MEASURED FLUID FLOW IN AN ACTIVE H_2O-CO_2 GEOTHERMAL WELL AS AN ANALOG TO FLUID FLOW IN FRACTURES ON MARS: PRELIMINARY REPORT.

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Introduction: Water in the Earth's crust generally contains dissolved gases such as CO_2. Models for both "Blue Mars" (H_2O-driven processes) and "White Mars" (CO_2-driven processes) predict liquid H_2O with dissolved CO_2 at depth. The fate of dissolved CO_2 as this mixture rises toward the surface has not been quantitatively explored. Our approach is a variation on NASA's "Follow the Water" as we "Follow the Fluid" from depth to the surface in hydrothermal areas on Earth and extrapolate our results to Mars. This is a preliminary report on a field study of fluid flow in a producing geothermal well. For proprietary reasons, the name and location of this well cannot be revealed, so we have named it "Earth1" for this study.

Field and Geochemical Data: Earth1 extends to 1328 meters, a depth equivalent to nearly 4 km under conditions of Martian gravity. Although it is slightly deviated in the last 300 m, the deviation is only a few meters vertical height and we give all distances here as downhole distances rather than true vertical depth (TVD) because the probe measurements give downhole distances, not TVD. There are multiple feed zones between about 1150 m and the bottom. Historically the major feed zone for this well has been from liquid water at 1295 m, and superheated water or steam within the next 100 m. However the feed zones change with time and production alters the hydrology of the hydrothermal system. From the pressure, pressure gradient, velocity, and temperature data in Figure 1, we hypothesize that there are feed zones at about 1300 m (temperature inflection), 1225 (pressure gradient inflection and change in velocity) and 1200 m (temperature inflection).

The 9-5/8" (0.244 m) production casing extends from the surface to 1057 m, and the 7-5/8' (0.1936) slotted liner extends from 1034 to 1328 m. In October, 2003, we inserted a PTQ probe into the well to 1309 m under production conditions. During production, the well is networked to other producing wells, and the discharge is variable because it is controlled by needs for the steam. The probe measured pressure and temperature at 1/3 m intervals. The probe contained a spinner whose spin rate (measured in Hertz) gives flow velocity and direction under ideal conditions (pure liquid or pure gas flow); data in the two-phase flow regime are difficult to interpret and therefore this data set is potentially unique if we can recover velocity data for the whole length of the well, as these preliminary results suggest is possible.

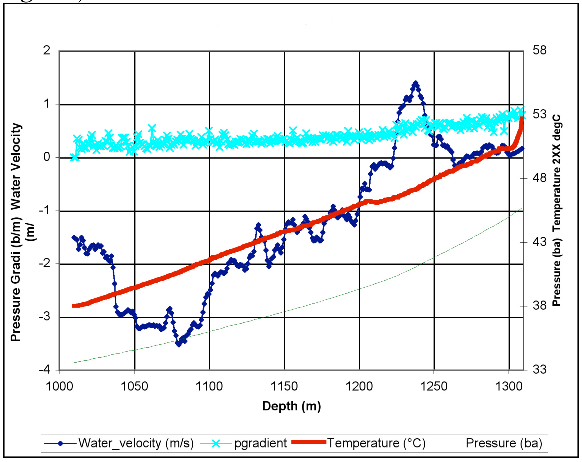
During the experiment, the wellhead pressure dropped from 17 to 9.6 b.g. (18-11.6 b.a.) Samples were collected at the surface at a pressure of 11 b.a. and the steam fraction in the samples was 0.23. The pressure at the bottom of the well was 45.5 b.g. (46.5 b.a.) and the temperature at the bottom was 253°C. The discharge rate was 156 tonnes/hr (43 kg/s). The temperature at the top of the well was 199 °C.

The pH was 7.83. In the liquid water component, there were 211 mg/kg CO_2 and negligible quantities of other gases. In the steam sample, there were 14,267 mg/kg CO_2 and 278 mg/kg H_2S.

The interpreted spinner data for the lower part of the well, below 1000 m, in the slotted liner are shown in Figure 1. Negative velocities imply that the fluid was moving upward. The existence of positive velocities below 1220 m indicates that there was probably downflow at greater depths.

The surface geochemical data were inverted to give reservoir conditions. In the reservoir, the pH was 6.56. The deep water CO_2 content was 3426 mg/kg.

Figure 1: Water velocity (dark blue), pressure gradient (light blue), temperature (red) and pressure (thin green) in Earth1.



The quartz geothermometer gives a reservoir temperature of 280.3°C, corresponding to an enthalpy of 1239 kJ/kg.

At all depths, the pressure measured exceeded the saturation pressure for the measured temperature by several bars. For a pure water system, this would imply that the fluid was in the liquid phase. However, the pressure gradient data shown in Figure 1 (top light blue line) shows a change in slope above the 1225-1240 m that indicates that two-phase flow exists above this level. This is probably what is causing the irregular behavior of the velocity data (dark blue line in Figure 1) because the spinner is designed to operate either in steam or liquid, but not in two-phase flow.

We hypothesize that the difference between the saturation pressure for pure water at these temperatures and the measured pressure is due to a partial pressure of CO_2. We cannot simulate the effects of the CO_2 in this preliminary work, but we have used a H_2O simulator to begin our studies [1].

Preliminary Model: In the simulator WELL the pressure drop between the bottom and top of the well is calculated from three components: work against gravity, work against friction, and acceleration or deceleration due to heat gain or loss (a small term in geothermal wells, but large in nuclear reactor cooling problems). The pressure change can be calculated by either stepping up or down the well; we step up the well from bottom conditions. At each step, empirical correlations must be invoked to specify the flow regime: in the direction of increasing velocity these are *liquid*; slug (liquid slugs separated by relatively large bullet-shaped gas pockets so flow alternates between high-liquid and high-gas composition); *churn* (irregular slugs of gas move up the center with entrained droplets and the rest of the flow along the pipe walls); *wispy or wispy-annular* (lighter fluid with pockets of denser aerosol or emulsion in the center and heavier fluid on the wall); or *annular* (lighter fluid in center of pipe and heavier on a thin film on the wall).

In order to simulate the liquid-to-two-phase transition, we assume that the fluid entering the well at 1309 m is a slightly overpressured H_2O (253 C, 4.6 Mpa). The enthalpy of this fluid is 1100 kJ/kg, much lower than the inferred enthalpy from the actual data.

Many parameters (such as roughness heights, heat loss, and multiple feed zones) remain to be explored. A nominal simulation was performed using the known geometry and thermodynamic properties and a roughness element height of 0.00004 m.

The calculated pressure at the well-head is 1.4 Mpa, in good agreement with the measured well-head pressure range. The dryness is 0.125, well below the measured steam fraction of 0.22. The temperature is 198^{o} C in excellent agreement with the measured temperature of 199^{o} C.

The simulation suggests that the fluid is *liquid* to 1255 m, in good agreement with the inferred location of the onset of two-phase flow at 1225-1240 from the pressure gradient curve. The flow changes to *slug flow* up to 1170 m and to *churn flow* to 1131 m. These regimes are liquid dominated and so can be considered to be the boiling regions of the fluid. The velocities would be expected to be low in boiling fluid because the volume of gas is relatively small.

Above 1131 m, the flow changes to gas dominated *wispy flow* up to 1057 m, where the pressure drop associated with expansion into the cased part of the well (actually at 1034 m) causes a reversion to *churn flow* for about 8 m. The flow is then *annular* to the top of the well.

Very broadly, these transitions correspond to inflections in the velocity data of Figure 1. At the bottom of the well the fluid is liquid, probably convecting vigorously and producing a zone of downflow as inferred from the velocities. Slug and churn flow between 1225 and 1131 m is liquid dominated and therefore the velocities are low, but increasing. Wispy flow characterizes the regime between 1131 and 1057 m where the velocities increase up to 3.5 m/s because of the volume expansion of the now-dominant gas phase. The expansion from the slotted liner into the production casing at 1034 m causes the flow to decelerate. The obvious difficulty of measuring flow properties in two-phase flow is apparent by the velocity reversals and the irregular velocities, but in a broad picture, the measured velocities are consistent with the expected nature of the calculated flow regimes.

Summary: Field data in a flowing H_2O-CO_2 geothermal well has been successfully obtained for extrapolation to conditions of flow in a Martian fracture system. Preliminary modeling with an H_2O geothermal well simulator shows a complex series of flow regimes complicate the analysis of the fluid flow but that a reasonable interpretation can be made of the boiling and dispersed phase flows. In future work, we will attempt to recover data from 0-1000 m, incorporate CO_2 into the flow model, and then extrapolate to Martian subsurface conditions.

References: [1] Brennand A.W. and Watson A. (1987) Proc. 9th New Zealand Workshop, 65-68.

Acknowledgments: We thank the individuals who permitted, helped organize, and did excellent field measurements for this project. This research was sponsored by NASA NAG5-12747 and the Geothermal Institute at the University of Auckland.