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VAPOR MASS RATIO MEASUREMENTS IN GEOTHERMAL PRODUCTION WELLS

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ABSTRACT

Measurements in geothermal wellbores are very difficult because of the high-fluid pressures, high borehole temperatures, and limited data transmission links. Here the extraneous effects on transducers and associated signal conditioning are very difficult to eliminate and if not carefully controlled may be the only variables measured. All the effects of these severe environments are not found in text books but come primarily through experience. Calibration of all transducers and instruments under simulated environmental conditions is absolutely essential. All materials and equipment used in the instrumentation systems must be carefully chosen, well understood and properly used. The time and effort spent in good planning and preparation will greatly increase the probability of meaningful data processing and prove to be much more efficient.

The applications of conscientious calibration methodology together with applicable data analysis can result in very meaningful information concerning fluid flow in geothermal wells. Recently a number of geothermal production wells were logged using a high-temperature spinner/temperature/pressure (STP) tool developed under the Hot Dry Rock Geothermal Energy Program.

To determine the thermodynamics state of the flowing wellbore fluid when the fluid can be in both the liquid and/or vapor state, absolute values of temperature and pressure are necessary. Consider, for example, the analysis of data obtained from one particular well, PGM-10, where the fluid flow was reported to be 21 kg/sec and the fluid temperatures at the surface was 240°C.

SPINNER/TEMPERATURE/PRESSURE INSTRUMENT CALIBRATION

A high-temperature (300°C) well-logging tool was developed to measure fluid velocity, temperature and pressure in geothermal environments (Fig. 1).

The fluid velocity (spinner) transducer consists primarily of a rotating impeller with a

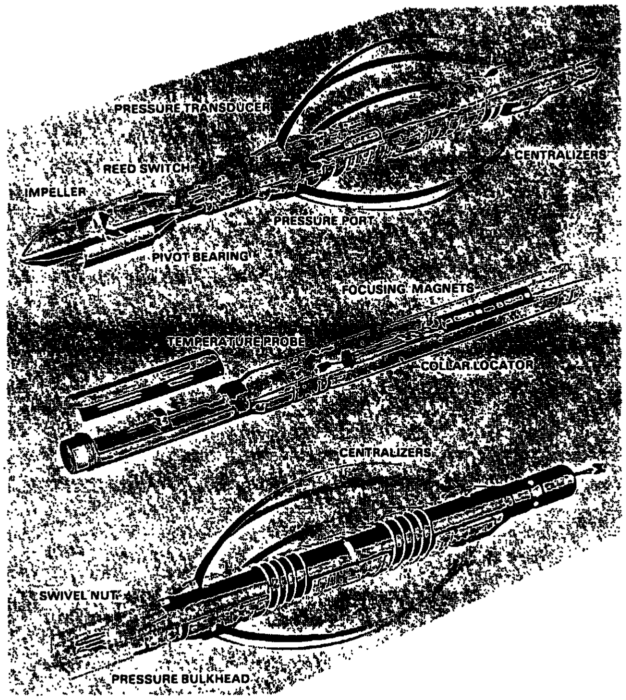

Figure 1. Spinner/temperature/pressure tool.

hardened steel pivot bearing. The rotating shaft operates a reed switch giving the rotational speed of the impeller in hertz. The rotational speed of the impeller is proportional to the velocity of the fluid relative to the logging tool. This proportionality is determined when logging both in and out of the well under static conditions. The temperature sensor is a thermistor that is calibrated to an accuracy of 0.10°C up to 300°C.

State-of-the-art mini computer technology providing relatively large memory and data storage capacity along with very high speed through put rates allows the use of more extensive calibration processing resulting in accurate on-line conversion of transducer output data to engineering units. The pressure transducer was calibrated for the pressure range from 0 to 5000 psi at 6 discrete temperatures of

20, 100, 150, 200, 250, and 300°C using an excitation voltage of 5 Vdc. Calibration data at temperature is plotted in Fig. 2. The same calibration was repeated with the excitation and output signals transmitted over 20,000 ft of logging cable. Since the excitation voltage is sensed at the gage, the power supply (at the uphole end of the cable) compensates for line losses.

A least-square fit combining both temperature and pressure calibration will provide accurate conversion of transducer output voltage to pounds per square inch while running the log in the geothermal well. The deviation is minimized using a second order fit for pressure and a third order fit for temperature resulting in a standard deviation of 0.584 with a maximum deviation of 1.384 (Fig. 3). The proper coefficients for this particular transducer can now be entered into the computer program. Real-time data is plotted on-line using the equation:

$$p = a + bV + cV^2$$

where V is the ratio output volts/excitation volts and:

$$a = a_1 + a_2T + a_3T^2 + a_4T^3$$

$$b = b_1 + b_2T + b_3T^2 + b_4T^3$$

$$c = c_1 + c_2T + c_3T^2 + c_4T^3$$

The CEC 1000-9 pressure transducer has proven excellent performance up to at least 300°C. Future testing will determine its capability at 350°C.

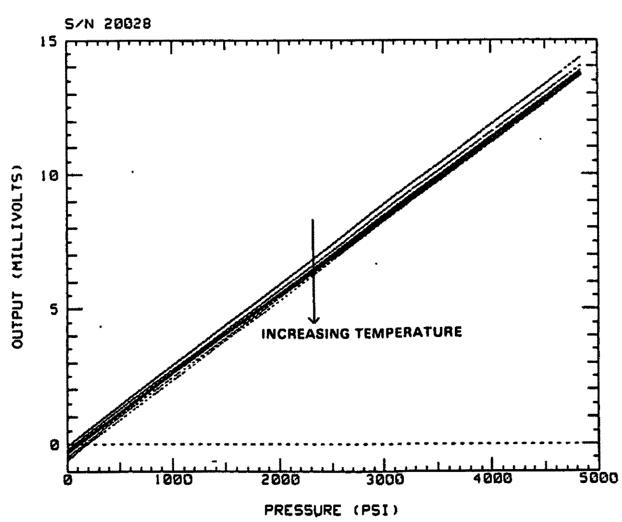

Figure 2. Calibration of pressure transducer at specified temperatures.

Serial No. 20028
Coefficients for SUM C(I) * T^((I-1) MOD 4) * V^((I-1) DIV 4)

16.412693	0.5511505	-0.000298738	0.000001728006
1656203.74	447.4448	-1.426106	0.0010322
4646487	-11890.3	144.472	-0.380888

Standard Deviation - 0.5843
Maximum Deviation - 1.3838

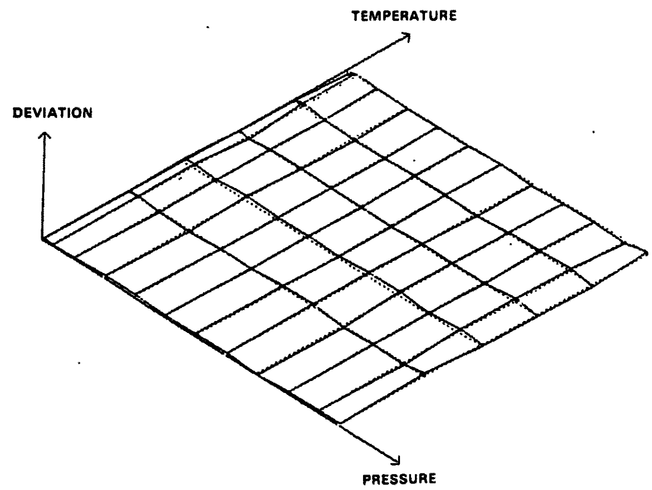

Figure 3. Second order fit pressure and third order fit temperature.

MEASUREMENTS IN WELL PGM-10.

This instrument along with a high-temperature fluid sampler and borehole caliper was used to investigate the condition of the geothermal production well PGM-10. This well was cased with 9-5/8-in. casing (8.853-in. i.d.) to a depth of 745 m. A 7-5/8-in. slotted liner was hung from 733 m to 1782 m with the slots starting at 756 m. It was suspected that there was significant calcite buildup in the liner.

The well was logged under both static or shut-in and flowing conditions. Static logs were used to confirm calibration data for the spinner and pressure transducers.

In the static log the spinner data (Fig. 4) shows a turbulent region between 300 and 480 m which is a boiling zone. The fluid is all liquid below the depth of 480 m. This is also confirmed in the static temperature log (Fig. 5). The temperature data describes a vapor only region from the surface to 300 m, a 2-phase region from 300 to 480 m, and liquid below that.

In the liquid region of the well, the pressure gradient is the hydrostatic gradient. Geochemical analysis from a downhole fluid sample gave a value of 1.00+ for the specific gravity.

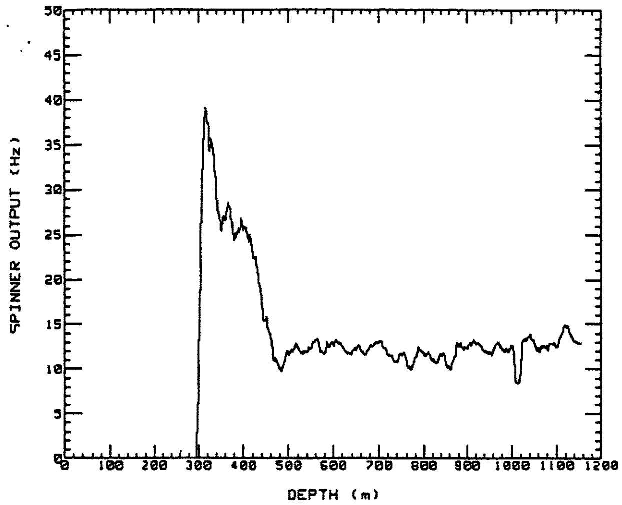

Figure 4. Spinner output static log of Well PGM-10.

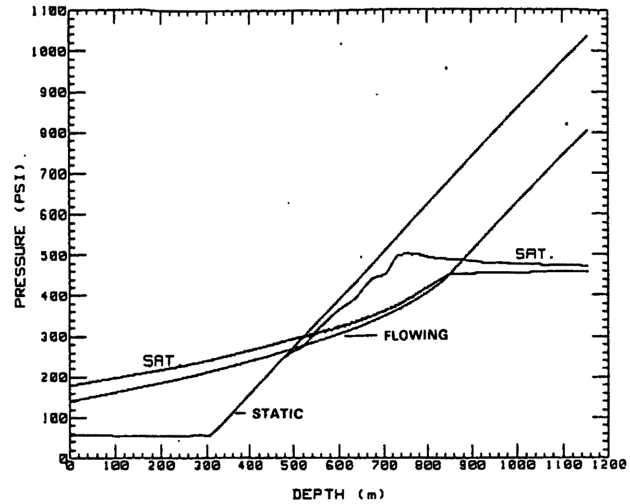

Figure 6. Pressures and saturation pressures of static and flowing logs of Well PGM-10.

At an average temperature of 236°C the pressure gradient would be 1.165 psi/m. The pressure at the liquid surface must be the saturation pressure based on temperature. The static log pressure (Fig. 6) is quite linear in the 2-phase region and when compared to the saturation pressure indicates the fluid is in thermodynamic equilibrium.

Now consider the data acquired from the flowing logs with maximum fluid flow conditions in the well. The flowing temperature log (Fig. 5) and the flowing spinner log (Fig. 7) show the 2-phase fluid to liquid interface at 850 m. This is in agreement with the saturation pressure.

The flowing spinner data also shows the transition from the casing to the slotted liner at 733 m. Note that the 2-phase fluid in the flowing well from 0 to 850 m is not in thermodynamic equilibrium. The fluid pressures are lower than the saturation pressures meaning the vapor phase is in the superheated region.

The vapor mass ratios (steam quality) may be calculated using steam table data and assuming no total heat loss (enthalpy) from the 2-phase fluid. The calculated vapor quality is plotted in Fig. 8.

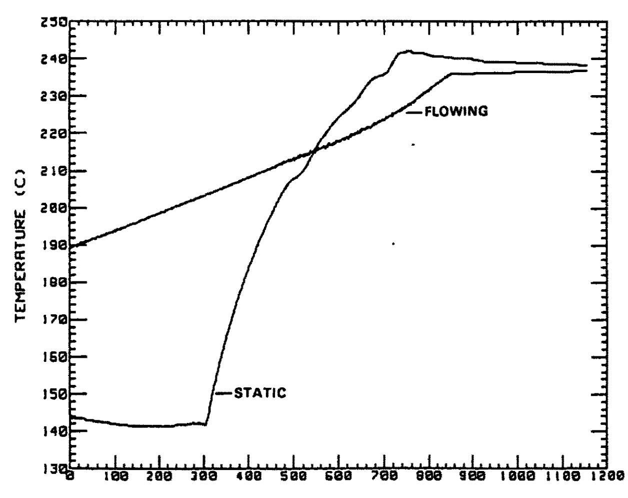

Figure 5. Temperatures of static and flowing logs in PGM-10.

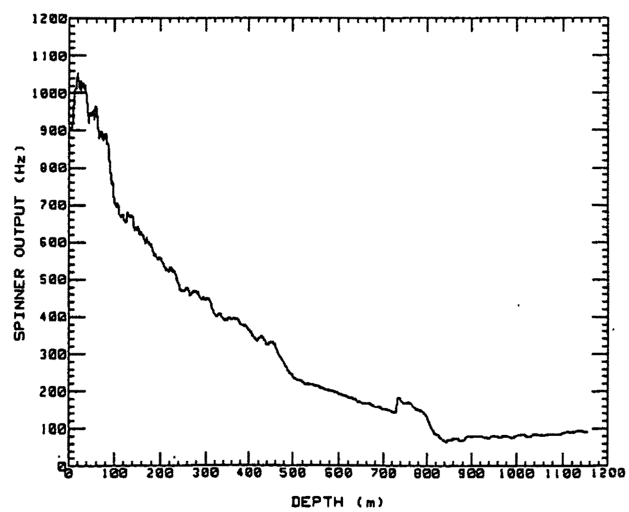

Figure 7. Spinner output of flowing log in Well PGM-10.

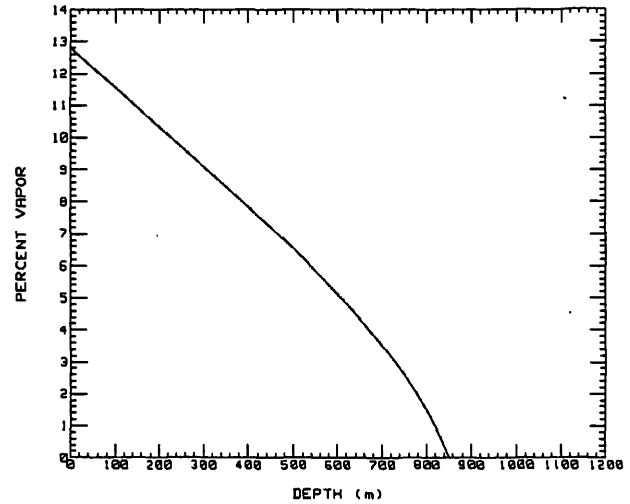

Figure 8. Calculated vapor quality of flowing well, Well PGM-10.

Spinner data from the liquid region of the well below 850 m was used to confirm spinner calibration and calculate fluid velocities. Using averaged spinner data over this region, the calculated proportionality constant for the spinner is 0.0558 ft/sec/Hz. The measured fluid velocities using this conversion factor over the entire wellbore is plotted in Fig. 9. Fluid velocities were also calculated knowing the mass flow rate and vapor qualities of the fluid in the 2-phase region and compared to the measured values as shown in Fig. 9.

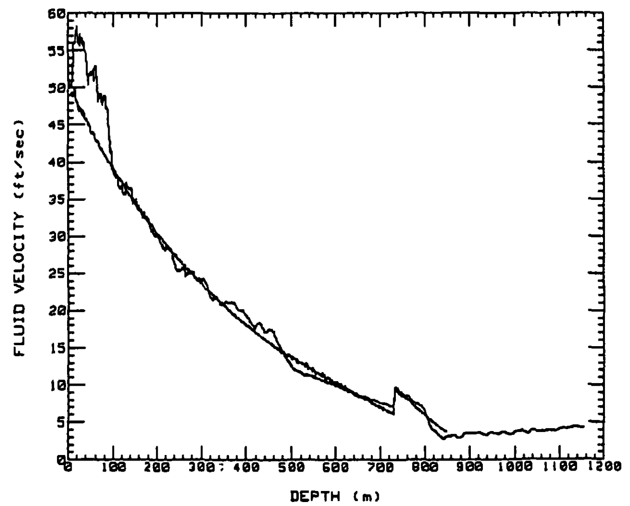

Figure 9. Measured and calculated fluid velocity of flowing well, Well PGM-10. The calculated flow rate is 23 kg/s.

Caliper data, from the 3-arm caliper log, measured a minimum radius of 3.22 in. at a depth of approximately 1150 m. The maximum measured fluid velocity in this region was 4.4 ft/sec. Using these values and the fluid density, the mass flow rate was determined to be 23 kg/sec (50.6 lb/sec).

Knowing the fluid velocities and the mass flow rate, the flow radii in the slotted liner can be calculated (Fig. 10). This data compared to the slotted liner inside diameter shows the reduction in the liner due to chemical deposits on the inside of the liner and also indicates the buildup of deposits behind the liner. The slots below 1000 m are blocked or at least partially blocked. The caliper data obtained using the high-temperature 3-arm caliper (Fig. 11) also shows the decrease in measured radius from 1050 to 1150 m and the disappearance of the slots in the liner. Figure 12 is a plot of the caliper log and the flow radii showing the excellent agreement of the measured variables and the calculated radii.

CONCLUSION

The analysis of data obtained in the geothermal environment depends upon the quality of the measured variables. The measurements are accurate and precise when the limitations of the equipment in the geothermal environment and when the effects of all extraneous variables in the instrumentation are well known. The instruments used to obtain the desired data in the PGM-10 well were designed specifically for operation in the geothermal boreholes with fluid temperatures up to 300°C. The downhole instruments have been used in numerous geothermal wells where fluid temperatures ranged from 230 to 355°C. The data obtained in the PGM-10 well is one specific example of determining the borehole conditions and quality of well fluids.

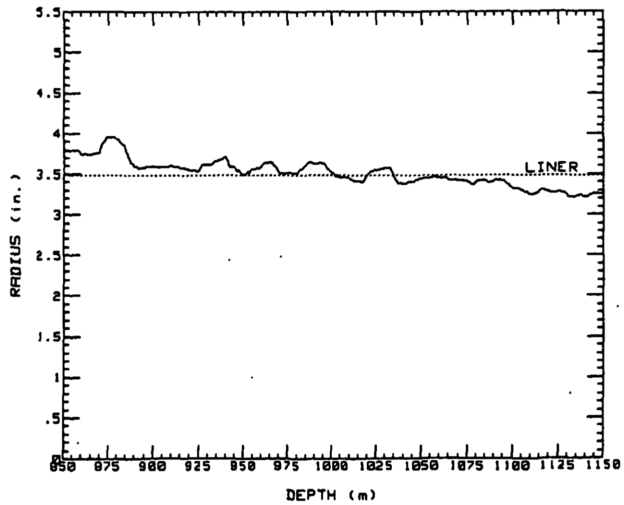

Figure 10. Effective flow radius from spinner data of flowing well, Well PGM-10.

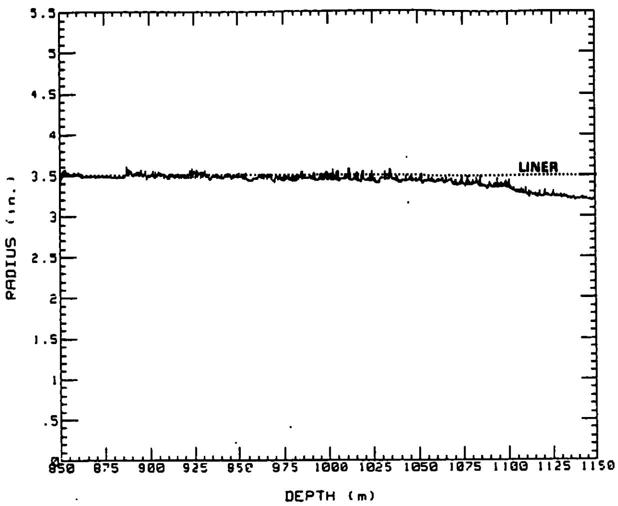

Figure 11. Radius from caliper data of Well PGM-10.

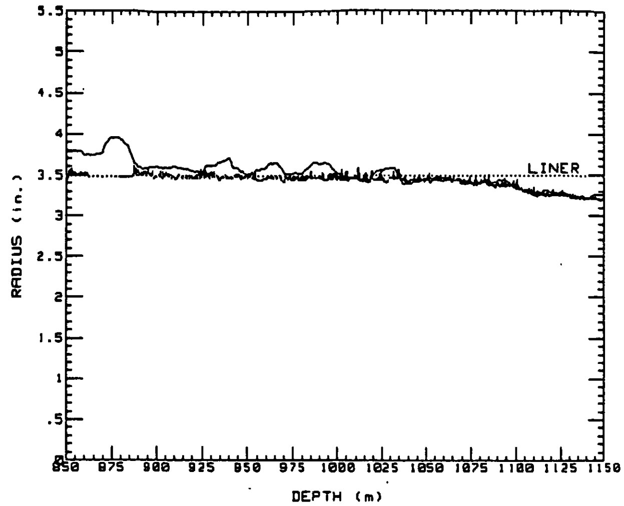

Figure 12. Plot of caliper log and flow radii of flowing well, Well PGM-10.

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