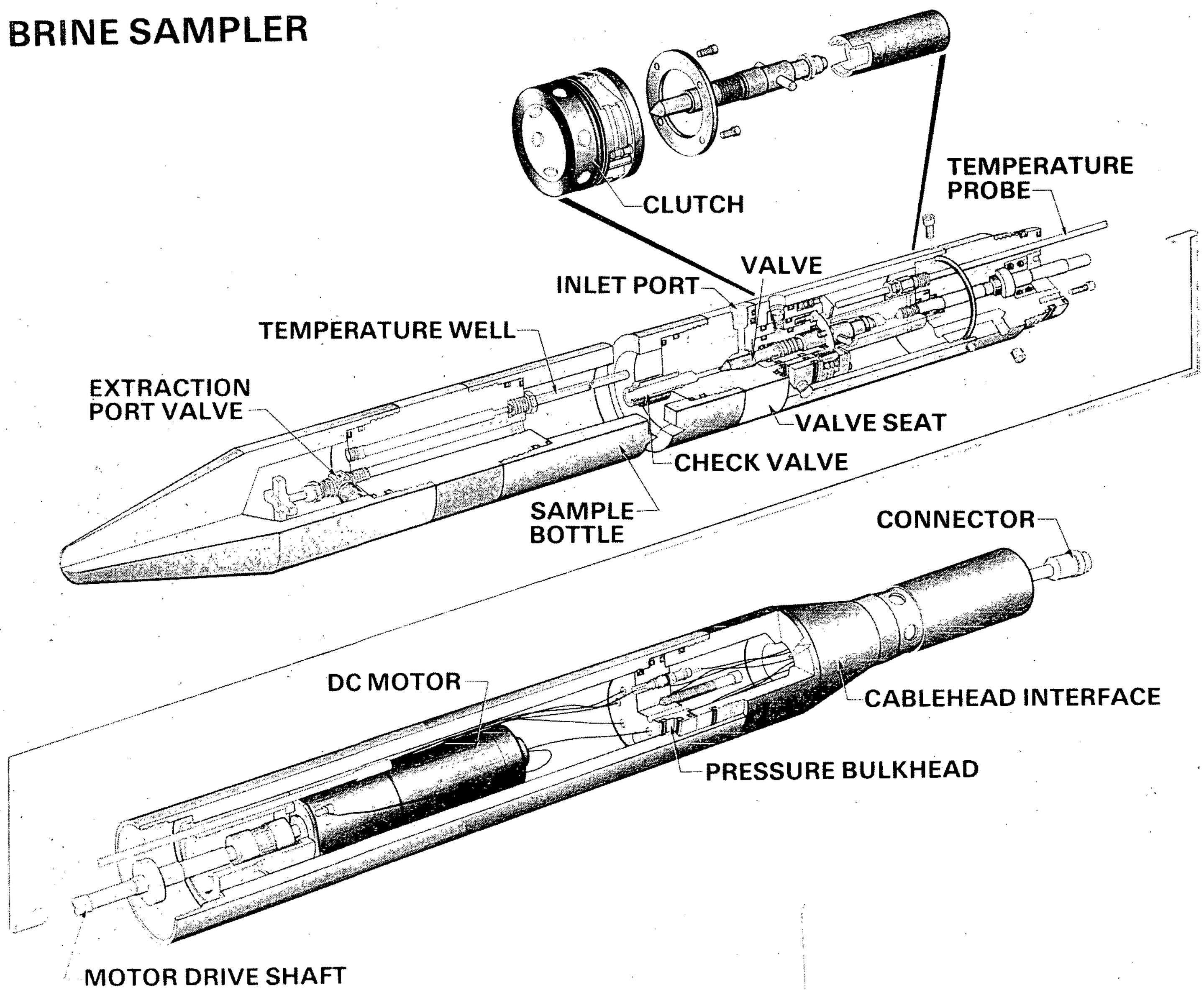

Fig. A-4. Schematic diagram of the Los Alamos *in situ* fluid sampler used during this investigation.

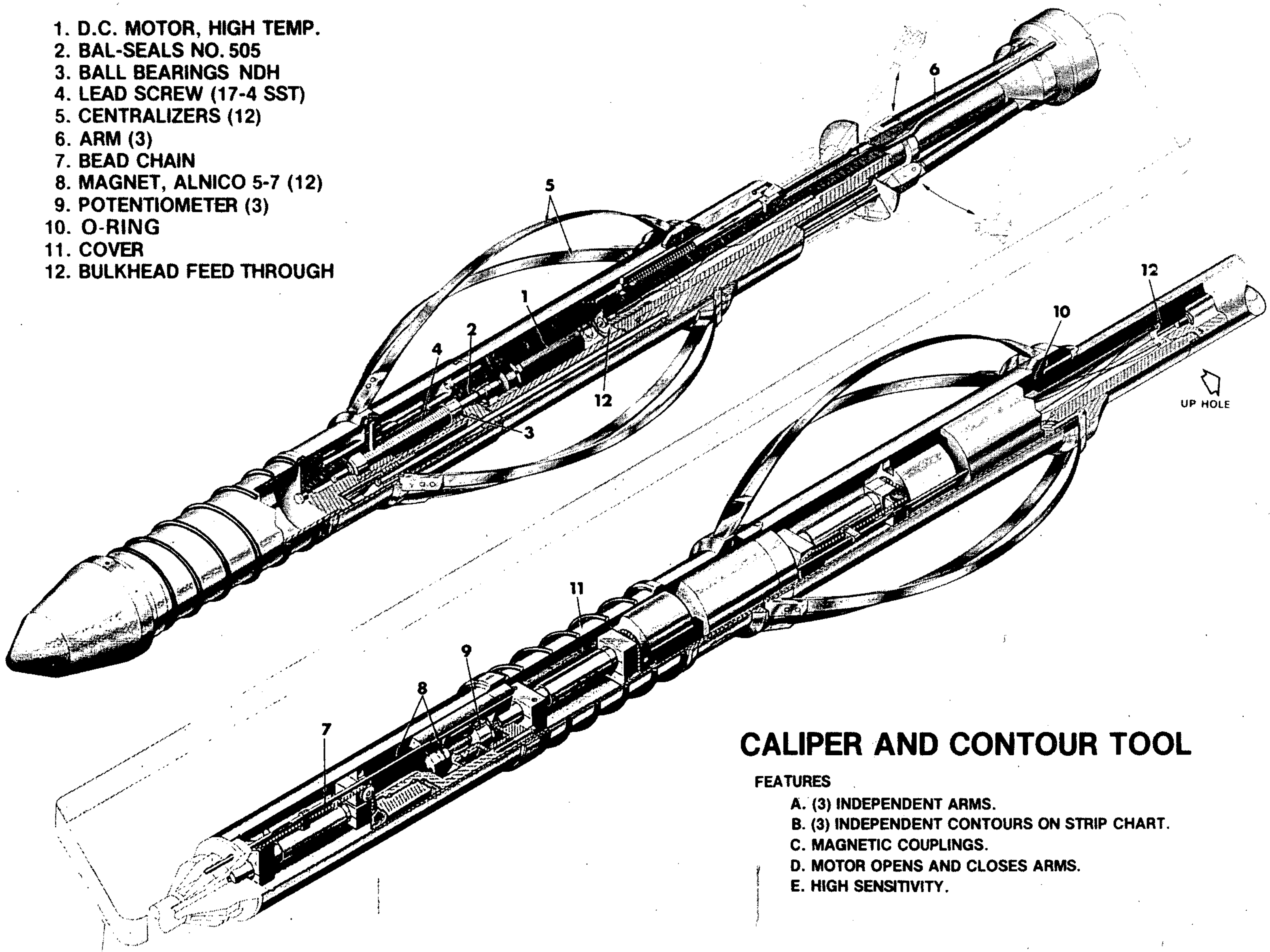

Fig. A-5. The three-arm caliper tool.

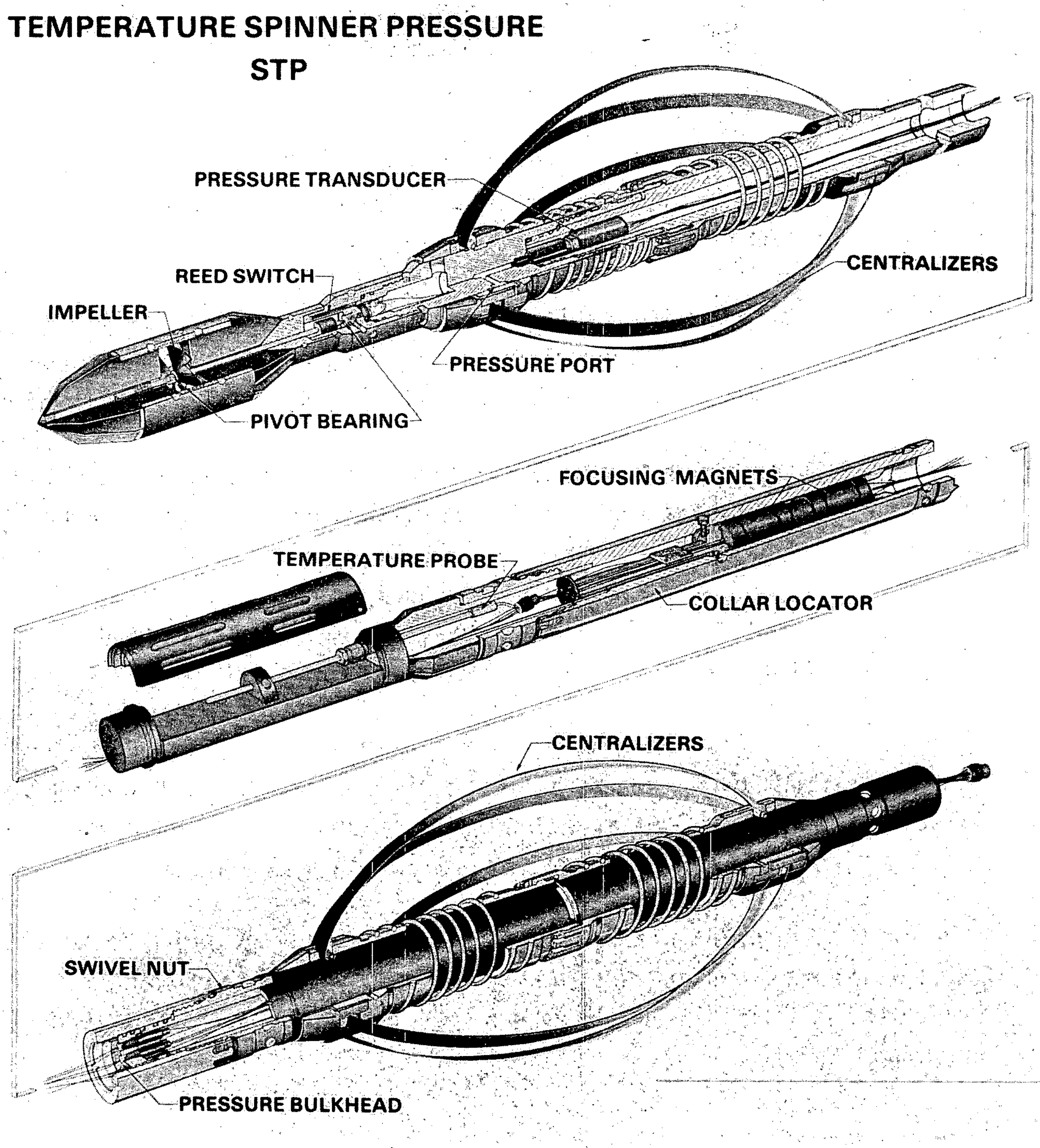

Fig. A-6. The spinner/temperature/pressure (STP) tool.

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