PROCEEDINGS, Twenty-Ninth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 26-28, 2004

LABORATORY OBSERVATIONS OF AN ADVANCING BOILING FRONT IN A POROUS MEDIUM AND CORRELATION TO SELF POTENTIAL MEASUREMENTS

Jeffrey R. Moore and Steven D. Glaser

University of California, Berkeley
440 Davis Hall
Berkeley, CA 94720, USA
e-mail: moore@decf.berkeley.edu

ABSTRACT

We present new laboratory observations of an advancing boiling front radiating from an injection point in a simulated geothermal reservoir. The Berea sandstone model is a 26 cm cube that is either heated to a dry 125°C, or saturated with 145°C steam in two separate testing configurations. Cool water is applied at the sample center, and the advancing boiling front is identified by a radial array of 4 temperature sensors spaced at 1 cm intervals from the injection point. Using this data, the location of the vaporization front is observed, and temporal variations noted.

Temperature information is correlated to self potential measurements made at the injection point. We show that these measurements can identify the point at which local fluid flow changes from 2-phase water / steam to single phase water, or that point when 2-phase flow *ceases* at the injection point. This is made possible by a large difference in resistivity between water and steam, and the resulting increase in self potential coupling for 2-phase flow. Furthermore, pressure fluctuations resulting from 2-phase flow in a porous medium can be observed in the self potential record and used to indicate the state of local pore fluid. Extrapolation of this work to field sites will lead to a better understanding of vaporization at injection points and more economical injection strategies.

INTRODUCTION

As geothermal reservoirs are taxed from over-production, operators look to injection strategies to maintain and even increase the supply of vapor to the power plants. When ambient temperature injectate migrates through the porous reservoir rock, it is heated and a fraction vaporizes. Theoretical models of vaporization in a porous medium resulting from a cool water injection have produced important results and have allowed operators to better understand the fundamentals of this process (Pruess et al., 1987; Fitzgerald and Woods, 1993, 1997, 1998). Still lacking, however, is a reliable way for operators to know when fluid at the injection point has ceased to vaporize, or similarly, when the local reservoir rock has been quenched. Beyond this time it is inefficient to continue to inject fluid, since vapor production is decreased. Current injection strategies are limited to an operator's intimate knowledge of the field. Often the observation of single-phase water flow at a nearby well is the only way to know when vaporization of injectate has ceased.

In this testing, we investigate the use of self potential signals to identify the point in time after the beginning of injection when 2-phase flow of liquid / vapor has ceased and single phase fluid flow has begun. We employ a passive monitoring technique in the form of a single electrode at the injection point, with an arbitrary reference. This method is thereby extremely cost efficient and, if proven successful, could provide operators with relevant information about the state of fluid flow at the injection point.

THEORY

Self potential, in this case streaming potential or electrokinetic potential, is a widely recognized passive monitoring method for identifying fluid flow conditions through rock and rock/soil matrices (Bogoslovsky and Ogilvy, 1970; Corwin and Hoover, 1979; Wurmstich and Morgan, 1994). This method is based on the existence of an electric double layer at the liquid-matrix interface where a diffuse mobile layer of ions can be effectively *dragged* away from their adsorbed immobile counterparts under a pore pressure gradient, creating a charge imbalance (Ishido and Mizutani, 1981). Since many minerals have a negatively charged surface, a diffuse layer of positive ions from the local pore solution is attracted to the surface and can be carried away yielding a negative anomaly.

The Helmholtz-Smoluchowski equation describes the relationship between streaming potentials and the pressure gradient by which they are created.

$$\Delta V = -\frac{\varepsilon\zeta}{\eta\sigma}\frac{F}{F_o}\Delta P \qquad (1)$$

Where ε is the dielectric constant of the fluid, ζ is the zeta potential, σ is the conductivity of the fluid, and η is the dynamic fluid viscosity (Overbeek, 1952). Additionally, F is the formation factor, while F_o is the formation factor when surface conduction is not present. The ratio F/F_o accounts for the effects of surface conduction, which can be significant when pore fluid conductivity is low (Lorne et al, 1999). The quantity $(\varepsilon\zeta/\eta\sigma)$ (F/F_o) is known as the streaming potential coupling coefficient, Cc.

Experimental studies of 2-phase self potential signals are limited, and theoretical discussion is of great need. In one of study, Morgan et al. (1989a) admitted small amounts of air to crushed granite samples and noted that the coupling coefficient increased by 2 to 5 times. They attributed this observation to increased bulk resistivity caused by the presence of the air. Other work by Marsden and Tyran (1986) showed that 2-phase self potential signals could reach as high as 100 volts for the flow of wet steam through a capillary tube, while the flow of dry steam produced no observable self potential. They attributed the large potentials to slugs of water passing through the system. As a follow up to this study, Marsden and Wheatall (1987) designed a test where wet steam was simulated by mixing a known quantity of nitrogen gas with distilled water, such that the volumetric gas content was known. Their results for the capillary tube experiment indicate that the coupling coefficient is relatively constant until the gas content approaches 50%. At a gas content of 95%, the coupling coefficient increased rapidly to a maximum before falling to zero at 100% gas. The maximum coupling coefficient was 4 to 5 times larger for high gas contents than for low gas contents. Other investigations by Antraygues and Aubert (1993) simulate hydrothermal convection and discuss both thermoelectric and electrokinetic observations. Finally, Sprunt et al. (1994). summarize some work that has been done investigating 2-phase mixtures of oil and brine.

EXPERIMENTAL

The testing device is a true-triaxial cell capable of 3 independent confining pressures up to 14 MPa while being flooded by up to 250° C steam. In this testing, the vertical stress was held constant at 1 MPa, while the horizontal stresses were equal at 0.6 MPa. The sample is surrounded by non-conductive PEEK plastic plates, which have a dense grid of machined grooves to allow for unimpeded movement of steam and condensate around the sample. Four 2000 watt heater coils embedded in aluminum plates outside the PEEK plates can be used simultaneously with the steam to apply superheat, or independently, as in modeling a hot dry rock (or EGS) system. Steam (57 kg/hr) is produced in a Lattner 480 V, 2 MPa electric boiler fed with pre-heated water.

The injection pump was created by coupling a hydraulic cylinder to a variable speed actuator. Injection rates up to 50 cc/sec are possible at pressures up 14 MPa. Injectate for all testing was 125 Ω-m tap water at room temperature.

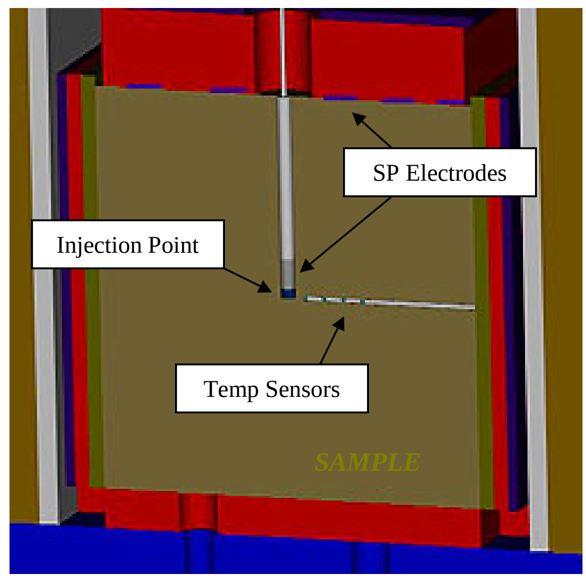

Figure 1: Berea sandstone sample and placement of instrumentation. Self potential electrodes are located on the top surface of the sample and at the injection point. Temperature sensors are spaced 1 cm radially from the injection point.

The sample (Figure 1) is a 26 cm cube of Berea Sandstone (Lang Stone, Columbus, Ohio) of 17.6 l total volume, 17% porosity, 50 mD permeability. An array containing 4 temperature sensors spaced at 1 cm was embedded into the sample radiating from the injection point (Figure 2). The first sensor in the array was located 1 cm from the injection point. Using this array we were able to track the location of vaporization front as it moved outward from the injection point, and plot its movement with time. Temperature data was recorded at a rate of 2 samples per second.

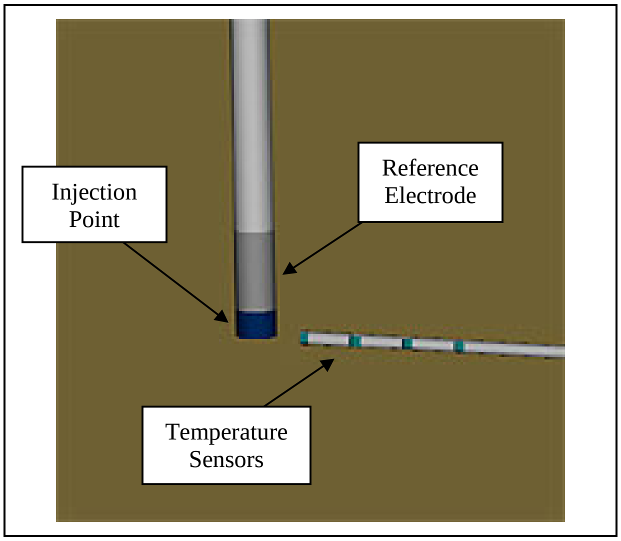

Figure 2: Blow up of a slice through the center of the sample showing injector coming down from the top surface, temperature sensor array radiating from the center of the sample. Individual temperature sensors are spaced at 1 cm. The electrode at the injector was a bare wire end pressed against the sample and isolated from the injector by the silicon packer.

Self potential signals were observed in two ways. The *primary* observation was the self potential signal at the injection point. The electrode here was a bare wire end pressed against the sample and isolated from the injector by the silicon packer (Figure 2). The location of this electrode was thus slightly above the injection point by distance of about 0.5 cm. This electrode was referenced to an arbitrary 'out of system' ground and recorded independently.

Secondary self potential signals were recorded on the top surface of the sample, which had an electrode pattern shown in Figure 3. This pattern was intended to simulate a ground-surface SP field survey. The reference for these electrodes was the electrode at the injection point. Since the reference was an 'active' electrode, its signal was subtracted from each measuring electrode, leaving the residual anomaly of interest. The sampling rate for all self potential measurements was 100 samples per second for 640 second sweeps.

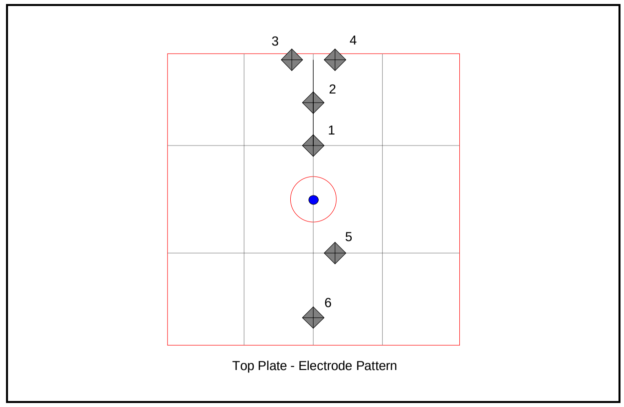

Figure 3: Top surface electrode pattern. Each electrode is referenced to the electrode at the injection point. The residual anomaly for each electrode is calculated by subtracting the independently measured signal at the reference electrode.

In our testing, which is designed to simulate an in situ field study, we cannot determine a coupling coefficient as strictly defined by the theory and thoroughly discussed by Morgan (1989b). Doing so requires that both potential and pressure drop observations be made at coincident locations on the edges of the sample, and that strict flow conditions be met. Our instrumentation, on the other hand, cannot measure the pressure distribution radiating from the injection point into the sample, and our measurements of self potentials near the injection point are referenced to an arbitrary 'out of system' ground.

We therefore define the *effective coupling coefficient* (Ecc) to be the ratio of the observed potential to the injection pressure at any time. Analysis of relative magnitudes in effective coupling coefficient will be shown to provide useful information to distinguish between single phase and 2-phase fluid flow.

Three trials were conducted using the same Berea sandstone sample:

1. Preliminary observations and verification test of sensors and methodology using water-saturated sample at room temperature (20°C).
2. Hot-dry sample at 125°C, zero pore pressure.
3. Hot steam-saturated sample at 145°C, pore pressure = 310 kPa.

PRELIMINARY OBSERVATIONS

We hypothesized that self potential signals due to 2-phase flow would be much larger in magnitude owing to the increased resistivity of a 2-phase water / steam pore fluid. Preliminary observations indicate that indeed the *effective* coupling coefficient (Ecc) for

2-phase flow could be nearly 2 orders of magnitude larger than that for single phase flow in the same sample. For example, we measured an effective coupling coefficient of 6 mV / 0.1MPa for single-phase liquid water flow, and an Ecc of up to 300 mV / 0.1MPa for 2-phase liquid / gas flow in the same sample; a value 50 times larger.

Researchers have shown that pressure fluctuations about the saturation pressure are observed as 2-phase fluids migrate through a porous medium (Pruess et al., 1987). These fluctuations are simply understood by noting that pressure changes occur as vapor moves through constricting pore boundaries into larger pore volumes. Resulting pressure variations can be quite regular as the 2-phase fluid flows through a near homogenous sample. We were able to observe self-potential signals generated during a steam flood of a cool, wet sample. The results (Figure 4) clearly show a regular oscillation about a mean with amplitude significantly above the noise level. We propose that this type of signal is indicative of 2-phase fluid / gas flow, where self potential fluctuations occur rapidly and independently of any *bulk* pore pressure gradient.

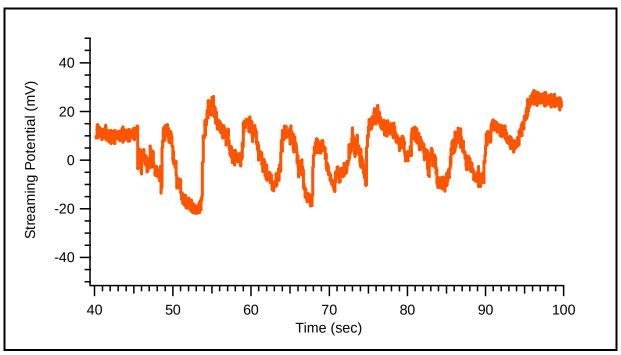

Figure 4: Self potential observations at the center of the sample cube resulting from a steam flood of a cool, wet sample. In this case, steam was applied at the sample perimeter and infiltrated under a pressure gradient. Regular oscillations observed are unique to 2-phase flow, and their pressure counterpart is predicted by theory.

We were able to validate our physical model and sensors by performing a fluid injection into the center of a water-saturated sample at 20°C. The injection pressure and self potential observations at the injection point are noted in Figure 5. We observe that these independently measured quantities parallel each other exactly. By noting the SP change induced by the pressure event, we calculate an effective coupling coefficient (Ecc) of 6 mV / 0.1MPa for this single-phase water flow scenario.

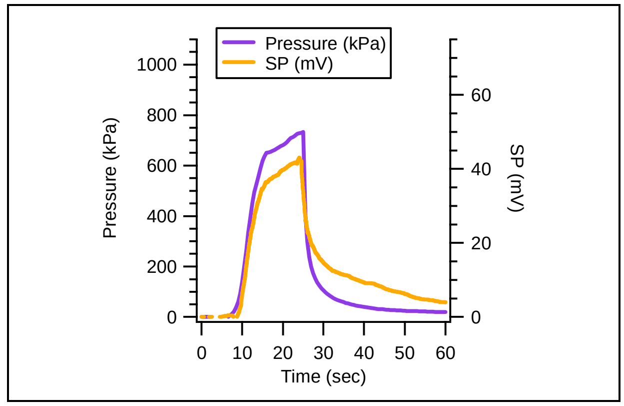

Figure 5: Injection pressure and self potential at the injection point resulting from a cool water injection into the center of a cool, water-saturated sample. Results indicate an effective coupling coefficient (Ecc) of 6 mV / 0.1MPa.

The residual SP anomaly for each of the top surface electrodes is shown contoured in Figure 6. On the left side, the magnitude of the residual SP anomaly is plotted against distance away from the injection point. The results show good fit to the theoretically predicted Gaussian variation for a dipole current source in a homogeneous half space, shown by the solid line (Nourbehecht, 1963).

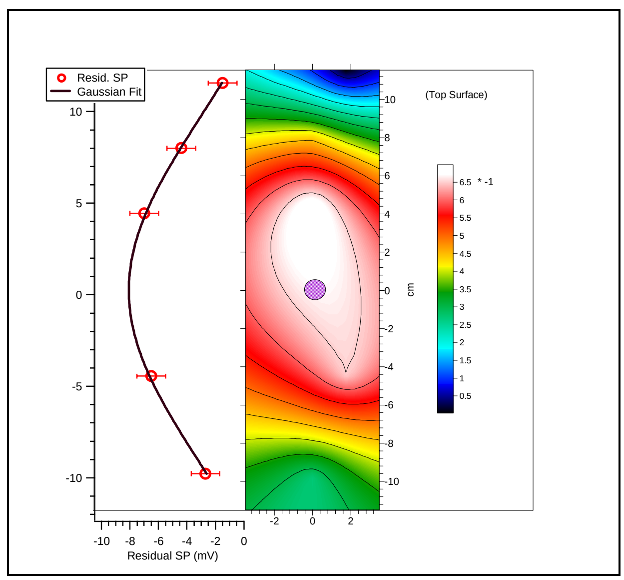

Figure 6: Contoured spatial variation of the residual SP anomaly along the top surface of the sample during the injection event shown in Figure 5, and Gaussian fit (left). Results show excellent correlation to theoretically predicted Gaussian potential variation for a dipole current source in a homogeneous half space. The injection point is indicated by the hatched circle at center.

RESULTS

In the first of two testing configurations, the sample was brought to a temperature of 125ºC through application of the heater coils surrounding the sample perimeter. The sample was heated over the course of 12 hours and considered to be fairly dry. Ambient temperature injectate was applied at time = 17 sec to the sample center at a flow rate of 0.4 ml / sec. Temperature, injection pressure, and self potential were monitored for approximately 10 minutes. Figure 7 shows the temperature record for the array of temperature sensors radiating horizontally from the injection point in the center of the sample. In this figure the vaporization front can be seen as the sharp decrease in temperature, as predicted by Pruess (1987) and by Fitzgerald and Woods (1993, 1997, 1998). The temporal location of the vaporization front is thus observed, and the rate of its advance is seen to decrease with distance from the injection point because of its 3-dimensional flow pattern and the constant rate of injection.

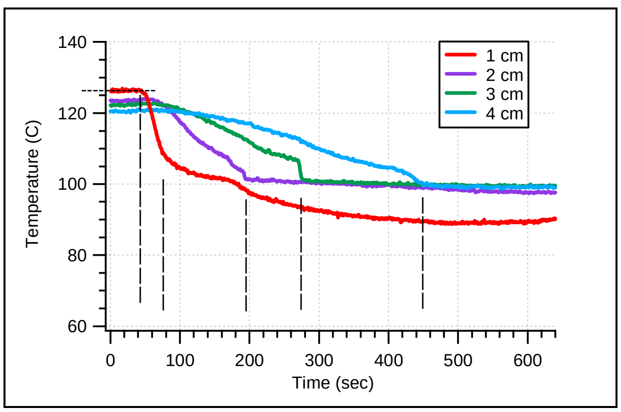

Figure 7: Temperature record from sensors spaced at 1 cm radiating from the injection point. The sharp drop in temperature indicates the temporal advance of the vaporization front.

From Figure 7, the time when the vaporization front progresses past 1 cm from the injection point is estimated to be 75 seconds, as identified by the change in slope of the temperature record. Analysis using the fluid flow simulator MODFLOW (USGS) indicates that a small pore pressure should exist at this location due to the injection pressure, raising the saturated steam temperature to a predicted 103°C. The temperature record from the sensor 1 cm from the injection point therefore indicates that 2-phase flow has *ceased* at a time of about 75 seconds.

Figure 8 shows the observed pressure and self potential at the injection point. For a short period of time immediately following the beginning of injection, the SP record shows an overall large and rapid increase with one large spike of 12 mV that occurs at 30 seconds. This spike is reminiscent of 2-phase SP observations indicated in Figure 4, and is caused by a pressure change of only 1.5 kPa, yielding an Ecc for this event of 800 mV / 0.1MPa. For times greater than about 60 seconds, the SP record exhibits little variation, despite continued increases in injection pressure. From earlier discussions regarding coupling for 2-phase versus single phase flow, we believe that the change in the magnitude of coupling observed at 60 seconds indicates a change from 2-phase to single phase flow conditions at the location of the electrode.

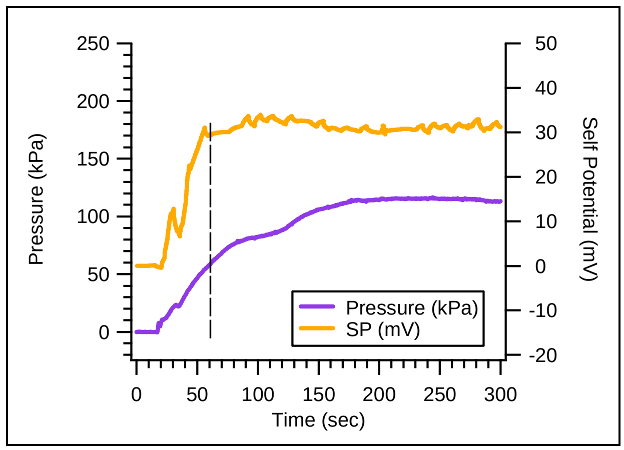

Figure 8: Injection pressure and self potential temporal variation. Large magnitude coupling is observed for times less than 60 seconds, while coupling is decreased for times greater than 60 seconds. The SP spike at 30 sec is reminiscent of 2-phase SP observations from Figure 4, and has an Ecc of 800 mV / 0.1MPa.

In the second test, the Berea sandstone sample was saturated with steam at 145ºC (P_{sat} = 310 kPa). Ambient temperature injectate was applied at a rate of 0.4 ml / sec beginning a time = 17 sec. A plot of the temperature record for this test is shown in Figure 9. Note that the change from 2-phase to single phase flow in this figure is indicated by that time when the temperature at each sensor first drops below the saturated steam temperature of 145ºC. For the nearest sensor located 1 cm from the injection point, that time is observed to be 70 seconds.

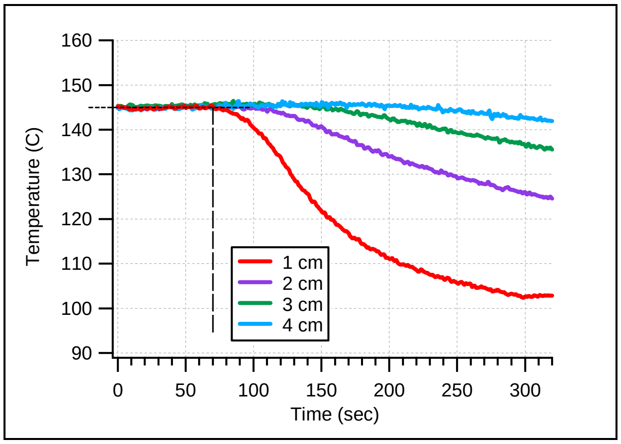

Figure 9: Temperature record for sensors spaced at 1 cm radiating from the injection point for the steam-saturated sample. The deviation from saturation temperature indicates the time when local conditions have changed from 2-phase to single phase fluid flow.

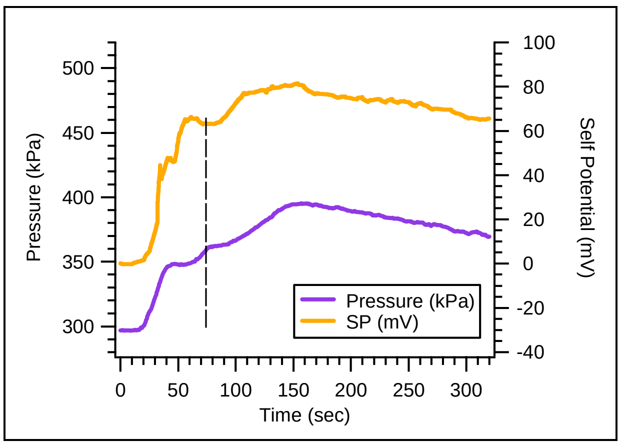

Figure 10: Injection pressure and self potential temporal variation. Large magnitude coupling is observed for times up to 75 seconds, while coupling is decreased for times beyond 75 seconds. The SP spikes at 40 and 60 sec are reminiscent of 2-phase SP observations from Figure 4, and occur independently of injection pressure changes.

In Figure 10, the self potential and injection pressure records are shown. Again, an initial large and rapid jump in self potential is observed for times less than 75 seconds. Thereafter, changes in potential are subdued, and the SP record parallels the injection pressure. The spikes observed in the SP record before 75 seconds do not necessarily correlate to changes in injection pressure, but are instead reminiscent of 2-phase SP observations from Figure 4. We believe that these SP observations indicate that at 75 seconds the state of the pore fluid has changed from 2-phase steam / water to single phase water at the injection point, in approximate agreement with the temperature record form the sensor located at 1 cm.

DISCUSSION

Our observations of increased coupling for 2-phase versus single phase flow are consistent with other author's observations, as discussed previously. In this study we observed that the effective coupling coefficient for 2-phase flow is 2 to 50 times higher than that for single phase flow. This effect is largely attributed to increased bulk resistivity of the sample (see equation 1).

The term "self potential" encompasses 3 phenomena: thermoelectric, electrokinetic, and electrochemical self potentials. In our testing, we predict that the most significant portion of the observed signal arises from electrokinetic phenomena, or streaming potential (Corwin and Hoover, 1979). However, thermoelectric potentials resulting from currents induced by a temperature gradient will certainly have an effect. It is difficult to ascertain whether such thermoelectric potentials will be additive, or act in opposition to electrokinetic signals, but previous work indicates that the magnitude of thermoelectric coupling is small. An average value of the thermoelectric coupling coefficient taken from the review by Corwin and Hoover (1979) is 0.25 mV / ºC. Therefore, in our testing where temperature gradients could reach 50ºC, thermoelectric potentials approaching 15 mV could be expected. This has not been accounted for in our analysis since the sign of these potentials in relation to streaming potentials is thus far unknown. Future work to quantify the effect of thermoelectric potentials is needed.

We propose in this report that self potential observations can indicate the state of the injectate in the vicinity of the electrode. Therefore, placing an electrode at the injection point can indicate when local fluid flow changes from 2-phase liquid / gas to single phase liquid. The results presented here show that this event is indicated by a decrease in coupling between self potential and injection pressure, and a 'smoother' SP signal, lacking the high-frequency voltage oscillations shown to accompany 2-phase flow. As water infiltrates the area displacing steam, local formation resistivity drops significantly, as does observed coupling of self potentials. Furthermore, with water as the pore fluid, we no longer observe high-frequency SP oscillations, which are thought to be related to pressure oscillations caused by a 2-phase fluid / gas mixture flowing through porous media.

In this testing program, self potential observations were accompanied by temperature records from radial sensors that provided the known temporal location of the 2-phase / single phase transition boundary. We have shown correlation between observations from the self potential log at the injection point, and the actual known time of phase transition from the temperature record. For the *hot-dry* sample, the phase transition at the nearest temperature sensor occurred at 75 seconds, while the SP electrode indicated the transition at 60 seconds. For the *steam-saturated* sample, these times were 70 and 75 seconds respectively. Considering that the SP electrode and the first temperature sensor were not in exactly the same location, we feel that these predictions are accurate. The correlation between the self potential log and the temperature record indicates the validity of using SP measurements as an indirect predictor of phase transitions at the injection point.

Residual self potential measurements at the top surface were recorded to simulate a ground surface self potential field survey. These results were meaningful for the experimental verification test conducted at ambient temperature (Figure 6), but were erratic and asymmetric during both of the *hot* tests. Even after these voltages were adjusted to assume an active-ground reference potential measured at the injection point, our results indicate that this type of surface observation cannot be used to predict the state of the local pore fluid at or near the injection point. Further study is required to fully understand this response.

CONCLUSION

We present evidence that self potential observations from the point of water injection into a geothermal reservoir can reveal the state of the injectate at this point, thereby indicating when local fluid flow changes from 2-phase liquid / gas to single phase liquid. Our results show that this change is denoted by a decrease in coupling between self potential and injection pressure, and a 'smoother' self potential signal, lacking the high-frequency voltage oscillations shown to accompany 2-phase flow. Evidence was also presented that surface measurements of self potential will not provide meaningful indications regarding the state of the injectate. Self potential observations were accompanied by temperature records from radial sensors, which provide a record of the 2-phase / single phase transition boundary. Future work aimed at improving the efficiency of injection strategies will include modeling fluid flow at the injection point with coupling to a self potential model.

ACKNOWLEDGEMENTS

This work was supported in part by the U.S. Department of Energy contract no. DE-AC07-991D13727 to the Idaho National Engineering.

REFERENCES

Antraygues, P., and Aubert, M., 1993, Self potential generated by two-phase flow in a porous medium: experimental study and volcanological applications; J. Geophys. Res., 104, 29,485-29,508.

Bogoslovsky, V., and Ogilvy, A., 1970, Application of geophysical methods for studying the technical status of earth dams; Geophysical Prospecting, Vol. 18, 758-773.

Corwin R. F., and Hoover, D. B., 1979, The self potential method in geothermal exploration; Geophysics, 44, no. 2, 226-245.

Fitzgerald, S.D., and Woods, A.W., 1993, The injection of water into and extraction of vapor from a bounded geothermal reservoirs; Proceedings, 18th Stanford Workshop on Geothermal Reservoir Engineering.

Fitzgerald, S.D., and Woods, A.W., 1997, Injection into geothermal systems; Proceedings, 22nd Stanford Workshop on Geothermal Reservoir Engineering.

Fitzgerald, S.D., and Woods, A.W., 1998, Instabilities during liquid migration into superheated geothermal reservoirs; Water Resources Research, Vol. 34, 2,089-2,101.

Ishido, T., and Mizutani, H., 1981, Experimental and theoretical basis of electrokinetic phenomena in rock-water systems and its application to geophysics; J. Geophys. Res., 86, 1763-1775.

Lorne, B., Perrier, F., and Avouac, J., 1999, Streaming potential measurements: 1. Properties of the electrical double layer from crushed rock samples; Journal of Geophysical Research, Vol. 104, B8, 17,857-17,877.

Marsden, S. S., and Tyran, C. K., 1986, The streaming potential generated by flow of wet steam in capillary tubes; Proceedings, 11th Stanford Workshop on Geothermal Reservoir Engineering, 225-229.

Marsden, S. S., and Wheatall, M. W., 1987, Two phase streaming potentials; Proceedings, 12th Stanford Workshop on Geothermal Reservoir Engineering.

Morgan, F. D., Williams, E. R., and Madden, T. R., 1989a, Streaming potential properties of Westerly granite with applications; J. Geophys. Res., 94, 12449-12461.

Morgan, F. D., 1989b, Fundamentals of streaming potentials in geophysics: laboratory methods; Lecture Notes in Earth Sciences, Vol. 27.

Nourbehecht, B., 1963, Irreversible thermodynamics in inhomogeneous media and their applications in certain geoelectric problems; Ph.D. thesis, Mass. Inst. of Tech., 1963.

Overbeek, J. Th. G., 1952, Electrokinetic Phenomena; in Kruyt, H. R., Ed., Colloid science, Volume I, Irreversible systems, 194-245.

Pruess, K., Calore, C., Celati, R., and Wu, Y. S., 1987, An analytical solution for heat transfer at a boiling front moving through a porous medium; Int. J. Heat Mass Transfer, Vol. 30, No. 12, 2,595-2,602.

Sprunt, E. S., Mercer, T. B., and Djabbarah, N. F., 1994, Streaming potential from multiphase flow; Geophysics, 59, 707-711.

Wurmstich, B., and Morgan, F.,1994, Modeling of streaming potential responses caused by oil well pumping; Geophysics, Vol. 59, 46-56.