Quarterly Progress Report

DOE Instrument DE-FG07-97ID13532
Determination of Silica Scale Deposition Rates and Thresholds Applied Toward Protection of Injection Reservoirs

Reporting Period: July 1, 1998 through September 30, 1998

Synopsis

The program objective aims to identify the highest temperature at which silica scale will develop from partially evaporated and significantly cooled geothermal liquid. The approach involves tracking deposition of silica scale by monitoring the apparent electrical conductivity of the geothermal liquid in an isolation chamber. A decrease in apparent conductivity occurs because silica deposited on electrode surfaces is less conductive than the geothermal liquid.

The major technical hurdle is building a conductivity monitoring system that is sensitive enough to distinguish between no silica deposition and almost no silica deposition, while accounting for other factors which also affect conductivity, such as temperature and varying fluid composition.

Activities This Period

Due to the success of the test chamber built to investigate the benefits of directly measuring the temperature of the reactor fluid at a point very near the reactor fluid conductivity probe, a final version of the combined temperature and conductivity probe was built. This allowed the use of the existing chamber, which maintained the advantage of using a fully Teflon lined system.

In addition, the computer data logging system was fine-tuned to achieve the optimum sampling rate for the two temperature signals and two conductivity signals.

The system was tested on August 27, 1998, by Dr. Michels at the Caithness Plant. Also tested at that time was a prototype system to achieve improved temperature control of the liquid in the reactor. The prototype system worked well.

Methodologies for data interpretation were then developed. At the end of the quarter, the only significant equipment-related improvement yet to accomplish concerned finalizing the temperature control system to utilize corrosion resistant materials.
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Dr. Michels authored an in-depth status report on the project dated September 16, 1998. This report is included herein as Attachment 1.

**Findings**

With the data collected at Caithness during August, Dr. Michels proceeded to develop methods for data interpretation. A draft treatise of these methods has been included herein as Attachment 2. In this evaluation, it is demonstrated that the system is indeed showing favorable electrode responses due to changed physical aspects, changes which are consistent with scale formation.

**Schedule**

Dr. Michels is traveling to Costa Rica in early November. It is anticipated that data can be analyzed by early December, and the final report will be available for distribution by the end of the year.

**Budget**

As of September 30, 1998, Don Michels Associates invoiced the project $45,750 for labor. Dr. Michels has $12,450 left in the budget to complete the experiments in Costa Rica, and to co-author the final report.

As of September 30, 1998, Geothermal Development Associates invoiced the project $34,330. The unexpected difficulties with signal conditioning have required a substantial number of hours from our electrical engineer and technician. GDA has $14,195 left in the budget to provide project management and co-author the final report.

The original budget for equipment, materials, chemical analyses, and outside services was $25,180. At the end of the third quarter of 1998, $7,682 had been expended in these categories. DMA and GDA have confidence that the existing equipment will prove suitable.

In summary, $91,745 has been spent, representing about 67% of the total funded by the DOE. Table 1 has been included detailing expenditures and budget amounts for the various categories.

**Summary**

In this period, the temperature and conductivity probes for the chamber fluid were combined into a single probe. A data logger was added to facilitate statistical analysis of the data. Final field testing in Nevada successfully demonstrated that the system can detect changes in conductivity consistent with scale formation. Methodologies to evaluate the data were developed. The system will be transported to the Miravalles geothermal field in Costa
Rita in November to determine the lowest practical temperature to which separated brine can be cooled without forming detrimental silica scale.

Respectfully submitted,
GEOTHERMAL DEVELOPMENT ASSOCIATES

[Signature]
G. Martin Booth, III    Date
President
INTRODUCTION

This status report concerns three parts of the project; equipment construction, data acquisition in the field, and data reduction.

One principle objective of this project aims to identify the highest temperature at which silica scale will deposit in a field situation from partly flashed geothermal liquid, which may be still super-heated. This serves two practical issues, designating engineering criteria for designing a bottoming cycle for additional energy recovery from the liquid and protecting the fluid disposal system from silica scale deposition.

The novel approach developed here uses the apparent electrical conductivity of a captured sample of geothermal liquid as an indirect signal for active deposition of silica on a test piece immersed in the geothermal liquid. Specifically, the apparent conductivity of a liquid depends jointly on the dissolved ions and the physical characteristics of the electrode used to measure conductivity. If silica scale deposits on the electrode, a change in apparent conductivity would result, even if no changes occurred for the intrinsic conductivity of the liquid. Thus, the field objectives aim at placing a conductivity electrode in an environment where silica may deposit on it while the electrode system is monitoring the apparent conductivity for changes that could be assigned to silica deposition.

Important Technical Issues:

In the field situation several factors must be accounted for with good precision in order to unambiguously assign the conductivity changes to silica deposition. Foremost among these is the strong dependence of conductivity on temperature. Temperature in the vicinity of the conductivity electrode must be monitored with high precision. Complicating this task, the composition and temperature of geothermal liquid moving through a pipeline is not constant, hence a sequence of captured samples involves a random component of variability which must be accounted for. A means is needed to characterize each sample. In this case, continuous monitoring of temperature and conductivity for pipeline liquid enables each captured sample to be characterized, at least in a relative way as regards their conductivity. That is, overall data collection involves four channels, two each for temperature and conductivity in the captured sample and in a sidestream from the pipeline. This is a change from the original
proposal which presumed that the geothermal pipeline conditions would be sufficiently stable that measurements on the captured sample alone would be sufficient.

The main objective also requires that good control be established for the temperature of the captured sample. This incubation temperature is the experimental control which enables silica deposition to proceed. A series of experimental runs at various temperatures are required to define the highest temperature at which silica can form. Lastly, data interpretation must be quite precise because it is intended to determine conditions for threshold deposition—conditions for the very slightest amounts of silica deposition. That is, this procedure operates at the edge of technical feasibility to recognize and quantify silica deposition. Accordingly, data collection is required to have excellent precision and the methods of data reduction must yield excellent resolution with a quantifiable statistical precision for results.

EQUIPMENT
The equipment system has evolved somewhat during the course of development. Currently it consists of:

- A Teflon-lined probe assembly that passes through an access valve on the geothermal pipeline in order to bring fresh, uncontaminated geothermal liquid to the reactor with a sidestream to the temperature control unit.
- Conductivity electrodes and thermometers to monitor the accessed liquid in the reactor and in the sidestream.
- An electrical system to stimulate the conductivity electrode and monitor the electrical resistivity of liquid at the electrode.
- A jacketed reactor wherein temperature and conductivity of a captured sample are monitored in a Teflon-lined space and temperature is controlled.
- A system for controlling temperature of the liquid which controls jacket temperature around the reactor.
- An electronic system to convert four electrode voltages (two each for conductivity and temperature) to digital values that are input to a computer software program.
- A computer software system to receive the digital electronic output, store results, and display data in a computer.
- Portable (laptop) computers to run software systems for data acquisition, display, and interpretation.
- Procedures for interpreting data and checking its validity and precision in regard to silica scale detection.

Conductivity-Temperature Electrode:
The current conductivity electrode incorporates a platinum resistance thermometer (PRT) as one element. The electrode outer casings are stainless steel tubes (1/4 inch OD) which pass through fittings that hold the electrode in place (one in the reactor, another in the fluid access assembly), seal against pressure and liquid loss, and serve as
the electrical (AC) source element for the conductivity measurement. The PRT is 1/8 inch OD and fits inside (coaxial with) the stainless tube. PRT and stainless tube are electrically insulated by temperature resistant rubber cast in the annulus around the PRT. The flat end of the stainless shell of the PRT serves also as the sensing part of the conductivity electrode system. An alternative electrode has a tip (1/4 inch OD) made of carbon steel of the same composition as common geothermal pipelines. This enables temperature sensing and conductivity sensing to occur at nearly the same physical point.

The reactor is lined with a Teflon tubing 1/4 inch ID so the stainless tube fits closely. Thus, the active electrode surfaces are the co-planar ends of the PRT and stainless tubing. These are the only exposed metal surfaces in the reactor, all others are of Teflon, so that silica deposition, if it occurs, will be disposed to occur on the electrode face. All cylindrical surfaces of the electrode are insulated or shielded from the geothermal liquid.

The proximity of conductivity and temperature sensors provides negligible time lag, a few seconds, for measured temperature to stabilize and coordinate with measured conductivity upon a change in temperature of the electrode face. This is faster than the response of internal reactor temperature to changed jacket fluid temperature, which involves nominally three minutes of time. Since reaction times involved with the silica deposition are several tens of minutes, this relatively rapid response of the electrode, PRT, and temperature control system are most satisfactory for this monitoring method.

Temperature Control:

The jacket temperature control system uses a sidestream of liquid from the geothermal pipeline. Using geothermal liquid provides a convenient and stable method to control experimental temperature of the reactor. The sidestream can be passed directly through the jacket, to yield a maximum reactor temperature, or selectively cooled before passing into the jacket. The system has multiple sub-loops of stainless tubing that dip into a water bath to incrementally cool the sidestream water. Jacket temperature is controlled jointly by the number of sub-loops activated and the flow rate through them. Temperature control to several tens of degrees below pipeline temperature is convenient and appropriate. Stability of controlled temperature is better than ±1°C. With this system, water discharged from the jacket, sometimes still superheated with steam flashing, emerges in the water bath below liquid level so that no splashing or uncontrolled discharge occurs. Overflow, nominally 20 liters per hour, or less, is collected for disposal. Temperature control below atmospheric boiling temperature is possible with this system. Even 60°C is accessible in the reactor due to substantial vapor and heat losses from the open water bath.

Data Logging:

The electronic data logging system continuously monitors the four probes (two each for temperature and conductivity) and reports values for each to the computer system once per second. These values are plotted on the computer screen in real time. Real time computer display shows the most recent 30 minutes of conductivity and temperature (four channels) plotted versus minutes. Current numerical values are also shown alongside the analog display. This display provides the main basis to monitor data gathering.
Displayed data are collected and averaged over 10-second intervals to yield values that are stored for later use in other data reduction programs. Since single runs for scale forming tests involve periods from one-half to three hours long, six data averages per minute yield more than 100 and up to 1000 data points for interpretation. In practice, selected sequences of 60 to 100 data are used to quantify results, as described later.

Operationally, the signal which indicates silica deposition is a decrease in apparent conductivity in the reactor that is not due to a decrease in reactor temperature, purposeful or inadvertent. Although significant effects can be noticed via the analog display on the computer screen, precise analysis and detection of subtle effects requires careful data reduction after the field experiment is concluded.

Data Interpretation:

Final data analysis involves a fundamental relationship between absolute temperature and conductivity:

$$\log(C) = a + b/T_{\text{abc}}$$

Wherein values of a and b depend jointly on the ionic content of the liquid and the physical features of the electrode. The measured values of C and T (six per minute) provide for computing values of a and b, via ordinary linear regression, which also yields important statistical values. In principle, a and b can be determined to any desired precision by including a larger number of data pairs and/or operating over a larger range of temperature.

Because deposition of silica does not affect the ionic content of geothermal water, changes in computed values of a and b over time for a single filling of the reactor indicate a change in some physical aspect of the electrode, presumably, fouling by deposited silica. Thus, Eq. (1) is applied to sequential segments of reactor data to detect trends or increments of change. Correspondingly, the reactor is operated in the field so as to yield data that optimize the data interpretation step. The intent is to maximize precision of computed numerical values (estimates) for a and b in order to more securely (statistical sense) identify the presence or absence of trends or incremental changes.

Although the experimental determination of silica deposition is, in principle, an experiment at "constant" temperature, the values of a and b are more accurately determined if the conductivity is monitored over a range of temperature. An appropriate compromise is achieved by periodically pulsing the reactor with hotter (or cooler) jacket fluid, in order to momentarily shift the temperature about 10 degrees C. Such shifts involve only 5 to 10 minutes of time which is negligible for experiments which involve several tens of minutes of time. The computable values for a and b over successive temperature pulses can provide a sensitive indication of trends, qua silica deposition, for a single filling of the reactor.

When silica has deposited on the electrode then liquid in the reactor becomes depleted so trends in values for a and b cease. That is, trends becomes simple increments of change in values for a and b. To further confirm that silica has deposited, the reactor liquid can be replaced by fresh liquid and a repeat experiment performed. An expectation is that additional silica will deposit on top of material which affected the electrode in the previous run, extending the changes in values for a and b. Whether or
not the new reactor filling is conductively similar to the previous liquid can be
determined by the monitoring results for the sidestream liquid, via the other two data
channels. This avoids an ambiguity about possible causes of apparent trends or
incremental changes. Because multiple runs in the reactor can be “unlimited” the
precision of the experimental determination of \( a \) and \( b \) is limited only by time and
patience for monitoring refillings of the reactor.

Cumulative Progress:

All essential features of this silica deposition detection method have been demonstrated
in field situations at a Nevada geothermal power plant site:

- The Teflon-lined system for tapping into a geothermal pipeline and containing
  liquid in a Teflon-lined reactor was demonstrated in April 1998.
- Susceptibility of the stainless electrode to receive silica deposition was demonstrated
  in April 1998.
- During July and August 1998, methods were developed and demonstrated for
  electronic data acquisition from the reactor and sidestream system.
- Temperature control of the reactor jacket was demonstrated in August 1998.
- During September 1998, methods for data reduction and interpretation were
devolved.

Near-Term Objectives

Although the complete physical system has been constructed and demonstrated, some
refinements are necessary and planned, before the system is taken to new field sites for
serious work. These adjustments are planned for September and October of 1998.
Specifically:

- The electronic data acquisition system requires boxing so it will be secure during air
  transport, as well as secure and convenient to set up in the field.
- The temperature control system will be rebuilt to an all stainless steel system with
  more sub-loops for cooling. The new system will be configured for easy air
  transport.
- Spare electrodes and other key items need to be fabricated, or purchased, as
  appropriate, prior to field studies.
- Electrode performance will be calibrated at the lab bench so that results from this
  non-standard configuration can be related to conventionally measured
  conductivities. This will also provide a basis for checking of electrode degradation
  or other effects.

Successful completion of these items will demonstrate a complete, useable, air
transportable system. Thereupon, a schedule for field studies in Costa Rica can be set.
CONDUCTIVITY-TEMPERATURE TESTING
FOR
SILICA SCALE RATES AND THRESHOLDS

METHODS FOR DATA INTERPRETATION

EXAMPLE:
CAITHNESS-RENO 27Aug98

INTRODUCTION:
Detection of silica scale deposition via conductivity measurement requires that:
• an electrode measures an apparent conductivity of the liquid
• silica deposits on and fouls an electrode surface, altering the apparent conductivity
• effects of temperature variations on measured conductivity can be accounted for
• sequential increments of liquid may be introduced to the electrode to yield
  successive silica deposits and successive fouling effects
• different intrinsic conductivities of these successive liquids can be accounted for
This note describes how field data can be analyzed in order to accomplish those things and presents an estimate of the sensitivity for the method.

DATA COLLECTION
On 27Aug98 a set of data was collected from the injection pipeline at the Caithness geothermal plant, Reno, Nevada. The set involves about 180 minutes of continuous record, 6 data points per minute, 1086 data sets. Each data row (set) consists of five elements:
• elapsed minutes
• reactor conductivity (C_R)
• reactor temperature (T_R)
• cross temperature (T_C)
• cross conductivity (C_C)

Reactor refers to the Teflon-lined chamber that holds a sample of fresh, hot geothermal liquid. Reactor temperature is controlled by a flow of tempered (cooler) geothermal liquid through a jacket around the reactor. It is intended that silica deposition will occur on the conductivity electrode which forms one end of the chamber and provides the only metallic surface available in the reactor. A Teflon-lined probe that is an integral part of the reactor penetrates the pipeline access valve to reach moving pipeline liquid. From time to time, liquid in the reactor is displaced by fresh liquid from the pipeline access.

Cross refers to a fitting between the reactor and the geothermal pipeline. Liquid which controls reactor temperature passes through this fitting and represents a continuous
sampling of pipeline liquid. Measurements of conductivity and temperature inside the cross effectively monitor this side stream of pipeline liquid. Temperature-conductivity indicated by monitoring the cross at the time of displacement characterizes the new liquid charge to the reactor.

Liquid moves from the cross through a heat exchange unit on its way to the jacket of the reactor. Thus, $T_R$ can be varied over a considerable range. The amount of heat lost in the heat exchanger can be varied by selecting 0, 1, or 2 heat-exchange loops and by changing the liquid flow rate through them. In this experiment, the rate was not changed, but the number of cooling loops was changed several times. Changes in $C_R$ associated with changes of $T_R$ are an important feature of this report.

Conductivity measurements in the cross and the reactor are not made with calibrated electrodes. For the same liquid, $C_C$ is numerically about half that for $C_R$, which relates to the different physical aspects for the electrodes, not to the electrical properties of the liquids. Thus, direct comparisons of electrode readings are not appropriate. However, the relative values or relative shifts in readings vis-a-vis the two electrodes applied to similar liquid samples can be an appropriate comparison.

**DATA**

Results are shown in Figures 1A through 1D; respectively, $T_C$, $C_C$, $T_R$, and $C_R$. Fig. 1E represents a version of $C_R$ that has been adjusted, referencing apparent conductivity ($C_{Ref}$) to a convenient temperature, 100°C.

Variations in $T_C$ and $C_C$ represent instability of the geothermal liquid which is not controlled during the experiment. Fig. 1A shows that $T_C$ varied irregularly over a range of about 3.5°C during the 180 minutes of observation. Fluctuations of $T_C$ involve variable time periods with a random aspect that appears fractal. Although short-period trends are common, they follow no obvious pattern.

Fig. 1B shows $C_C$ to have intervals with relatively small oscillation around a central value followed by prompt changes to intervals with different $C_C$ values but similar oscillations. There does not appear to be any correlation between these shifts in $C_C$ and trends for $T_C$. It is presumed that changes in $T_C$ and $C_C$ reflect operations in the power plant related to changed settings within the steam control systems and irregular dosing to liquid in the pipeline, e.g. additives at the cooling tower or other sub-systems. A component of shifts in $T_C$ or $C_C$ may relate to operations with geothermal production wells.

Figures 1C and 1D show that $T_R$ and $C_R$ are highly correlated. Only a few details in $T_R$ (Fig. 1C) do not have a counterpart in Fig. 1D. *[The first 15 minutes of the plots represent fiddling with the system and have no other interpretation.]* Data traces for $T_R$ and $C_R$ are punctuated with seven reversing figures which represent refilling of the reactor chamber with fresh liquid from the pipeline. These occur at about minutes 3, 18, 49, 66, 108, 130, and 157.
The trace in the vicinity of minutes 48-50 is representative. When the reactor is re-filled, liquid which had been held at jacket temperature is first displaced by cool liquid that was stagnant in the tubing between the reactor and the access point on the pipeline; hence the plunge in \( T_R \) and \( C_R \). The first reversal, \( R_1 \) in Fig. 1C represents fresh, hot liquid from the pipeline reaching the electrode in the reactor. The second reversal, \( R_2 \), represents the moment that the reactor discharge valve was closed to capture the fresh liquid sample. The first two re-fillings, at minutes 3 and 18, have weakly developed \( R_2 \) reversals. This is because jacket water was moving directly from the cross to the jacket without losing heat via the cooling loops.

After fresh liquid is captured, measured \( T_R \) trends toward the temperature held by the jacket. The measured response of \( C_R \) precedes the \( T_R \) response by about 10 seconds because the temperature-sensing resistor of the PRT is located a few millimeters away from the electrode surface which senses conductivity.

The first cooling curve, segment A in Fig. 1D, represents the initial stabilization of reactor temperature upon activating a single cooling loop of the temperature control system. Similarly, interval B represents activating the second cooling loop (series arrangement) and interval C represents deactivation of the first cooling loop.

The loops are approximately equal in length, hence the stable temperatures for intervals A and C are about equal, 96-97°C. However, it is clear that the cooling effect of two loops is much less than twice the effect of a single loop. The no-loop temperature, prior to interval A, is about 123°C, \( T_A \approx 96° \), \( T_B \approx 88° \), \( T_C \approx 97° \). One loop shifts the reactor chamber \( \approx 27° \) while the second loop shifts temperature only an additional 8°C. These results provide a basis for designing a new 3-loop system to yield more convenient temperature increments.

The temperature increments among intervals A, B, and C were obtained with a constant liquid through-put rate, stabilized by a small orifice in the extreme downstream end of the system. Jacket through-put during the experiment was about 20 liters per hour (0.08 gallons/minute). Using an alternative orifice to regulate a different through-put rate will change the heat balance in the loop and water bath system so that different temperature increments would be obtained. When a very low rate orifice is used, considerable cooling of the liquid occurs in the tubing between the pipeline, through the cross, and prior to entering the cooling loops, thus providing another means to obtain lower reactor temperatures.

When the pipeline temperature shifts during a run it can be sensed as shifts in \( T_C \) with smaller shifts (about half as large, numerically) in \( T_R \), which correlate with shifts in measured \( C_R \). These relationships can be seen most clearly in the Figs. 1A and 1C in the vicinity of minutes 120 and 140, where \( T_C \) values show sudden decreases. Since these fluctuations cannot be avoided experimentally, it is necessary to accommodate them in the data reduction stage.
DATA REDUCTION

Comparison of Figs. 1C and 1D shows that $T_R$ and $C_R$ are highly correlated. The applicable mathematical function is:

$$\log C = a + \frac{b}{T_{abs}}$$

As an example, using temperature as the independent variable (x-axis) in a linear least squares regression, the 41 data pairs in the A-interval of Fig. 1C yield $a=4.523$ and $b=-412$ with $r^2=0.9972$.

The $b$-value (slope=temperature coefficient) depends on how the population of dissolved ions with their hydration shells move within the viscous liquid wherein the viscosity also changes with temperature. The $a$-value, intercept, is mainly associated with the physical aspects of the electrode; its physical dimensions, the presence of fouling, and electrical driving forces. Importantly, the least squares method, through $r^2$, yields a measure for the relative statistical certainty of the computed values for $a$ and $b$.

Although values for $a$ and $b$ in a specific situation depend on several factors the empirical precision of (1) is high. Using handbook values for equivalent conductivity over a range of temperature, $r^2$ values of 0.999+ are obtained for a considerable range of ion molarities that brackets the concentrations of most geothermal resources. Thus, for purposes of this application Eq. (1) will be considered exact and the differences between $r^2=unity$ and computed values for $r^2$ will be assigned to measurement uncertainty and/or confounding due to real changes in the temperature-conductivity relationship during a time interval over which data are selected for a least squares regression.

APPLICATION OF Eq. (1)

Figure 2 contains a set of plots based on Eq. (1); data for the lettered segments (A through O of Fig. 1D) have been plotted in a field of log Conductivity versus reciprocal Kelvin temperatures. Except for certain transition intervals, the plotted data are the experimental manifestations of Eq. (1). Values of $a$, $b$, and $r^2$ for all lettered intervals are listed in Table 1, corresponding to the plots in Fig.2 and Fig. 1D. In Fig. 2, all plotted segments have similar slopes but over time the successive data sets tend to plot lower in the figure. That is, apparent conductivities progressively diminish in that $a$-values (intercepts) are less stable than $b$-values. Ten intervals have $r^2$ values of 0.99 or greater and their average slope ($b$-value) is 461 with a standard deviation of 39, about 8.5%.

CONDUCTIVITY AT A REFERENCE TEMPERATURE

A useful alternative to the $a$-values (intercepts) can be obtained by referencing the measured conductivity to a single temperature, such as 100°C. In effect, this displaces the concept of intercept and its involvement with the electrode's physical aspects to a position in the central part of the data field. It is obtained by using computed $b$-values in Equation (2), an inverted form of Eq. (1).

$$C_{Ref} = \exp(\log C_R + b(1/373.15 -1/(T_R+273.15)))$$
Values of $C_{Ref}$ for intervals A through O are given in Table 1. They correspond to the (computed) intersections, in Fig. 2, of the plotted data sets with the vertical line segment at $1000/K = 2.68$. For the ten plots with $r \geq .99$, the average $C_{Ref}$ is 2562 with a standard deviation of 62, about 2.4%.

This concept can be extended to continuous monitoring of reactor conductivity over the entire 185 minutes of record. Because all intervals yielded similar slopes it is reasonable to use an average slope value to characterize the electrode response to the conductive properties of the liquid. Ten intervals showed $r^2 > 0.99$ and the average $b$-value for those is $-466$ with standard deviation of 38, about ±8%. Using Eq. (2) with $b = -466$ and sequential pairs of $C_R$ and $T_R$ values over the whole data set yields a continuous record of $C_{Ref}$ which is plotted in Fig. 1E.

Ideally, this adjustment would compensate the conductivity measurements for temperature fluctuations. Comparison of Fig. 1D with Fig. 1E shows that a considerable effect of this sort has been obtained. Thus, the plot of Fig. 1E may be considered to mainly represent apparent conductivity as affected by physical aspects of the electrode. It remains to connect the progressive downward changes of apparent conductivity to causes which may include the effects of silica deposition.

**PUTTING ORDER INTO THE $C_{Ref}$ SEQUENCE**

Since the reactor liquid was recharged several times, the lettered intervals of Fig. 1 have natural groupings, viz., ABC, DE, FGH, IJ, KLM, and NO. Each group was involved with a single filling of the reactor so the electrical properties of the liquid may be expected to differ negligibly, if at all, during the temperature changes which define the intervals within groups.

However, Fig. 1B shows that the pipeline liquid did not change conductively ($C_C$) during the time that reactor recharges were made for intervals ABC, DE, and FGH. Thus, ABC, DE, and FGH may be treated as having the same parent liquid. Accordingly, shifts in conductivity during the combined intervals, ABC-DE-FGH, cannot reasonably be assigned to changed electrical properties of the liquids used to recharge the reactor.

Based on Fig. 1B, a different parent liquid was involved with re-charging the reactor for intervals IJ and KLM. Furthermore, the parent liquid for interval NO is clearly different from the IJ-KLM parent and possibly different from the parent for ABC-etc.

Intervals IJ and KLM occurred during the time period 103 through 138 minutes when $C_C$ values were relatively elevated. Thus, one should expect a corresponding contrast (increase) in $C_{Ref}$ to occur between the intervals FGH and IJ. This is shown sharply in Fig. 2 after the doubly reversing trace for refilling the reactor at about minute 108. Similarly, the lower value for $C_{Ref}$ after the refilling at minute 157 corresponds to the lower conductivity liquid that was moving through the pipeline between minutes 140 and 164, indicated in Fig. 1B.
The proportionality of the above shifts of $C_{\text{Ref}}$ in Fig. 2 to the changes associated with $C_C$ in Fig. 1B indicate that the reactor electrode is responding favorably. Thus, the progressive downward trends for $C_{\text{Ref}}$ during intervals F, IJ, and KL must be assignable to changed physical aspects of the electrode. The estimates for $C_{\text{Ref}}$ in Table 1 follow approximately this pattern, except that $C_{\text{Ref}}$ values based on intervals with $r^2<0.9$ tend to be out of pattern, perhaps because of poorer mathematical resolution, not real differences.

**TRANSITIONS IN $C_{\text{Ref}}$ VALUES**

Shifts in conductivity of pipeline liquid are superimposed on $C_R$ values independently of temperature effects when the reactor is re-charged. However, Fig. 1E shows that at other times temperature-compensated $C_R$ values (qua $C_{\text{Ref}}$) change while a single charge of liquid is in the reactor. The most prominent shift in $C_{\text{Ref}}$ values occurs between intervals E and H which involve the same liquid in the reactor. Their $C_{\text{Ref}}$ values are 2633 and 2457. Their difference is about 6.8% of the average value for $C_{\text{Ref}}$. This relative range represents the scope of variations in $C_{\text{Ref}}$ wherein data interpretations will be made. It shows the demands to be placed on precision measurements in order to obtain useful results.

Most of the contrast between $C_{\text{Ref}}$ for intervals E and H developed between intervals F and G, which is emphasized in Fig. 2. The F-G transition involved about 12 minutes of time, which is longer than the time periods assigned to letter intervals F and G.

Temperature change during the F-G transition was a small, irregular increase, from 117.4 to 119.3°C, about 0.17 deg/min. Such a temperature increase would imply a conductivity increase of about 3 units per minute. Instead, conductivity diminished 87 units, about 8 units per minute.

The F-G transition is shown enlarged in Figure 3, along with five other transitions, A-B, B-C, D-E, J, and L. All except the D-E transition involve decreasing $C_{\text{Ref}}$ during a time period when temperature change was negligible. A listing of time durations for letter intervals and transitions is given in Table 2. The six downward transitions involved an average change in conductivity of 2.24 percent.

These are the kind of conductivity signals to be expected if silica deposition fouls the electrode surface;

- occurs when temperature is relatively steady
- involves a finite interval of time
- yields a diminished apparent conductivity.

The D-E transition was also unusual in that most of the change in $C_{\text{Ref}}$ occurred during the last, small part of the interval. It cannot be considered as a possible indicator of silica deposition. Plausibly, it might represent some physical change in the integrity of a (postulated) silica layer on the electrode.
CONDUCTIVITY-TEMPERATURE TEST "A" 27Aug98
at CAITHNESS -- RENO

FIGURE 1: DATA versus TIME

A
CROSS TEMPERATURE

B
CROSS CONDUCTIVITY

C
REACTOR TEMPERATURE

D
REACTOR CONDUCTIVITY

E
REACTOR CONDUCTIVITY

Elapsed Minutes
TEMPERATURE–CONDUCTIVITY TESTS
CAITHNESS–RENO -- 27Aug98

FIGURE 2: T–C LINEARITY

100 C Reference

F–G Trans
A–B Trans
B–C Trans
J Trans
L Trans
### TABLE 1: RESULTS OF LINEAR FITS TO DATA IN LETTER INTERVALS

<table>
<thead>
<tr>
<th>Letter</th>
<th>$a$</th>
<th>$r^2$</th>
<th>$n$</th>
<th>$b$</th>
<th>$\log_{10}a$</th>
<th>$C_{bas}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>4.62</td>
<td>0.9987</td>
<td>28</td>
<td>-456</td>
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<td>2484</td>
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<td>4.62</td>
<td>0.9986</td>
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<td>18</td>
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<tr>
<td>A</td>
<td>4.49</td>
<td>0.9975</td>
<td>22</td>
<td>-401</td>
<td>3.420</td>
<td>2629</td>
</tr>
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<td>0.9957</td>
<td>25</td>
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<td>3.414</td>
<td>2595</td>
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<td>0.9916</td>
<td>18</td>
<td>-401</td>
<td>3.415</td>
<td>2598</td>
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<td>0.9914</td>
<td>17</td>
<td>-533</td>
<td>3.420</td>
<td>2628</td>
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<tr>
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<td>0.9900</td>
<td>23</td>
<td>-469</td>
<td>3.390</td>
<td>2457</td>
</tr>
<tr>
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<td>4.98</td>
<td>0.9583</td>
<td>18</td>
<td>-589</td>
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<tr>
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<td>0.8675</td>
<td>71</td>
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<td>2397</td>
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<tr>
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<td>0.7400</td>
<td>66</td>
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<td>95</td>
<td>-910</td>
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<tr>
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<td>0.5525</td>
<td>82</td>
<td>-1030</td>
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</tr>
</tbody>
</table>

Avg $r^2 > 0.99$ = 4.65, 0.9950

SD: $r^2 > 0.99$ = 0.10

### TABLE 2: TIME LENGTHS FOR LETTER INTERVALS AND TRANSITIONS

<table>
<thead>
<tr>
<th>Minutes</th>
<th>Duration</th>
<th>Int</th>
<th>Trans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>End</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>21.1</td>
<td>26.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Trans</td>
<td>26.9</td>
<td>30.9</td>
<td>4.0</td>
</tr>
<tr>
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<td>30.9</td>
<td>33.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Trans</td>
<td>33.6</td>
<td>41.4</td>
<td>7.8</td>
</tr>
<tr>
<td>C</td>
<td>41.4</td>
<td>45.6</td>
<td>4.2</td>
</tr>
<tr>
<td>D</td>
<td>49.9</td>
<td>52.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Trans</td>
<td>52.9</td>
<td>60.7</td>
<td>7.8</td>
</tr>
<tr>
<td>E</td>
<td>60.7</td>
<td>64.2</td>
<td>3.5</td>
</tr>
<tr>
<td>F</td>
<td>69.7</td>
<td>72.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Trans</td>
<td>72.7</td>
<td>84.3</td>
<td>11.6</td>
</tr>
<tr>
<td>G</td>
<td>84.3</td>
<td>89.0</td>
<td>4.7</td>
</tr>
<tr>
<td>T</td>
<td>89.0</td>
<td>95.2</td>
<td>6.2</td>
</tr>
<tr>
<td>H</td>
<td>95.2</td>
<td>99.0</td>
<td>3.8</td>
</tr>
<tr>
<td>I</td>
<td>110.3</td>
<td>115.0</td>
<td>4.7</td>
</tr>
<tr>
<td>J-trans</td>
<td>115.0</td>
<td>129.2</td>
<td>14.2</td>
</tr>
<tr>
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<td>130.9</td>
<td>133.8</td>
<td>2.9</td>
</tr>
<tr>
<td>L-trans</td>
<td>133.8</td>
<td>150.7</td>
<td>16.8</td>
</tr>
<tr>
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<td>150.7</td>
<td>156.4</td>
<td>5.7</td>
</tr>
<tr>
<td>N</td>
<td>159.2</td>
<td>170.6</td>
<td>11.5</td>
</tr>
<tr>
<td>O</td>
<td>170.8</td>
<td>182.9</td>
<td>12.1</td>
</tr>
</tbody>
</table>

Avg | 5.2 | 9.8 |
Sum | 67.3 | 68.5 |
Avg except NO | 4.0 |

GEOTHERMAL DEVELOPMENT ASSOCIATES -- RENO, NEVADA
DON MICHELS ASSOCIATES -- MISSOULA, MONTANA
TEMPERATURE–CONDUCTIVITY TESTS
CAITHNESS–RENO -- 27Aug98

FIGURE 3: TRANSITION DETAILS
Table 1. Budget Summary by Task  
Period Ending September 30, 1998

<table>
<thead>
<tr>
<th>Section of Form 424A</th>
<th>6a, 6b</th>
<th>6a, 6b</th>
<th>6f</th>
<th>6d,6e</th>
<th>6f</th>
<th>6c</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Description</td>
<td>GDA</td>
<td>DMA</td>
<td>Chemical Analysis</td>
<td>Components &amp; Materials</td>
<td>Machine Shop</td>
</tr>
<tr>
<td>1</td>
<td>Project Management</td>
<td>25,497</td>
<td>32,400</td>
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<td></td>
</tr>
<tr>
<td>2</td>
<td>Finalize Design &amp; Procure Components</td>
<td>7,958</td>
<td>4,000</td>
<td>6,527</td>
<td>15,980</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>Build and Assemble Components</td>
<td>11,980</td>
<td>6,300</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Field Test in Nevada</td>
<td>8,833</td>
<td>4,875</td>
<td>23,312</td>
<td>11,900</td>
<td>239</td>
</tr>
<tr>
<td>5</td>
<td>Field Experiments in Costa Rica</td>
<td>21,000</td>
<td>6,200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Data Reduction and Reporting</td>
<td>11,250</td>
<td>2,500</td>
<td>15,000</td>
<td></td>
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<tr>
<td>Total</td>
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<td>$ 48,525</td>
<td>$ 45,750</td>
<td>$ 58,200</td>
<td>$ 239</td>
<td>$ 7,700</td>
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</table>

Total DOE Funding (Budget) $ 136,150

Total to date (Actual) $ 91,745

Balance remaining $ 44,405