DOE/ID/13532

DETERMINATION OF SILICA SCALE DEPOSITION RATES AND THRESHOLDS APPLIED TOWARD PROTECTION OF INJECTION RESERVOIRS

SUMMARY PROJECT REPORT

Prepared For

U.S. Department of Energy
Project: DE-FG07-97ID13532

Prepared By

GEOTHERMAL DEVELOPMENT ASSOCIATES
251 Ralston Street
Reno, Nevada 89503
Telephone: 775-322-0938
Facsimile: 775-322-1320

and

DON MICHELS ASSOCIATES
17 September Drive
Missoula, MT 59807
Telephone: 406-728-2576
Facsimile: 506-721-7671

July, 1999

DISCLAIMER

SUMMARY PROJECT REPORT

TABLE OF CONTENTS

FIGURES

TABLES

APPENDICES

Appendix A In-Depth Status Report of September 16, 1998: *Silica Scale Deposition Rates and Threasholds*

Appendix B In-Progress Development of Methods of Interpretation: *Conductivity-Temperature Testing for Silica Scale Rates and Thresholds–Methods for Data Interpretation, Example: Caithness-Reno 27Aug98*

Appendix C *Miravalles Project–Summary of Activities in Costa Rica, Nov 29 thru Dec 16, 1998*

Appendix D GRC Poster Session Paper: *Using Apparent Electrical Conductivity to Detect Silica Deposition from Hot Geothermal Liquid,* by Donald Michels, David Mendive and Lawrence Green

- Figure D1 Combination Electrode Senses Temperature and Conductivity
- Figure D2 Reactor and T-C Electrode Setup
- Figure D3 Example Data: Four Simultaneous Channels
- Figure D4 Analysis of logAC versus 1/T
- Figure D5 Electron micrograph of silica; *in situ* on a conductivity electrode
- Figure D6 EDAX Spectrum for Fig. 5 showing silica dominance

Appendix E Instrumentation

- Figure E1 Intrumentation Block Diagram
- Figure E2 Data Acquisition and Analysis: Data Flow Block Diagram
- Figure E3 General Purpose Conductivity Transducer Block Diagram

Appendix F Letter dated 16 July, 1999 to Dr. Alfredo Mainieri Protti, Instituto Costarricense De Electricidad.

DETERMINATION OF SILICA SCALE DEPOSITION RATES AND THRESHOLDS APPLIED TOWARD PROTECTION OF INJECTION RESERVOIRS

SUMMARY PROJECT REPORT

1.0 INTRODUCTION

Geothermal Development Associates (GDA), in cooperation with Don Michels Associates (DMA) and with partial support by Instituto Costarricense de Electricidad (ICE), the Costa Rican government-owned utility company, carried out a program to quantify certain aspects of silica scaling deposition processes at the Miravalles Geothermal Field, Costa Rica.

Principal funding to support this program was provided by the US Department of Energy due to the potential to upgrade the technology involved with silica control, and because the resulting improved science and engineering will extend overseas markets for US commercial services and equipment.

The one-year study contract period commenced on July 31, 1997, and was subsequently extended, at no cost, to June 30, 1999. During the period of progressive design and bench-test development, field tests were conducted at the Miravalles project facility, as well as at three US geothermal power installations: Caithness Energy LLC facilities at Steamboat Springs, Nevada and Coso, California, and Oxbow Power Services at Dixie Valley, Nevada.

2.0 OBJECTIVE AND APPROACH

The program objective was to identify the highest temperature at which silica scale will develop from partially evaporated and significantly cooled geothermal liquid under operating conditions. Integral to the study objective was the quantification of certain aspects of silica deposition processes at the Miravalles Geothermal Field, Costa Rica. There, the objective was to reduce the scaling risk associated with adding a bottoming-cycle to generate more electricity from the liquids already being produced.

The approach involves tracking deposition of silica scale by monitoring the apparent conductivity of the geothermal fluid in an isolation chamber. A decrease in apparent conductivity occurs because silica deposited on electrode surfaces is less conductive than the geothermal liquid.

A physical system to track such silica-moderated conductivity, and relate it to temperature effects, involves several sub-systems: isolation chamber, heat exchanger, conductivity modules, temperature probes, data recording, and data handling. Temperature control of the isolation chamber depends on liquid flow through its jacket. Jacket input temperature is moderated via a heat exchanger which is fed by a fresh (hot) sidestream of pipeline liquid. Temperature and conductivity are each monitored in both the isolation chamber and pipeline sidestream. Analog signals from conductivity and temperature probes are digitized via electronic modules. Digitized data are stored and displayed in a laptop computer. Final data interpretation is done via graphs and mathematical software.

The study scope was limited to:

(i) designing, building, assembling, and testing in the US, equipment to be used for the field studies;

(ii) performing the field studies in the US and Costa Rica, obtaining relevant data in amounts and quality to meet the study objective;

(iii) interpreting and presenting the data and conclusions in a form useful for plant design, plant operation, and reservoir protection; and

(iv) reporting technical aspects of the study to the geothermal community at large.

While the work was focused on a specific geothermal resource, the equipment and methods demonstrated, through tests at three additional geothermal sites, important chemical facts about fluid/scale behavior under similar conditions.

3.0 ORGANIZATIONAL PLAN

GDA was responsible for overall management, coordination and reporting for the project. Planning, design, fabrication, and implementation of the study was a blend of GDA and DMA engineering and scientific expertise, with important input from ICE engineers and scientists on-site at Miravalles.

DMA conceived, developed and incrementally modified the basic testing equipment and field procedures, and conducted most of the field studies. GDA's principal technological input focused on the instrumentation and data recording format which permits data analysis and interpretation at the high level of sensitivity required.

4.0 FUNDING SUPPORT

USDOE funding was under Contract DE-FG07-971ID13532 for $136,150, with recipient share of the total approved budget, $14,700, for a total budget of

$150,850. The original project and budget period was for 12 months, beginning July 31, 1997. No-cost time extensions were approved through June 30, 1999.

5.0 DESIGN AND PROCEDURE DEVELOPMENT

5.1 General Design Criteria

Equipment design and testing procedures took into into account the general reservoir fluid conditions at Miravalles and other generally similar geothermal fields which were a part of the development process. Table 1 provides a comparison of the principal chemical components of the geothermal liquids tested in each of these fields.

At Miravalles about 55 megawatts of electrical energy are produced from the first plant using flash steam supplied from ten production wells. Steam separation temperatures are in the range of 162° to 172°C, a choice based mainly on requirements for turbine pressure.

Silica in the separated fluid is substantially under-saturated at the separation temperatures, which is one point on which this proposal is balanced. Based on pure water, equilibrium silica saturation would occur in the vicinity of 125° to 150°C (Figure 1). Accordingly, there is considerable heat energy available in the separated liquid, between the steam separation temperature and the silica saturation temperature. It could be used for electricity generation via a binary-type system.

The appeal of implementing this option derives from the additional electricity that could be generated without increasing the rate of liquid withdrawal from the reservoir. An additional 60 thermal megawatts could be obtained by cooling 30°C for the current liquid rate of 450 kg/sec. Based on 15 percent conversion efficiency, about 9 MWe more electricity could be produced from separated liquid if it were taken to about 130°C using a binary-type plant. That would significantly augment the 55 MWe already derived from the flashed steam.

In addition to heat available above the temperature of equilibrium silica saturation, even more heat could be recovered if the operation were to take advantage of the delayed start for silica deposition reactions. When silica over-saturation is small, not only is the deposition reaction slow, but a significant time interval occurs before deposition begins. Based on Weres and Others (1980), the modest over-saturation of silica in Miravalles waters would involve nucleation delays of two hours, or more, at temperatures between 100°and 60°C (Figure 2). Taking advantage of this kinetic effect would enable binary-type energy extraction to temperatures substantially below 100°C, providing another nine or 10 MWe without increasing liquid flow rate through the system. These two power increments could boost the electrical output at Miravalles above 70 MWe, nearly 30 percent, without increasing liquid throughput. However, the second kinetically-derived increment of power implies that silica deposition will occur in the reservoir.

If the deposition occurs sufficiently far from the injection well, then no practical harm results to the injectivity.

ICE would like to install such a power system, the design and construction of which is within the purview of US industry.

5.2 Proposed Concepts

The basic concepts of silica scale deposition have been demonstrated by Weres and Others (1980). They performed laboratory experiments with systems based on pure water and a few selected major and trace components. Their lab studies, which extended the work of others, quantified three peculiarities about silica deposition, the first two of which are apparent in Figure 2:

(i) rates of deposition depend greatly on the initial over-saturation;

(ii) a substantial delay, or nucleation time, seconds to hours long, precedes deposition activity. The amount of delay depends greatly on temperature and over-saturation; and

(iii) nucleation intervals, and the subsequent deposition rates, are affected by the system pH, concentration of major dissolved components, e.g. sodium, and the presence of certain trace components, e.g. fluoride and alumina.

A significant, innovative product of the proposed studies, was to devise two charts based on empirical data, relating temperature and silica concentration to (i) the duration of post-cooling delays that precede silica deposition, and (ii) the rates at which silica eventually deposits. Such graphs would provide temperature targets for engineering design of a power system to produce electricity from the separated liquid. Implicitly, the design temperature selected on the basis of such charts will also protect the reservoir in which thermally depleted water is injected.

Of course, fluid characteristics will change over time at Miravalles, as elsewhere. It will become important to change the operating conditions for the energy recovery systems in order to accommodate those evolutionary changes in the resource. The same charts for silica deposition used by design engineers would enable power plant operators to select updated low operating temperatures for their binary units.

This approach will maximize the total energy ultimately recovered by the binary system, while providing maximum protection to the surface systems and to the injection reservoir.

5.3 Study Implementation

Study with initial design choices, fabrication and assembling of the testing and recording equipment and instrumentation. Laboratory and field testing brought about an evolution of the equipment and procedures, as summarized in the following two subsections.

5.3.1 Early Design and Testing

Design and fabrication, laboratory testing, and modification of equipment continued throughout 1997. A major hurdle addressed during this period was building a conductivity monitoring system that would be 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. Probe assemblies, for compatibility assurance, were built from the same materials used in the Miravalles pipelines and vessels.

The initial field tests, of several days' duration, began in February, 1998 at the Caithness Power Plant, Steamboat Springs, Nevada at the Cox I-1 injection well. Two versions of the isolation chamber were made. One involved a single stainless shell supporting the Teflon liner. Temperature was controlled by immersing the assembly in an open trough of boiling geothermal liquid obtained as a side stream from the pipeline. The other version involved a stainless jacket welded around the stainless liner support so the jacket could receive hotter, pressurized liquid from the pipeline. Temperature of the the liquid input to the jacket was moderated via a heat exchanger. In these first tests, the jacketed version was not used.

At this time, conductivity was measured via a modified field meter originally intended for open, cool water and temperature was monitored via thermocouple. Data was recorded on a dual-pen strip chart.

Later in February, testing on an injection pipeline began at the Oxbow Geothermal Company Dixie Valley Power Plant, Nevada. Encouraging data, which confirmed that the probe would respond to a build-up of scale, was gathered. The ends of several of the electrodes were examined under a scanning electron microscope at the University of Nevada, Reno. An energy dispersive spectrometry (EDS) attachment was used to confirm the scale sample was indeed a silica-based deposit.

However, the field testing revealed that the conductivity of the fluid in the pipeline was not constant. With a single probe in the isolation chamber it could not be determined whether temperature effects or slight variations in fluid composition were affecting the conductivity measurement, masking changes in conductivity which were caused by scale formation.

Thus, two conductivity probes and two temperature probes were required to monitor both the fluid in the reactor (isolated chamber) and the fluid in the pipeline. Improvements were also made in the equipment by adding a programmable logic controller (PLC) to linearize the signals from both the conductivity and temperature sensors prior to inputting them to the strip chart recorders. Other equipment and instrumentation modifications were made.

Laboratory testing continued to be a integral component of the program in DMA's Missoula facility and at GDA in Reno prior to the next phase of field testing which occurred in April. During field tests in April 1998, it was established that significant variations in pipeline fluid temperature and conductivity caused much larger changes in isolation chamber conductivity than anticipated from silica scale effects. Procedures were devised where each test run would involve multiple re-fillings of the test chamber with fresh pipeline fluid. Contrasts in basic conductivity could then be accounted for in the final interpretation.

Additional instrumentation refinements involved replacing the field conductivity meter and strip chart recorders with digital logging system that input to a laptop computer. Thermocouples were replaced by platinum resistance thermometers (PRT). The heart of this sub-system is a programmable logic controller (PLC) which digitizes the analog signals from the two RTDs and two conductivity electrodes. Software in the laptop stores the data and provides real-time displays. These displays serve the same function as the strip charts, but with much greater ease and better precision.

5.3.2 Later Design and Testing

Further improvements were made to coordinate data returns from conductivity and temperature sensors and to improve sensitivity for detecting small increments of silica scale. To improve signal coordination the conductivity sensor was redesigned to incorporate the RTD as the center electrode. This placed the sensing of temperature and conductivity in the identical place.

Sensitivity was improved by establishing procedures for multiple re-fillings of the isolation chamber so that a succession of silica buildups could be obtained. Additionally, temperature control within the isolation chamber was improved by redesigning the heat exchanger used to temper input liquid temperature. The modified valving system enabled temperature pulses, either + or –, to be impressed on the isolation chamber in a few seconds of time. Monitoring the temperature-conductivity correlation upon recovery from the temperature pulses yields an especially precise comparison of apparent conductivities between successive re-fillings of the isolation chamber. This data analysis, and the procedure that yields the data, are crucial to the final results.

At this juncture, it had been demonstrated that the system was indeed showing favorable electrode responses due to changed physical effects, changes which were consistent with scale formation. Dr. Michels authored an in-depth status report on the project dated September 16, 1998 (Appendix A), and a report providing an insight into methods for data interpretation (Appendix B),which were included in the July-September 1998 Quarterly Progress Report .

During the final quarter of 1998 final preparations were made to the equipment and software, prior to Dr. Michels' eight days at the Miravalles Geothermal Field in Costa Rica, running field tests, plus additional time for trouble-shooting and reconfiguring some equipment. A copy of Dr. Michels' report, Summary of Activities in Costa Rica, November 29 –December 16, 1998 (Appendix C), was included in the September –December, 1998 Quarterly Progress Report .

5.4 Study Developments

The testing procedures, equipment, instrumentation, data recording format and presentation, and analysis which were incrementally developed during the study, are concisely presented in the Geothermal Resources Council Poster Session Paper, *Using Apparent Electrical Conductivity to Detect Silica Deposition from Hot Geothermal Liquid,* authored by Donald Michels, David Mendive and Lawrence Green (Appendix D), and in a review of the instrumentation by David Mendive (Appendix E).

6.0 REPORTING

6.1 Quarterly Progress Reports

Quarterly Progress Reports have been submitted to the USDOE Project Manager, with copies to other appropriate USDOE representatives, for each of the four quarters of the original one year contract period, as well as the approved extension period.

6.2 Summary Project Report

The subject Summary Project Report is a compilation and summary of the technical and business components of this project, and includes Conclusions and Recommendations.

6.3 Guidance to ICE

The letter report to ICE is included as Appendix F.

6.4 Technical Reporting to Geothermal Community

6.4.1 A technical paper, *Using Apparent Electrical Conductivity to Detect Silica Deposition from Hot Geothermal Liquid*, authored by Michels, Mendive and Green, has been approved for presentation at the Poster Session of the Geothermal Resource Council Annual Meeting, October 17 - 20, 1999, Reno, Nevada.

6.4.2 Present updated, or more detailed, results at the Standford Geothermal Workshop, January 2000. (Schedule will be formed in December, 1999).

6.4.3 Present further updated results (or just this current status) at the DOE Geothermal Program Review in Berkeley, April 2000.

7.0 CONCLUSIONS

(i) The project team has developed a system for detecting silica scale deposition approximately in situ and almost in real time. The study results are positive and encouraging, though not yet entirely definitive.

(ii) Compared to other empirical methods, this approach can yield useful data within a few minutes. Several experimental runs using this method are required to accurately bracket the boundary temperature, but it appears that such bounds can be identified within just a few days at most, compared to weeks or months using alternative methods.

(iii) The results of the studies under this contract provide the basis to define the silica scale deposition processes more accurately than has been done before. These studies, although designed to apply expressly to the Miravalles brines, have been found to be applicable to other geothermal wellfield systems. Specifically, information has been developed about the rates of silica deposition and the nucleation delays over a range of temperatures and silica concentration.

The intent is to diminish the *zone of uncertainty* about details of silica chemistry in order to reduce or eliminate risks to equipment and to the reservoir. Through this work, the binary plant can be more precisely designed around the water's natural tendency to deposit scale. Furthermore, plant operations can then be more accurately and safely modified, over time, to accommodate natural changes that occur with the fluids that are produced from the reservoir. This will enable electrical energy to be recovered from separated liquids that currently are not further used. These strategies, which augment power generation, imply concomitant protection of the injection reservoir.

(iv) The equipment is compact and light enough to be carried on an airplane as personal baggage.

(v) Continuous, precise monitoring of pipeline liquid temperature and conductivity could greatly assist the work of plant and wellfield monitors and analysts by informing them of variations over time. These variations may signal important events within the reservoir, as well as in-plant behavior. Patterns of change are important and can be identified with the equipment developed for this project.

(vi) Some field problems, typical of operating experimental or newly developed equipment in a wholly different field environment, were encountered in Miravalles. These mainly involved electrical connections and electronic responses relating to magnitude of scaling and instability, apparently influenced by environmental temperatures, humidity, and rain.

8.0 RECOMMENDATIONS

Based on the success of the project in developing a complete, field-tested prototype system, two avenues for further work are now apparent. Both have strong potential for commercialization.

(i) Portable Instrument for Silica Studies in the Field
Refinement of the the silica scale detection concept, as originally intended in this study, is highly recommended.

First, a third generation monitoring system needs to be built, particularly solving problems related to operation in hot, humid climates, and improved field operations for efficient data acquisition, analysis, display, and storage.

Second, a sufficiently complete set of data (from a single resource) must be obtained, so that accurate charts or maps of (a) silica deposition rate, and (b) scale nucleation period (both in a field of temperature versus dissolved silica concentration) are created. Such maps would show, from empirical data, the boundary conditions (risks) for safely operating a binary-type heat exchanger and disposing of (possibly) pregnant liquid.

Third, establish credibility for the concept and the equipment by completing work at multiple field sites.

(ii) Fixed Instrument for Permanent Pipeline Monitoring

The dual CT electrode is adaptable to a simple role of monitoring pipelines. The dynamic changes in temperature and conductivity of ordinary fluids in geothermal pipelines are certain indicators of reservoir processes, but such variability is not now utilized as a means to monitor the health and status of a resource. Currently, many reservoir management decisions are made as reactions to "sudden" upsets. The inexpensive monitoring that could be provided via the CT dual electrode in the pipeline, without the silica monitoring chamber, would show ranges and patterns of reservoir behavior, as propagated through the pipeline and separator system upstream of the instrument point.

In operation, the equipment module would sense T and C, averaging respective results over an interval of time, then storing the digital averages. The time-averaging interval and the interval between data readouts would be selected to optimize the factors of needed numerical resolution, system variability, and the size of data packages that are conveniently interpreted. With experience, plant operators could learn what constitutes normal patterns and be on guard when monitoring shows a change in pattern. This approach would help managers be pro-active, instead of reactive, to changes in their resource. That would help reduce the number and severity of system upsets, making the monitoring modules cost effective. One may expect such monitoring to expose aspects of geothermal resources that have heretofore been obscure or unknown.

FIGURES

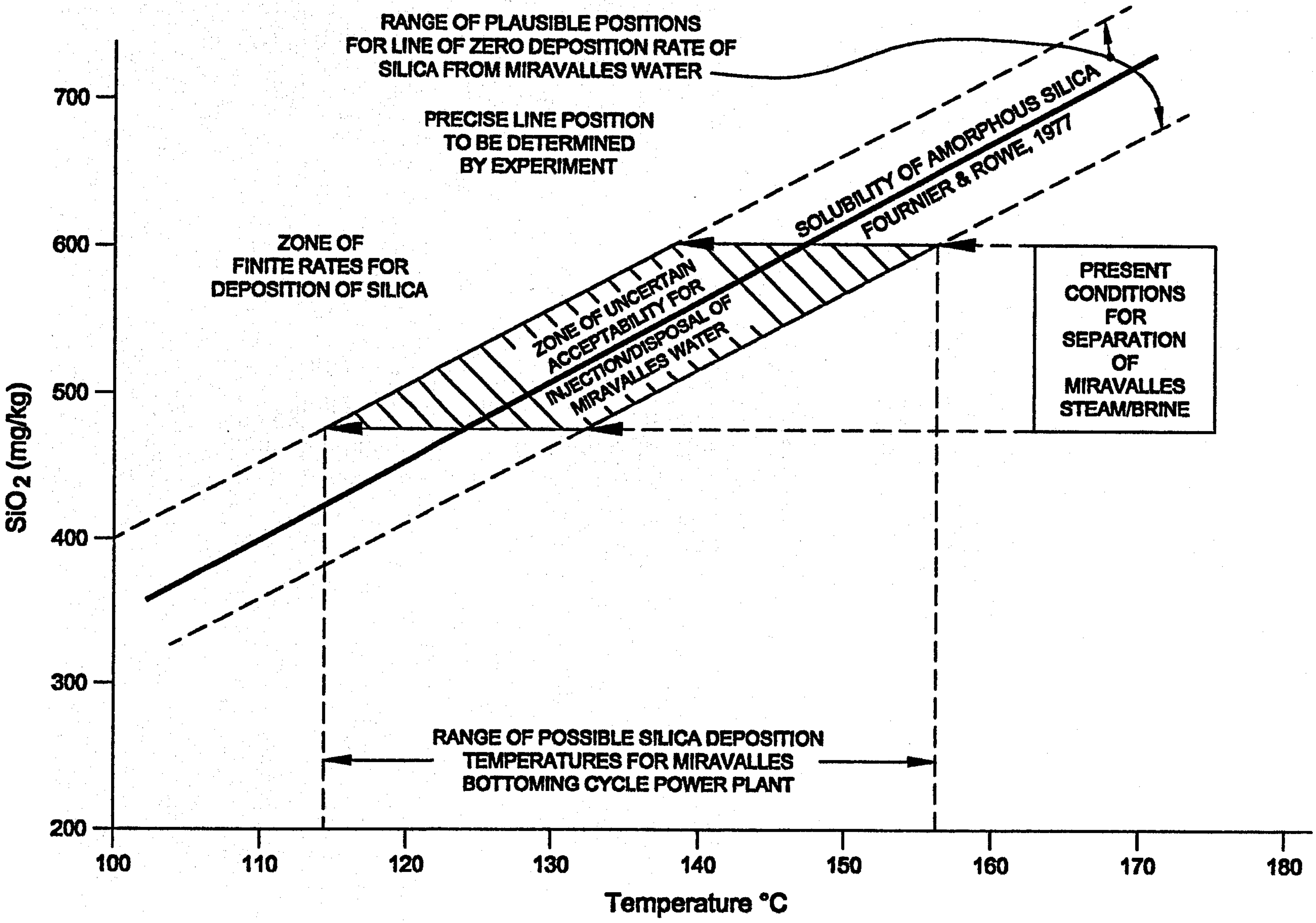


Figure 1: Uncertainty of Generalized Solubility Curve

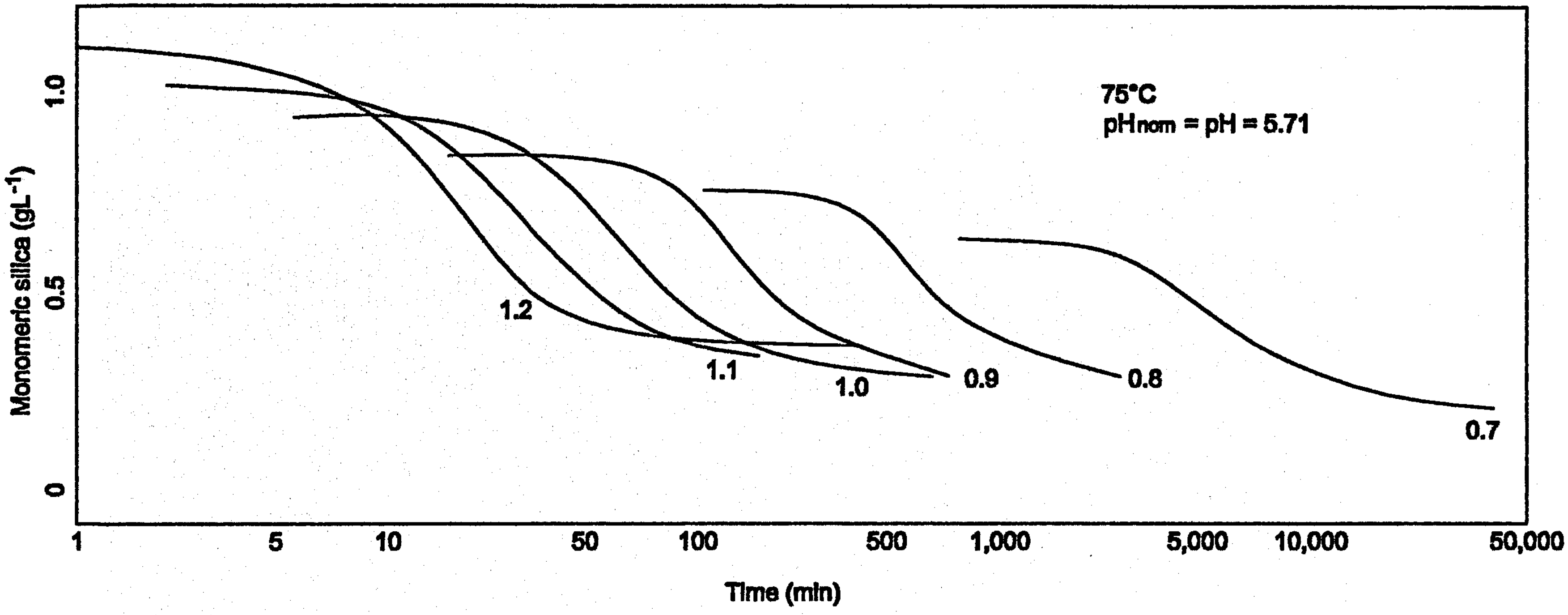


Figure 2: Theoretically Calculated Homogeneous Nucleation Curves

From Weres, et al.

TABLES

Table 1. Comparison of the Principal Chemical Components of Fluids Studied in Field Tests

		Na	K	Ca	Cl	SO4	HCO3	SiO2	TDS	pH (a)	Measured T °C
1	Caithness Steamboat Nevada, USA	680	86	9.9	903	111	228	448.0	2,570	8.09	134°
2	Caithness Steamboat Nevada, USA	714	91	2.8	903	109	160	459.0	2,568	8.45	134°
3	Oxbow Dixie Valley Nevada, USA	520	77	10.8	582	251	108	645.8	2,238	9.28	108°
4	Caithness Coso California, USA										
5	ICE Miravalles Costa Rica	2,445	302	80.0	4,093	50	23	644.0	8,244	8.15	145°
6	ICE Miravalles Costa Rica	2,205	267	81.0	3,768	42	43	479.5	7,243	7.59	150°

(a) Laboratory Measurement

Notes:

(1) Production Well 23-5 chemical analysis with Draw 815 antiscalant in use; single-stage plant separator temperature
(2) Production Well 23-5 chemical analysis with Draw 815 antiscalant not in use; single-stage plant separator temperature
(3) Injectate
(4)
(5) Separator Satellite 3 injectate
(6) Separator Satellite 4 injectate

APPENDIX A

SILICA SCALE DEPOSITION RATES AND THRESHOLDS

By

GEOTHERMAL DEVELOPMENT ASSOCIATES

Reno, Nevada

For

U.S. Department of Energy

Project: DE-FG07-97ID13532

STATUS

16 September 1998

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 enable 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:

$$\text{Log}(C) = a + b/T_{abc} \tag{1}$$

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 side:

- 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 developed.

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 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.

APPENDIX B

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 (CR).
- reactor temperature (TR).
- cross temperature (TC).
- 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 ≈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:

$$\log C = a + b/T_{abs} \qquad (1)$$

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).

$$C_{Ref} = \exp(\log C_R + b(1/373.15 - 1/(T_R+273.15))) \qquad (2)$$

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 $r \geq 0.99$, 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_{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_{Ref} during intervals F, IJ, and KL must be assignable to changed physical aspects of the electrode. The estimates for C_{Ref} in Table 1 follow approximately this pattern, except that C_{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_{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_{Ref}) change while a single charge of liquid is in the reactor. The most prominent shift in C_{Ref} values occurs between intervals E and H which involve the same liquid in the reactor. Their C_{Ref} values are 2633 and 2457. Their difference is about 6.8% of the average value for C_{Ref}. This relative range represents the scope of variations in C_{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_{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_{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_{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.

TABLE 1: RESULTS OF LINEAR FITS TO DATA IN LETTER INTERVALS

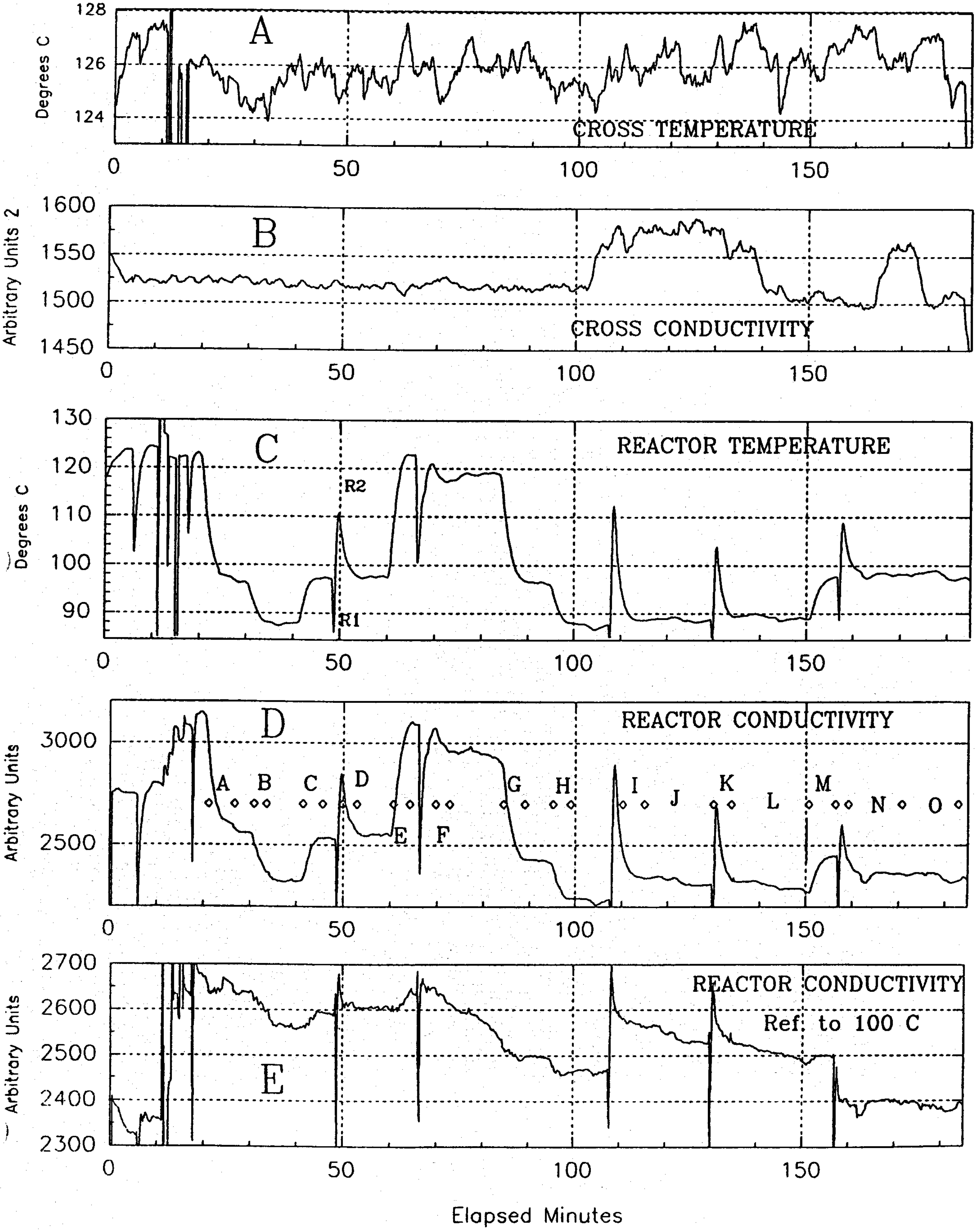
	a	r^2	n	b	$\log C_{Ref}$	C_{Ref}
G	4.62	0.9987	28	-456	3.395	2484
E	4.62	0.9986	21	-448	3.420	2633
K	4.69	0.9985	18	-481	3.405	2539
A	4.49	0.9975	22	-401	3.420	2629
C	4.77	0.9957	25	-504	3.414	2595
M	4.68	0.9953	34	-477	3.398	2500
I	4.61	0.9924	27	-450	3.408	2560
D	4.49	0.9916	18	-401	3.415	2598
B	4.85	0.9914	17	-533	3.420	2628
H	4.65	0.9900	23	-469	3.390	2457
F	4.98	0.9583	18	-589	3.402	2521
O	5.07	0.8675	71	-629	3.380	2397
N	4.76	0.7400	66	-514	3.379	2392
L	5.87	0.7346	95	-910	3.435	2721
J	6.21	0.5525	82	-1030	3.453	2836
Avg $r^2 \geq .99$	4.65	0.9950		-462	2562	
SD $r^2 \geq .99$	0.10	0.0032		39	62	

TABLE 2: TIME LENGTHS FOR LETTER INTERVALS AND TRANSITIONS

	Minutes		Duration	
	Start	End	Int	Trans
A	21.1	26.7	5.6	
Trans	26.9	30.9		4.0
B	30.9	33.6	2.8	
Trans	33.6	41.4		7.8
C	41.4	45.6	4.2	
D	49.9	52.9	3.0	
Trans	52.9	60.7		7.8
E	60.7	64.2	3.5	
F	69.7	72.7	3.0	
Trans	72.7	84.3		11.6
G	84.3	89.0	4.7	
T	89.0	95.2	6.2	
H	95.2	99.0	3.8	
I	110.3	115.0	4.7	
J-trans	115.0	129.2		14.2
K	130.9	133.8	2.9	
L-trans	133.8	150.7		16.8
M	150.7	156.4	5.7	
N	159.2	170.6	11.5	
O	170.8	182.9	12.1	
Avg			5.2	9.8
Sum			67.3	68.5
Avg except NO			4.0	

CONDUCTIVITY–TEMPERATURE TEST "A" 27Aug98
at CAITHNESS -- RENO

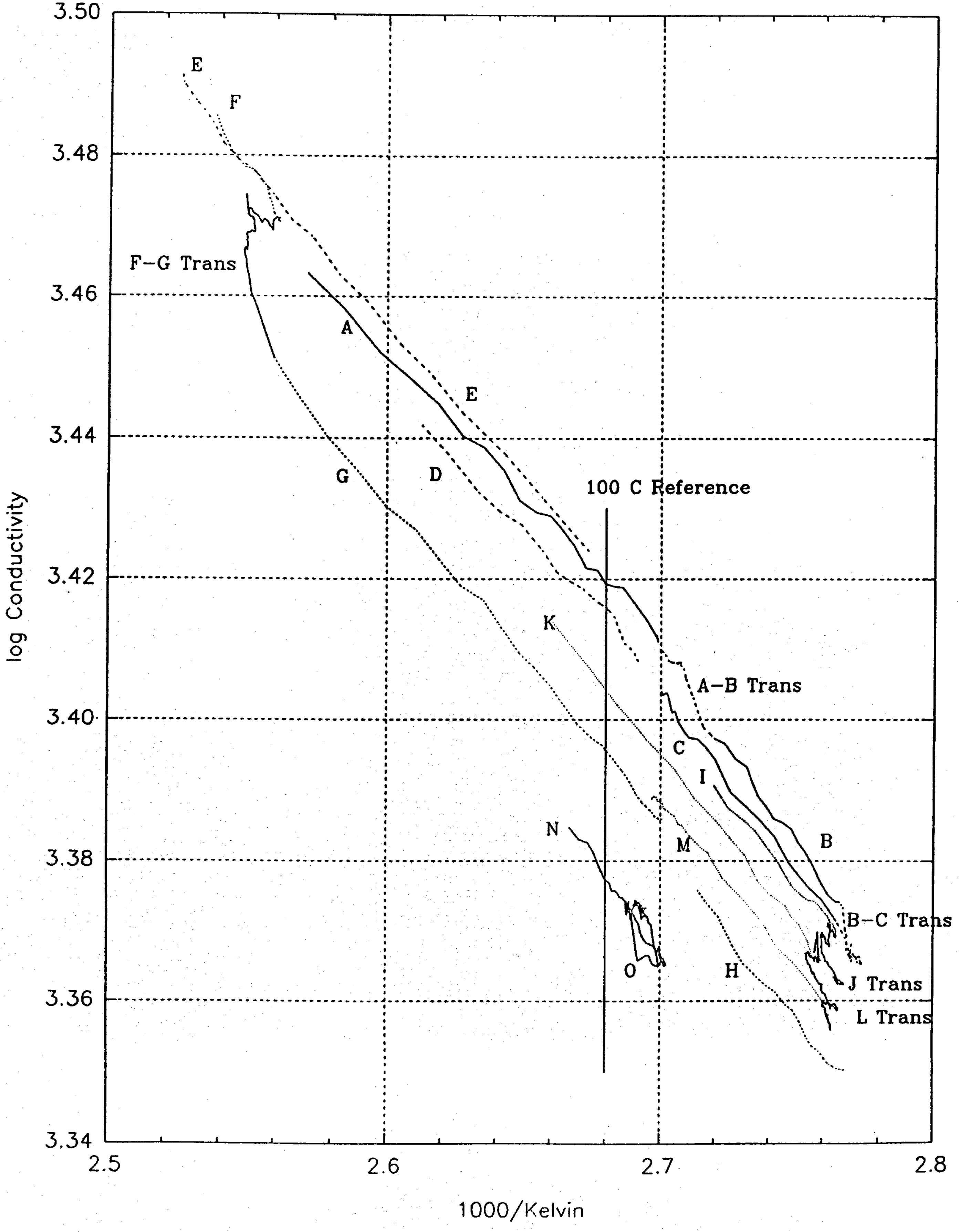
FIGURE 1: DATA versus TIME



TEMPERATURE-CONDUCTIVITY TESTS

CAITHNESS-RENO -- 27Aug98

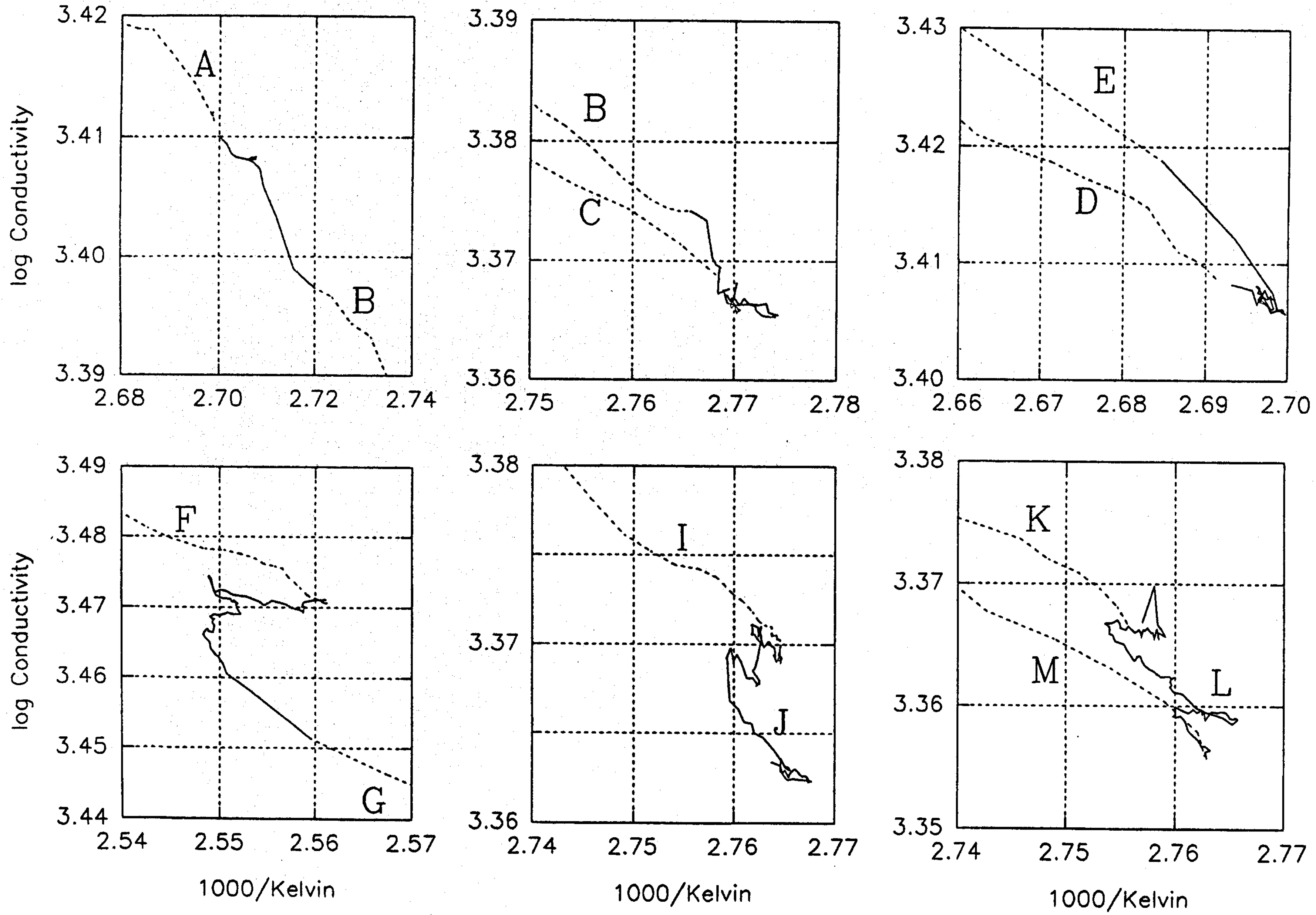
FIGURE 2: T-C LINEARITY



TEMPERATURE–CONDUCTIVITY TESTS

CAITHNESS–RENO -- 27Aug98

FIGURE 3: TRANSITION DETAILS



APPENDIX C

MIRAVALLES PROJECT

SUMMARY OF ACTIVITIES IN COSTA RICA
Nov 29 thru Dec 16, 1998

by

Donald Michels

29 November (Sunday)

Left Missoula for Reno about 915 pm, more than one hour behind schedule, missing connections in Salt Lake City. Delta Air put me up in a local motel at their cost.

30 November (Monday)

Underway for Reno at 5 am. Martin met me with the Explorer about 730. Checked into local motel then went to GDA to review plans for the Miravalles field work and install a memory upgrade into my IBM computer so it can efficiently operate the Excel program and the new Canon printer needed for making graphs in the field.

1 December (Tuesday)

The late-arriving memory upgrade was in hand and installed without complication. printer and Excel both worked normally.

Left GDA for the Reno airport about 430 pm with all gear in apparently good shape. Left Reno on schedule with all gear checked through. Made plane changes in San Francisco and Los Angeles on schedules. Los Angeles departure for San Jose via Guatemala City was about 1115 pm.

2 December (Wednesday)

Arrival in Costa Rica was on schedule (830 am) at the San Jose airport with all gear intact. ICE guide Antonio Yock and driver Juan Carlos Hernandez were there to meet me and we set out directly for Miravalles in the ICE truck. The trip took about 3 1/2 hours. We arrived in time to be introduced to my quarters and then eat lunch served in the company mess hall. The ICE Campus here is about 1/2 square kilometer located on the west side of the community of Guayabo, with surrounding fence and security gate. Access is screened by security personnel who also inspect vehicle cargos that leave the area.

After lunch, Antonio gave me a tour through his office area and the offices of the geophysics and geology-hydrology section which he supervises, located across the street from his office building. Later, we toured the geochemical laboratory, which Antonio also supervises, located about four blocks away amongst other buildings which house crafts that support the Miravalles field operations.

My quarters were in a free-standing one story building that contained four sleeping rooms at the building corners, two bathroom-shower combinations at the ends (each shared by two occupants), a common area in the middle of the building, a sunken area with TV and stuffed furniture, and a modest kitchen area, almost complete unstocked. Sleeping rooms are simple, about 12x14 feet, and furnished simply with worn, even tattered, items. The room nearest mine was the regular abode of Antonio Yock whose civilian home, with wife and three children (two in college), is in San Jose; his schedule is 10 days at Miravalles with 4 days off, except for special occasions, such as my presence, when he is available so long as a purpose appears served. Dr. Mainiere also uses this building when he is present as does another manager-engineer, Paul Moya (whose English skills are the best I found during my visit).

After dinner, Edie Sanchez, who lives in one of two sections of company housing for married employees with families, provided a "carne evening" for co-workers and their friends/spouses/children. About 20 were in attendance, nibbling on a variety of meats fresh off the barbecue with other condiments and light drinks while multiple discussion groups formed and dissipated. This made a pleasant, low-key social experience that seems to be a common form of entertainment here.

3 December (Thursday)

Antonio gave me a partial tour of the field area, mainly to choose a site for initial work with the conductivity apparatus. We selected *Satelite* #3 (S-3) due to availability of 110v electricity proximate to an access valve on the injection pipeline. Six *satelites* are operational and it was expected that eventually all would be visited and local liquids tested. In order to complete the set-ups, I borrowed two pipe wrenches, a 12-v truck battery, electrical extension cords, voltage stabilizers (put in series with the local 110v line to protect the computer from surges), and a 20-liter pail to collect overflow liquid from the heat exchanger; all from the geochemical lab. Generally, a truck and driver from the geochemical lab provided my transportation to and from the field sites. S-3 is near the middle of the developed field and about a 15 minute drive from the campus, over rough roads through Guayabo and across moderately rough volcanic terrain.

Initial set-up of the equipment took nearly two hours. Then, before pressurizing the temperature control side of the reactor, the center (sensor) piece of #2 conductivity electrode (C2) blew out; the central stainless rod had become unbonded from the high temperature (red) RTV used to fill the annulus on the hot end.

As a substitute, I placed the spare #1 Conductivity electrode (long version with center PRT and removable carbon steel tip) but it leaked through the annulus, shorting the electrode internally. Accordingly, I took down all equipment, re-potted the C2 electrode with fresh HT-RTV, and practiced with Excel while awaiting the scheduled arrival of the transport truck. No data were collected this day.

Antonio arrived in mid-afternoon, probably expecting to see some data, since his expression was somewhere between surprise and disappointment. Yet, he was too much a gentleman to be too questioning.

4 December (Friday)

Got to S-3 about 0800 hrs and equipment set up went much more quickly than yesterday. The re-potted electrode held pressure. However, when the heat exchanger was pressurized the #2 2-way valve leaked through the pack-off. Adjustment was delayed because I had no Allen wrenches with which to loosen the handle and give access to the compression nut. A phone call was made to the geochemical laboratory and before they arrived with a set of wrenches a visiting workman provided one of the right size and the adjustment was achieved directly.

At about 1045 the T2 RTD blew out of its fitting. In order to stop the blowout it is necessary to withdraw the probe from the access valve which requires moving the reactor and heat exchanger system as a unit. During the move some (near-) boiling water sloshed out of the heat exchanger and scalded a strip of my belly about 1 1/2 by 5 inches, to the right of the navel. Not badly damaging nor too painful, but a clear warning of risks. Water-filled blisters formed but remained intact for about four days. No medicine was ever applied, no infection occurred and healing (as of 2 Jan 99) is normal and complete except for mild redness which continues to fade.

The RTD ferrule appeared to have melted (and appeared to be made of nylon instead of Teflon). A Teflon ferrule was fashioned from Teflon tubing and the system reassembled and reinstalled with no further trouble.

With the set-up complete data was coming to the computer, but conductivity values were poorly scaled. Attempts to change the DIP switch settings succeeded on the first try for C1, but C2 behaved erratically. It took more than an hour to get stable readings in a useful range.

After the first attempt at pulsing the temperature in the reactor, C2 values began rising, eventually going off scale. That was consistent with failure of the bond between HT-RTV and the electrode. However, by changing the DIP switches a sequence of on-scale readings seemed stable enough to represent a new condition of the electrode and I proceeded to collect data.

Setting pulses of temperature (+) or (-) in the reactor, by changing the number of activated cooling coils in the heat exchanger, disclosed a hysteresis in C1. Furthermore, C2 suffered a progressive decrease in apparent conductivity punctuated with sudden increases or decreases (more increases than decreases) of apparent conductivity; a net decrease of >20% during the last 200 minutes of observation.

Both electrodes appeared to be malfunctioning.

5 December (Saturday)

Data from Dec 4 were plotted via Excel so as to better see what was happening. Compared to the detailed correlation between conductivity and temperature records from the Caithness data, the conductivity data from S-3 was quite anomalous in the reactor and in the flowline (cross). C1 (reactor conductivity) tends to show long steady trends of increasing (apparent) conductivity while T1 is stable. Also, pulses in T1 result in shifts of the trend lines for C1. Additionally, there are spikes in C1 that seem to be spontaneous after which the C1 values return to the trend line.

C2 (conductivity in the cross, representing the pipeline) shows a decreasing trend punctuated by sudden increases or decreases of (apparent) conductivity. I made an effort to levelize the C2 values by (1) removing the punctuation displacements by adding or subtracting their (cumulative) values from subsequent data, yielding a line of uniform decreasing trend and (2) removing the trend by assigning a cumulative value proportional to time to all the data. The result was a (revised) level plot of conductivity versus time that has a randomness and non-correlation with its T2 values quite similar to the appearance of the pipeline C and T series from Caithness. This outcome suggests that the trends and off-sets of C2 data can be considered as independent, at least for adjustment purposes. However, such an adjustment is not appropriate for the purposes of the silica deposition study unless real changes in pipeline conductivity can be distinguished from the adjusted trends and off-sets.

Later, I re-potted the C2 and C1 electrodes, after careful dismantling and cleaning. Then, they were placed into an oven at the geochemical lab (40_C) for overnight cure. Curing requires diffusional loss of acetic acid, a difficult process from the narrow annulus of the electrode which is bounded by stainless steel. Without escape of acetic acid vapor from the end of the electrode the inner liquid will not cure. Elevated temperature should be helpful if it is not so elevated as to induce bubbles to form.

6 December (Sunday)

Recovered the repotted electrodes from the oven about 0730. They looked OK under a hand lens. Excess rubber was trimmed away to make the end more regular and a file was used to refresh the metallic surfaces of the sheath and center electrode.

Set up at S-3 about 1100 hrs with repotted electrodes in #1 and #2 positions. A mutual interference between electrodes was indicated by a change in C2 from 3724 to 3660 (arbitrary units) when the lead from the C1 sheath was first attached the sheath of C2.

The heat exchange unit had a minor problem, perhaps a small blockage in the flow control orifice. It worked after the third effort to clear the tube. System temperature didn't line out until past noon.

C2 values began an irregular downward trend shortly after noon. C1 values were not trendy, but had spontaneous spikes (mostly downward) and some shifts of value (stepped responses). The range of stepped values for C1 was fairly small for the first two hours, but then strong trends began to develop along with spontaneous spikes within the trends. Clearly, neither C-electrode was functioning properly. Furthermore, the time to failure is too short to expect that intervals of good data might be obtained even if the electrodes were repotted every night. Thus, the RTV potting was not successful. Accordingly, using Teflon tubing as an insulator (as originally designed) is the proper structural form for electrodes.

7 December (Monday)

Three electrodes were rebuilt using 1/8 inch Teflon tubing as insulator in the annulus. [Two long-form versions with RTD's for center electrodes, one of these was built in a sheath which was adapted to receive a carbon steel tip. The third was the short form for C2 with solid 1/8-inch diameter rod for the inner electrode.] One of the C1 versions (without adapter for carbon steel tip) involved thinned Teflon due to severe stretching during assembly. To assemble, the Teflon tubing was first pushed fully over the RTD with an excess length, about 12 inches, of empty tubing beyond the functional end of the RTD. The fit was tight and required a lot of pushing and stroking which advanced the RTD only a fractional inch into the Teflon per motion. Then the empty tab end of the Teflon tube was pushed through the stainless sheath. Finally, by holding the sheath in a vise it was possible to pull the empty end of the Teflon tube with vise-grips while pushing on the RTD end and force the RTD-Teflon assembly past the constriction in the sheath due to the ferrule compression on the tubing. As a consequence, the Teflon insulation was stretched and thinned on the tension side of the constriction, but the RTD end could be located properly flush with the edge of the sheath. Eventually, the Teflon regained its original dimensions, which involved a retreat (shrinkage) of the tubing toward the ferrule constriction. Because the excess Teflon was trimmed flush with the sheath while in its stretched mode, relaxation involved retreat of the tube end into the sheath by about 3/4 inch. This retreat was further encouraged by placing the electrode in the boiling water of the heat exchanger. Subsequently, another length of Teflon tubing was pushed over the RTD so it could fill the open space, then trimmed appropriately. Although there is undoubtedly a gap between the two Teflon pieces where liquid can form a conductive bridge, such a bridge is small and stable, perhaps of negligible consequence for use of the electrode. [Of course, subsequent constructions of electrodes would allow for stretch and shrinkage of the Teflon and avoid this complication.]

The system was taken to S-3 and set up slightly before 1300 hrs. A mistake was made by interchanging two 1/8 inch tubing connections. This caused the fluid intended for the jacket temperature control to flow through the reactor instead. Of course, temperatures did not approach their intended values. Meanwhile, the flow rate intended for the jacket passed through the small orifices in the wall of the Teflon liner in the reactor and may have enlarged those holes. It could be worth while to make some sort of coding on these tube ends or fittings so such mis-connection is more difficult.

C-values were not stable and were sensitive to wiggling and fiddling with the clamps for the electrodes. Apparently constant, low-ohm connections were not makeable. A light rain made all thing a bit moist if they were not hot enough to evaporate. Since the Teflon liners of the electrodes were physically stable and continuous the problems with unstable conductivity values must be due to either the clamp connections or the modules. Rain became earnest after 1400 hrs and I dismantled all equipment, called for transportation and returned to the ICE campus.

A phone call was made to the GDA office. Dave suggested that I check all screw-type connections in both conductivity modules for tightness and build electrode connections that can be tightened with force. Upon turning all the screws in both conductivity modules, all moved a bit, 15-30 degrees, but only one, on the C2 (pipeline) module, moved more than 1/8 turn, maybe loose.

8 December (Tuesday)

In the morning, Antonio introduced me to the electrical department, described my problem of making clamp connections and obtained permission for me to rummage amongst their spare parts and junk and use their facility while making low-ohm connectors for the electrodes. Oscar and Juan became increasingly interested in what I was doing and performed the heavier soldering operations with great good humor and technique. Two sets were crudely fashioned from copper with bolts and nuts for clamping and soldered-on wires for (additional soldered) connection to the leads from the conductivity modules.

The system, with newly fashioned electrode clamps, was set up in the geochem lab to test the conductivity modules for function. A single C1-type electrode was placed into a sample of geothermal liquid and the leads connected appropriately to one of the conductivity modules at a time. For the test, conductivity readings were noted for each combination of DIP switch settings and the values compared between the two modules. Although there was some initial inconsistency, generally similar conductivity values were obtained with both modules, indicating, at least, that they were responding similarly. For the test, five switches were involved (#s 1, 2, 3, 4, 5) and all (32) on-off combinations were tested for both modules. For ten DIP combinations the readings were off scale (>4095) but the others were substantially similar, differing by less than 10%. A sixth switch (#9) was tested incompletely because its effect seemed small. These results indicated that both modules were probably behaving as designed. They also provided an empirical basis for changing DIP switches in the field with a more predictable effect on the conductivity reading, needed to place the value in proper scale for display and subsequent interpretation. Results for this latter aspect are complex and will be shown elsewhere.

9 December (Wednesday)

Rendezvoused with the transport truck at 0700, took about one hour to recharge the drive battery for the PLC, then set up in light rain with data coming in just before 1000 hrs. Even after several practices at setting up, it still seems to take about two hours before data can begin coming in.

In order to get both conductivities on scale at the same time, both leads of both modules were connected to sheathes and central stems of the electrodes - no jumper was used between sheaths. Also, packing around the PLC was propped away initially so the unit can breathe. Minor leakage through the C1 annulus was stopped by torquing the fitting nut, collapsing the sheath more tightly against the Teflon liner. No clue of leakage from C2. C1 and T1 values levelled out about 1013 hrs and the first exchange of reactor liquid was made.

Response of C1 did not mirror the T1 double reversal. Although the values of C1 and T1 initially dropped together as cool liquid from the exposed part of the probe displaced hot liquid in the reactor, the C1 trend reversed before T1 reached a minimum. Then, C1 reversed again (decrease) about the moment that T1 made its first reversal and began increasing. For the remainder of the time new liquid was displacing old (temperature rising) C1 decreased. Upon stopping liquid flow (finishing the liquid exchange in the reactor) C1 reversed trend (now increasing) while T1 reversed to a decreasing trend. T1 levelled out about 1019 hrs and oscillated _1_C until 1028 while C1 increased unsteadily from about 1530 to 2170 (arbitrary units), more than 40%. This represents seriously unexpected behavior on the part of C1.

A (+) temperature pulse was set up at 1029 with which C1 rose and did not decline, but did approximately stabilize. Additional temperature pulses were set up; (+) at 1043 and 1056, (-) at 1105 and 1112, (+) at 1119 and 1129. The T1-C1 relationship appeared essentially normal through all the T-pulses except the last. Then, C1 began an irregular decline.

Meanwhile, C2 had been on an irregular declining trend since about 1030. Suspecting overheating of the PLC, I lifted it partly out of its space (within allowance of short electrical leads), propped it up, and disconnected the drive battery for about 18 minutes. After reconnecting the drive battery a looseness was noticed in the lead clamp attached to the central electrode of C1. After tightening the clamp C1 values stabilized.

Three temperature pulses were set up (1228, 1237, and 1245) and all appeared normal. Accordingly, a replacement of the reactor liquid was made beginning at 1255. The C1 value dropped sharply, much more quickly than I remember the response to have been at Caithness. DIP switches were changed to place the display back on scale (this has an advantage over changing the computer display scale which loses data for 1 to 2 minutes). After closing the valve for liquid replacement, T1 began to decline while C1 began to rise. Rapping a few times on the tee which holds the C1 fitting caused the C1 value to jump more than 30% then continue a rise (at decreasing rate) during the next 10 minutes. The C1-T1 correlation was greatly similar to the description above. Additional rapping on the tee elicited small irregularities in C1 but did not change the trend which was now much above the "stable" value associated with the T-pulses. On the suspicion that the unusual response of C1 might be due to something loose in the reactor chamber I opened the liquid change-out valve and rapped the tee sharply with a small wrench.

The computer screen went blank during an attempt to change the display scale for C1. After a few unsuccessful attempts to restore the display I shut down the program, intending to restart. Restart was successful at 1331 including all displays.

Between 1340 hrs and 1525 the T1-C1 response upon recharging the reactor was tested six more times. Additionally, T-pulses were dispersed among the exchanges. All the T-pulse responses of C1-T1 were essentially normal while all the T1-C1 responses to liquid exchange were the complicated form described above. This seems to suggest that the liquid exchange elicits a change in the number (local concentration) of charge carriers available at the electrode while a T-pulse merely changes the efficiency that a fixed number of carriers can conduct AC current. Not explained is why the C1 value has an increasing trend across a series of liquid exchanges and how the "charge carrier number" overwhelms the temperature effect on apparent conductivity. Shutdown began at 1530.

Dr. Mainiere arrived in the afternoon and Antonio introduced us before dinner, which we later shared in the mess hall. Subsequently, we socialized (Dr. Mainiere, Antonio Yock, Paul Moya, and DEM) in our shared living quarters. I asked Dr. Mainiere about his expectations for our work here. He responded with comments about protecting the (injection) reservoir and being certain that design of the bottoming cycle was correct, very much like the language we used in the proposal to DOE. He did not convey a sense of urgency nor whether our work might be crucial to anything. However, on Dec 8, Paul Moya, during dinner, suggested that if the results are useful it would be of further use to present them to a panel that meets in Costa Rica in June 1999. The panel includes Bob Fournier (USGS) and others who are passing judgement on progress and direction of the Miravalles projects. During the early stages of proposal development I called Bob to get his opinion of whether experiments of this sort were worthwhile. His "yes" seemed more than a bit emphatic.

I described to Dr. Mainiere and the others the complicated C1-T1 relationship that today's field work had disclosed and described it as presently "not interpretable". If that condition persisted then we might not be able to specify a silica deposition temperature to help in their design of a bottoming cycle. I alternatively speculated that perhaps the strange character indicated that silica deposition was actively going on and was responsible for the peculiar relationship. If true, then the Caithness-type correlation might occur at Miravalles at higher experimental temperatures and the temperature for transition would indicate the critical temperature for silica deposition. Such a situation would simplify our task of identifying the "critical" temperature since it would change the decision from one of noting a small quantitative contrast to finding a substantial qualitative contrast, as a range of experimental temperatures are explored. This plausibility deserves close attention during the data interpretation stages.

10 December (Thursday)

Set up at S-3 was complete at 0850, but pipeline temperature (T2) was showing _200_C, too high for the 160_ design and the 155_ indicated on previous days. During the next 1 1/2 hours I chose to disregard the T2 error and stabilize the C1 and T1 values to prepare for experiments to test whether yesterday's odd C1-T1 relationship would be repeated. Blowout of a rupture disc in the ICE pipeline downstream of my set up point increased flow rate through the pipeline and the pipeline temperature increased, along with the reactor temperature. There was some instability of the C1 value traced to a loose clamp (mainly due to the non-round condition of the center electrode at the clamping point.

Between 1000 and 1030 I replaced the T2 sensor with the spare PRT and worked over the C1 clamp. After making two T-pulse stimulations at 1053 and 1106, which showed normal T1-C1 relationships, exchanges of reactor liquid were made at 1116 and 1136. Both exchanges showed the same unusual features of the C1-T1 relationship as found Dec 9.

As a device to further explore the unusual T1-C1 behavior I made a series of partial exchanges ranging from a small fraction of a reactor volume to multiple reactor volumes. (Reactor volume is about 5 ml, nominally 100 drops of liquid as discernibly falling from the control valve during exchange.) Partial displacements (in drops) of 10, 20, 30, 40, 80, 120, 200, 250, 300 and 400 were made between 1350 and 1530 hrs. From this it was immediately clear that the intermediate reversal of C1 (while T1 was decreasing) did not occur at a displacement of 120 drops (120% of a reactor volume) but was vestigially present at a displacement of 200 drops and prominent at a displacement of 250 drops (2.5 reactor volumes). A fuller meaning of this and other features will be explored and reported separately.

Dr. Mainiere, the Plant Superintendent, and the Field Superintendent visited me for a few minutes during this field period. The Plant person had the best command of English; I described the process and objectives to him while he asked questions and the others listened. This amounted to a once-through description which emphasized the main points. Additionally, I described the problem with the peculiar T1-C1 correlation and concluded that unless that could be interpreted I might not be able to deliver to ICE the silica temperature limits they wanted.

11 December (Friday)

Since no further experiments using S-3 seemed useful it was time to select another *Satelite* and its injection liquid for testing. The main question of the moment seemed to be, "Do other injection liquids yield the same C1-T1 relationship as found at S-3, that is, might some minor differences in chemistry be related to the strange behavior? As a first step, a set of brine compositions from pipeline samples was obtained and examined for contrasts with the brine of S-3. No prominent differences were noted so it was decided to set up on a *Satelite* which was convenient for our equipment. After a brief tour of the alternatives Antonio and I selected S-2, an unmanned installation that was serving a single production well. I was left there with appropriate equipment. Unfortunately, the selected access valve (3 o'clock position) was above the liquid level in the pipeline and only steam was emitted. As there were no other satisfactory valve access points at the site no test could be made. When Antonio reappeared at the agreed time we checked more closely at the other *satelites* and discovered that none of them had access valves that would yield liquid discharge. Accordingly, we visited some injection wells to determine their suitability as set up points. The most promising, PGM-26, turned out to be taking water from S-3. Accordingly, another well was sought and we selected PGM-22 which serves S-4. As there was no electricity at the site we would need to drive the computer with the storage battery via the STATPOWER converter, which places a heavy drain on the battery. The day ended with setting the battery on a charger and changing the cigarette lighter connection of the STATPOWER unit to clamps. No data were collected this day.

12 December (Saturday)

Arrived at PGM-22 about 0830 and was set up by 1000 hrs. The PLC was exposed greatly from its packing and shaded by the rain fly. Some initial problems occurred with partial plugging of the flow control orifice for the heat exchanger system. After twice clearing the 1-hole tube temperature was still cooler than I wanted so the 2-hole control tube was installed. There were no further troubles and temperature control was satisfactory.

Exchanges of reactor liquid were made at 1031, 1040, and 1051. The resulting C1-T1 correlations had most qualitative features similar to the S-3 data, but differed in detail. Furthermore, details among these three exchange curves were substantially dissimilar. In an attempt to test whether the conductivity modules might be behaving differently the leads from the C1 and C2 were interchanged at the module boxes. This caused the C2 value (now displayed as C1) to be out of range, even with the most advantageous DIP setting, so the leads were swapped back to their original positions. Thereupon, C1 then was much lower than the previous reading, but subsequently increased substantially while T1 was level.

A T-pulse was initiated at 1115 and the recovery was not normal; C1 and T1 varied almost precisely counter to one another instead of parallel. Shut down was begun since it was demonstrated that a "normal" T1-C1 relationship was not available with the liquid here. Also, the

T-pulse anomaly suggested that the C1 module might be malfunctioning. This ended the field study activities at Miravalles.

13 December (Sunday)

Antonio wished to treat me to a tour of ICE's geothermal prospect at Tenorio, on the southwestern flank of Volcan Tenorio, about 12 km ESE of the Miravalles geothermal field. The elevation there is higher (_1000 m) and two drill sites (not yet occupied) are located near a national park. Since there is only a circuitous road connection between Miravalles and Tenorio this seemed to promise a bit of a tour. The countryside drive was pleasant and interesting. We passed by two of ICE's hydroelectric installations and lovely Lake Arenal, (claimed to be) the largest reservoir in Central America. As we gained in elevation the wind increased and we passed several clusters of 3-bladed wind-electric machines. Rain was intermittent and at the drill sites clouds and fog obscured almost all the view of the forest.

On the return to Miravalles we detoured toward the seashore and after difficulty finding a continuous trail finally occupied a small beach on a bay. This beach was untracked and quite lovely, though short and narrow. Beach sand was totally shell fragments. We stayed only long enough to walk a few hundred yards and pick a couple handfuls of shells.

14 December 1998 (Monday)

Left Miravalles in an ICE truck with Antonio and all gear during the dark of the morning. We arrived in San Jose about 9am, met Antonio's wife and family, invited them to have dinner with me that evening, then I checked into the Hotel Costa Rica. Antonio guided me a bit for shopping near the hotel, then he left till dinner time.

15 December 1998 (Tuesday)

The ICE driver arrived at the Hotel on schedule (7am) and took me and all gear to the airport at Alejuela. The airplane left on schedule at 0920. After a stop in Guatemala City and plane changes in Los Angeles and San Francisco, I met Martin at the Reno Airport about 830 pm with all gear in hand.

16 December 1998 (Wednesday)

The initially short de-briefing time planned for DEM to GDA was made even shorter by an airline schedule change (leave Reno) from 1040 am to 950 am. Left at GDA were the computer, PLC, and conductivity modules, in their travelling case, with electrodes, PRT's, and connectors. I retained the reactor-probe assembly and heat exchanger unit for examination and cleanup in Montana.

Connections in Salt Lake City were OK and I arrived in Missoula, on schedule, shortly after 4 pm with all gear.

APPENDIX D

USING APPARENT ELECTRICAL CONDUCTIVITY TO DETECT SILICA DEPOSITION FROM HOT GEOTHERMAL LIQUID

Donald Michels, Don Michels Associates, Missoula, Montana
David Mendive, Geothermal Development Associates, Reno, Nevada
Lawrence Green, University of Nevada, Reno

Keywords: silica; scale; monitoring

ABSTRACT

A system has been developed to detect silica deposition under approximately *in situ* conditions. Data is collected simultaneously from an active pipeline and an associated isolation chamber containing a parcel of pipeline liquid at a controlled temperature. The equipment is compact and light enough to be air transported as personal baggage. Methods for collecting and interpreting data are crucial parts of the system. Measurements focus on the liquid's apparent electrical conductivity and temperature, but data interpretation aims at detecting silica deposition, which causes decreases in apparent conductivity. The main application aims to precisely identify the temperature boundary for deposition and non-deposition of silica, required for best designs of heat exchangers for binary-type power plants, liquid disposal, and reservoir management. Other applications involve pipeline monitoring and resource management.

INTRODUCTION

Silica deposition in pipelines and injection systems remains one of the truly durable problems for the geothermal industry. Prevention by chemical methods is not fully reliable and avoidance via temperature control limits heat extraction from the liquid resource. The actual solubility of amorphous silica, in a context of resource use, is only approximated by laboratory studies which involve simpler dissolved mixtures. The study of silica deposition under operational conditions has been troubled by poor sensitivity and the need for long experimental intervals. This work aims to overcome those complications.

During the past two years, GDA and DMA have developed a system aimed at monitoring silica deposition in approximately *in situ* conditions. The method is based on a specially designed dual electrode which simultaneously detects apparent liquid conductivity (AC) and liquid temperature (T). The conductivity is "apparent" because the electrode's conductivity signal depends jointly on true conductivity of the liquid and on the physical state of the detector surfaces which may receive scale (silica) deposits.

Monitoring T simultaneously with AC is essential because of the strong dependence between true conductivity and T. Data interpretation requires that variations of AC, due to T-effects on the chemical aspects of conductivity, be mathematically compensated before the physical effects of silica deposition on the electrode can be quantified.

SIGNAL DETECTION

Our dual detector utilizes a 1/4-inch stainless tube as one pole of the conductivity detector (Figure 1). Coaxial with the tube is a platinum resistance thermometer (PRT) in a stainless sheath 1/8 inch diameter. The two metal pieces are separated by a Teflon annulus so the exposed end of the PRT acts as the other pole of the conductivity detector. The outer pole is also surrounded by a Teflon annulus so that only the flat ends of the pole pieces are exposed to liquid. With this construction, T and AC are measured at the identical site.

The temperature sensing element of the inner conductivity electrode is about 2 mm inside from the flat end. Consequently, the temperature response lags the liquid electrical conductivity response by about 12 to 16 seconds. This effect is easily accommodated in the interpretation and becomes trivial when system temperature changes slowly.

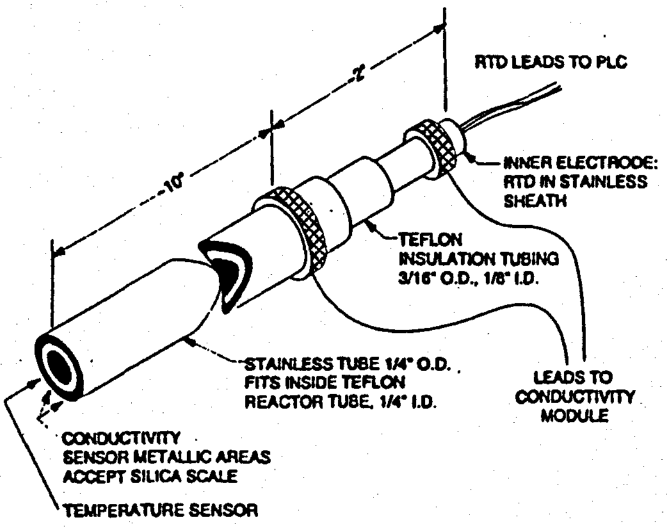


Figure 1:
Combination Electrode Senses Temperature and Conductivity

The dual detector may be inserted into pipeline liquid, via a valve and pass-through system. There, line conditions of temperature and apparent conductivity can be monitored. Apparent changes in temperature-compensated AC over time will be jointly due to variations in liquid composition (effective population of charge carriers) and deposition, if any, on the electrode surface by scale, which is electrically insulating. Strategies for data collection from pipelines will vary according to the on-line variability of the liquid resource and purposes to which data will be put. For example, in our experimental runs of a few hours, data collection rate is 6 sets per minute. This provides surprising information about resource variability irrespective of the scaling aspect. Specifically, pipeline liquids are strikingly more variable than most operators seem to perceive. This variability may account for a large portion of the difficulty in characterizing scale deposition in pipelines.

DATA COLLECTION TO DETECT SCALE

Determining the temperature boundary which divides regimes of deposition and non-deposition (DND) requires an environment more controlled than a pipeline. To find a DND regime boundary we use a second electrode in an isolation chamber (IC) (Figure 2). The IC contains a sample of fresh pipeline liquid and has a controlled temperature. The IC is lined completely with Teflon, except where the dual electrode enters. It is filled through a Teflon liner inside stainless tubing that connects the chamber with the pipeline interior. In this way, fresh pipeline liquid can be admitted into the IC without contacting any metal surfaces between the pipeline and the dual electrode. Silica deposition is thereby focussed, at least to the extent that the metallic electrode surfaces provide a chemically "most suitable" site for silica deposition.

Monitoring T and AC in the IC has two advantages; (i) liquid composition is essentially stable in regard to charge carriers that determine fundamental conductivity and (ii) successive runs at different temperatures permit bracketing the DND boundary. Precision of measured values for T and AC are on the order of 1:1000, or better. Accuracy of actual T measurements is about ±1°C. Accuracy of measured AC is irrelevant; that is, relative values are sufficient if the measurement precision is adequate.

In principle, monitoring scale deposition in the IC is essentially an issue of watching for a decrease in AC while T is held (approximately) constant. At least two factors complicate that simple concept, so more sensitive techniques are needed. First, the chamber volume is small, about five milliliters, so the amount of silica available

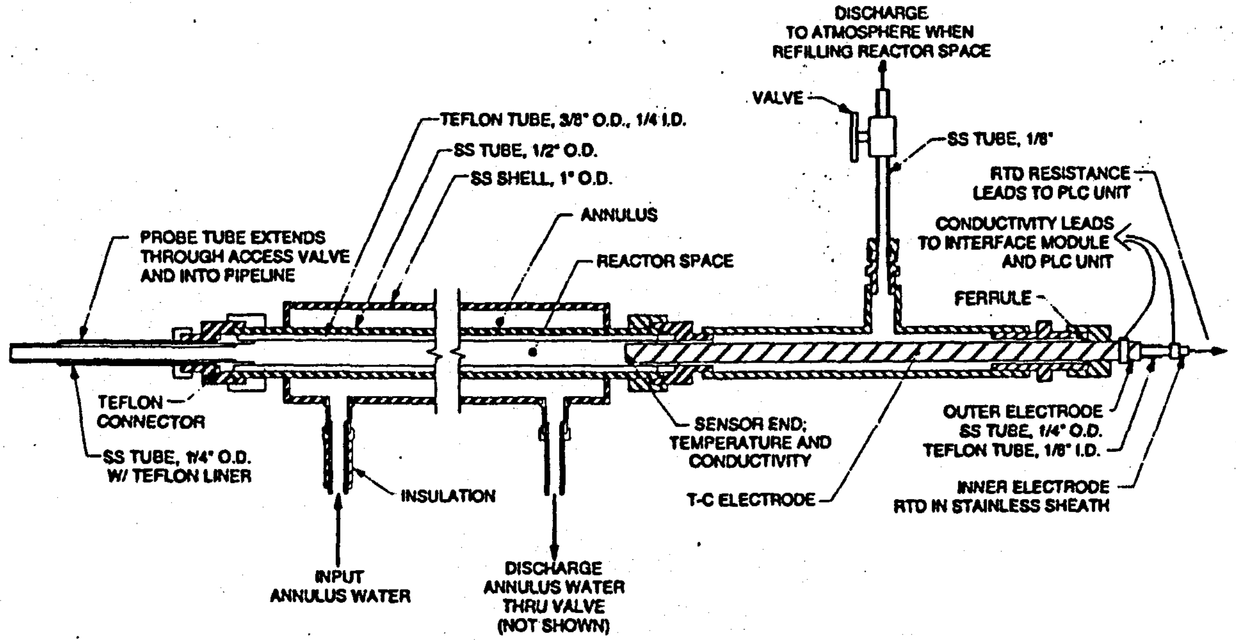


Figure 2: Reactor and T-C Electrode Setup

to deposit on the electrode, to satisfy some small over-saturation, may be minuscule. The effect of meager silica deposition on AC may be experimentally small and difficult to detect, especially when T is only slightly below the maximum temperature at which scale may form. Second, chamber temperature cannot be held steady enough to avoid the temperature effect on the true conductivity component of AC, blurring the simple detection of fouling effects.

The aspect of minuscule deposition of silica can be solved via successive fillings of the reactor. Under deposition conditions, successive fillings of the reactor chamber will result in successive increments of scale depositing on the electrode. As repeated depositions accumulate, successively decreasing values for AC indicate fouling of the dual electrode. Of course, this introduces complications due to variations in liquid composition (population of charge carriers) for successive fillings of IC. A sufficient compensation is achieved through monitoring the pipeline liquid continuously throughout the successive IC runs.

Curiously, solving the problem of conductivity variation due to unstable chamber temperature lies in forcing larger temperature changes on the chamber from time to time. In practice, chamber T can readily be held within a range of ±2°C via a jacket system that utilizes tempered pipeline liquid as a temperature control medium. The average temperature of the range represents the experimental T for a run which tests for silica deposition potential. By manipulating the jacket fluid temperature, a temperature change of 10 to 15 Celsius degrees (either + or -) can be impressed in the IC. The IC temperature subsequently approaches the run temperature during an interval of five to ten minutes, due to thermal inertia.

By analyzing the correlation between temperature and conductivity over that temperature range, conductivity at a reference temperature can be determined with very great precision.

DATA ANALYSIS

Precise analysis of data hinges on the fact that true conductivity and T are strongly linked. Specifically, the relationship between log conductivity and reciprocal absolute temperature may be taken as empirically exact over substantial intervals of temperature. Equation (1) applies:

$$\log(\text{conductivity}) = a + b/T_{abs} \quad (1)$$

In this form, the empirical value for (b) is dominated by the chemical aspects of dissolved charge carriers while the value of (a) is dominated by the physical aspects of electrode construction, chamber configuration, and electrode fouling.

By collecting data sets at a rate of six times per minute during the interval when IC temperature returns toward the run temperature, Eq. (1) can be used to determine values of (a) and (b). With linear least squares we find goodness of fit values exceeding 0.99.

Scale deposition may be inferred when calculated a-values display successive decreases for sequential fillings of the IC. Successive changes of (a) become convincing evidence of scale deposition at the experimental run temperature, even in the presence of modest variation in b-values. By repeating IC run series at a variety of run temperatures, the DND boundary for silica can be bracketed.

Precision of the method to detect and quantify scale effects is fundamental to success. Essentially, we aim to detect a minuscule amount of deposition under conditions where it will barely form at all, a challenging task in experimental sensitivity as well as precision. Through using two repetitive techniques, sequential fillings of the IC and monitoring of T and AC after repeatedly pulsing the IC temperature for a single filling of IC, there is (in principle) no limit to the precision of the method. Of course, experimenter patience, when changes happen slowly, and practical limits to available field time do impose limits that affect experimental sensitivity.

RESULTS

Examples of data obtained and interpreted can be summarized graphically. Figure 3 shows a time interval in which four data sets were obtained simultaneously, T and AC for pipeline liquid plus T and AC for the IC that was filled multiple times from that pipeline during the observation interval. For the pipeline, temperature variations (Fig 3A) appear fractal around a nominal value. Pipeline AC (Plot 3B) appears similarly fractal but is also subject to unpredictable changes in the nominal value. Four changes are prominent; near minute values 103, 140, 164, and 173. These variations of pipeline T and AC are taken to represent normal variations in the liquid discharged from a flashed steam separator.

For the IC, T (Fig. 3C) and AC (Fig. 3D) are highly correlated. Characteristic forms in both plots represent operations performed in the IC. Double reversal features represent refilling of the reactor. Cool liquid in the tubing which connects reactor with pipeline depresses T and AC soon after refill is begun. When fresh, hot pipeline liquid reaches the dual detector the first reversal occurs. The second reversal begins when the refill valve is closed. Then, T can begin to move toward the nominal run value. In Figures 3C and 3D, four IC refillings appear; near minutes 66, 108, 130, and 157.

By comparing the times of IC refills with pipeline AC (Fig. 1B), the IC refills at

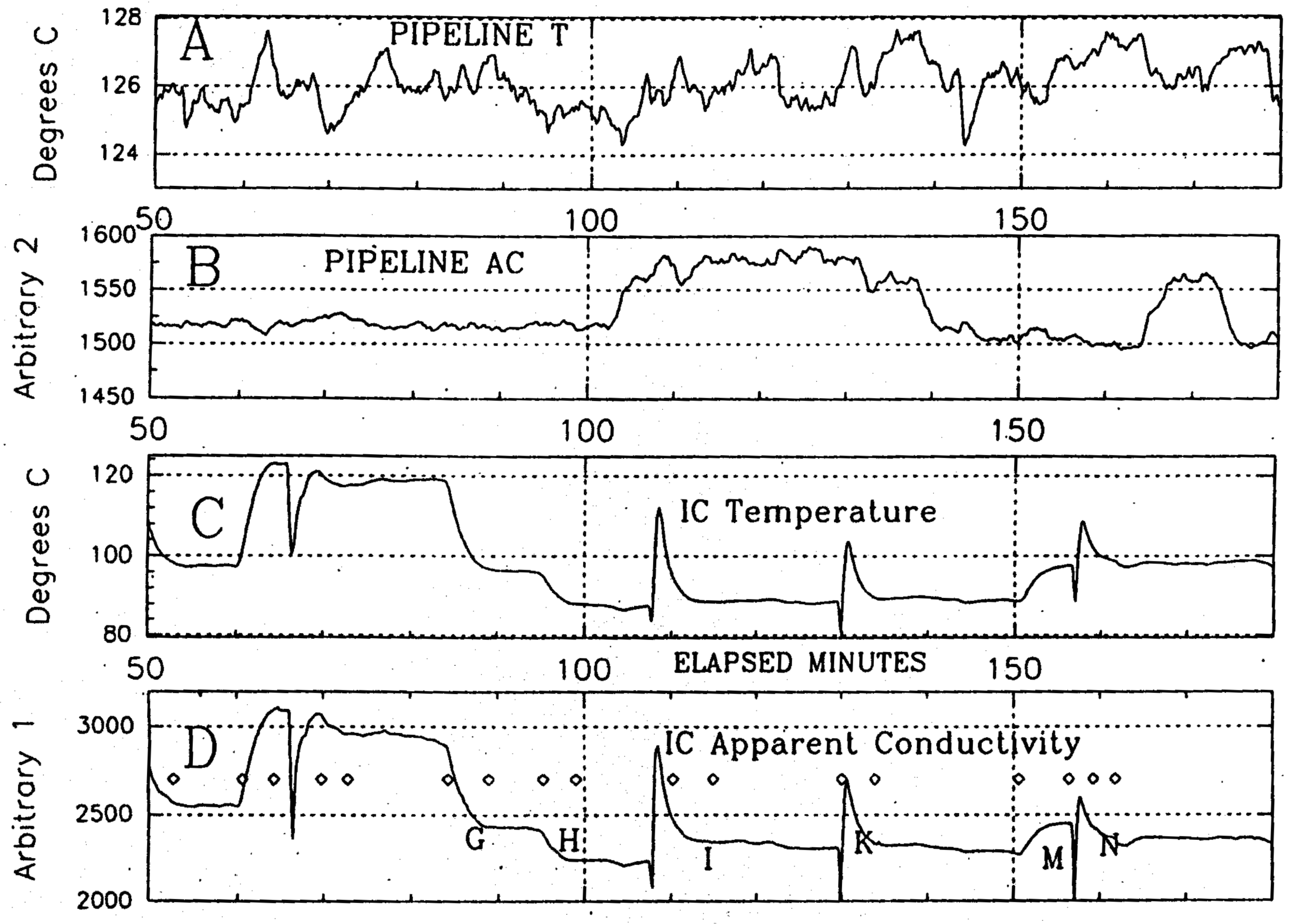


FIGURE 3: EXAMPLE DATA; FOUR SIMULTANEOUS CHANNELS

minutes 108 and 130 appear to sample a different liquid from refills at minutes 66 and 157. Similarly, the IC refill near minute 157 appears different from that of minute 66.

Step changes in T and AC of the IC represent temperature shifts impressed on IC by manipulations which modify the jacket fluid temperature. Four of these appear in Figures 3C and 3D, beginning near minute values 61, 85, 96, and 151.

Figure 4 shows values for T and AC plotted versus one another according to Eq. 1; that is, log(AC) versus $1/T_{abs}$. Figure 4 is a plot of y-axis values from Fig. 3C plotted versus y-axis values from Fig. 3D. Data sets used in Figure 4 correspond to the lettered intervals in Fig. 3D. For each interval, data points are plotted and thin lines are the linear least squares (LLS) fits to the data.

Slopes of the plots (except for N) are greatly similar, suggesting that compositional structures of the liquids are similar, even if the concentrations are not. The slightly contrasting slope for N suggests a modest difference (shift) in liquid composition structure.

The vertical offset of the several LLS lines is due jointly to different concentrations of charge carriers in the refill liquid parcels and fouling of the conductivity detector. We are particularly interested in whether the silica deposition can be identified separately from the concentration effect. Because the various data sets were obtained over different ranges of temperature, it becomes useful to find some reference condition to make comparisons more precise. The intersections of LLS lines with a line representing 100°C suffices.

An Indication of Silica Deposition

Consider intervals G and H in Figs. 3C and 3D. Both involve the same liquid filling of the IC, but represent two temperature shifts separated by an interval of relatively steady temperature. Experimentally, we are interested in whether or not some scale deposited during that intervening interval, when T was about 96.5°C. The LLS plots for G and H in Fig. 4 are clearly not co-linear and H has the lower intercept on the 100° reference line. This is the kind of shift in AC we expect due to silica deposition, suggesting that such occurred.

The IC refill made between intervals H and I appears to have sampled a liquid of intrinsically higher conductivity than was present during the G-H intervals, based on the plot of Fig. 3B. Accordingly, we are not surprised that the LLS intersection of the I-interval plot with the reference line occurs at a higher value than either the G or H plots. That is, the attempt to deposit another increment of silica on the electrode after the H interval may have succeeded, but the AC response is confounded by the compositional change.

A subsequent attempt, near minute 130, to deposit another increment of silica, appears to sample a liquid substantially similar in conductivity to that of the refill at minute 108. The K-interval for data applies.

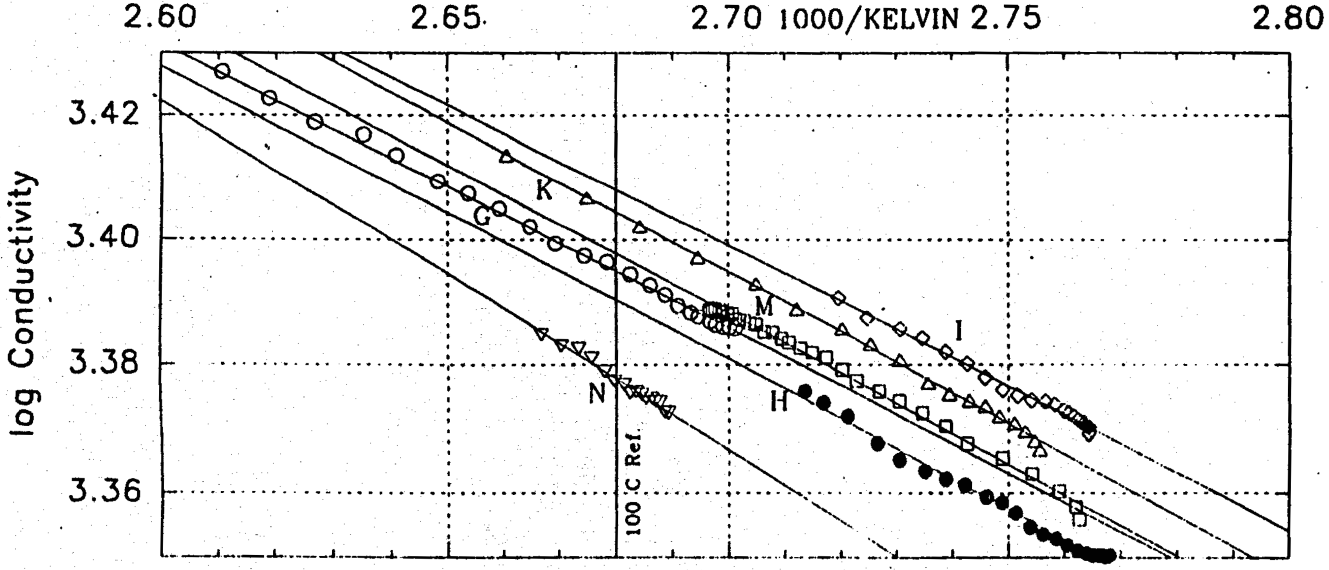


FIGURE 4: ANALYSIS OF logAC versus 1/T

In Fig. 4, the K-interval plot is not co-linear with I-interval and the offset is downward, consistent with the effect of scale deposition. Similarly, interval M (Figs. 3C and 3D) represents a temperature shift for the liquid admitted just before interval K. Its LLS intersection with the reference is successively lower than for K, suggesting that additional deposition on the electrode occurred during the 16-minute interval between K and M.

The refill near minute 157, intended to obtain another increment of scale deposition (interval N), is also confounded by the refill's having a lower intrinsic conductivity (Fig. 3B) than the refill for intervals K and M. Thus, intersection of the LLS line for interval N with the 100° reference is ambiguous.

Further Evidence for Silica Deposition

Subsequent to experiments with the IC, the dual electrode can be examined for the presence of scale and analysis made of any material found there. This was attempted following the runs which provided the data of Figures 3 and 4. No scale was found so no analyses were made.

However, an earlier version of the conductivity electrode used a solid rod for the center part. After removing the assembly from the reactor that rod could be moved outward and the end cut off with the deposited silica intact. This enabled an electron micrograph of the deposit; Figure 5. Confirmation of the silica composition was done by EDAX; Figure 6.

APPLICATIONS

We have devised a system for detecting silica scale deposition approximately in situ and almost in real time. The equipment is compact and light enough to be carried on an airplane as personal baggage.

Binary Power Plants and Injection Systems

This method was aimed initially at finding the boundary temperature between regimes of deposition and non-deposition for silica. Finding this boundary easily and unambiguously would assist the design of

Figure 5: Electron micrograph of silica; *in situ* on a conductivity electrode.

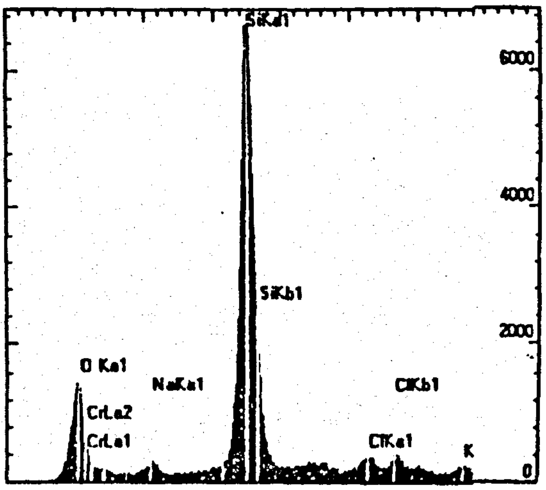


Figure 6: EDAX Spectrum for Fig. 5 showing silica dominance

binary power plants intended for resources where silica scale deposition on heat exchangers is a threat. Application also applies to protection of liquid injection systems associated with either flash- or binary-type power facilities.

Instead of estimating the silica deposition temperature for cooling (geothermal liquid) based on silica analysis and handbook solubility, this method will yield an empirical estimate of the temperature based precisely on the liquids involved with a specific geothermal field. This technique yields several useful data sets per day. Several experimental runs are required to accurately bracket the silica deposition boundary temperature, but such bounds can be identified in just a few days of experimental time. This is short compared to weeks or months involved with using skid-mounted heat exchangers to seek the same result. This method also involves no risks to the injection system.

Plant Monitoring

Importantly, precise, continuous monitoring of liquid electrical conductivity at one point along a pipeline, shows successive parcels of liquid have distinct and sharply differing compositions. These contrasts exceed the short-period variability that most operators expect from their geothermal resources, exposing a dimension of variability that has been under appreciated. Sampling geothermal pipelines has traditionally assumed that changes in liquid characteristics are slow, continuous, and minor. Our data show the changes to be sharp, irregular, and multiple during time intervals of a few hours. Recognizing this kind of variability would properly alter the sampling strategies commonly used.

Further study of the sources of this variability will likely impact strategies for resource management. Instrumentation developed for these studies can characterize basic geothermal produced fluids in ways that appear not have been made, so far.

Resource Assessment

Continuous, precise monitoring of pipeline liquid temperature and conductivity could greatly assist the work of hydrologists and geochemists by informing them of variations over time. These variations may signal important events within the reservoir, as well as in plant behavior. Patterns of change are important and can be found by using equipment developed for this project. When so informed, hydrologists and geochemists could better know what might be represented, and not represented, by the data they collect, either routinely or for special studies. By exposing patterns in liquid conductivity and temperature, hydrologists and geochemists could be better guided in regard to when to measure key parameters and in deciding the limits for what their measurements represent.

ACKNOWLEDGEMENTS

This work was supported by US Department of Energy Contract DE-FG07-97ID13532. We are grateful to Caithness Energy, L.L.C., Oxbow Power Services, and Instituto Costarricense De Electricidad for access to their geothermal pipelines and assistance in their fields. DEM is especially grateful to Antonio Yock Fung for his assistance and support while in Costa Rica.

APPENDIX E

DETERMINATION OF SILICA SCALE DEPOSITION RATES AND THRESHOLDS APPLIED TOWARD PROTECTION OF INJECTION RESERVOIRS

INSTRUMENTATION

General Description

Initial plans for the instrumentation included a single channel of conductivity measurement and a single channel of temperature. Both were to be measured in the sample chamber within close proximity of each other. After some early field trials, a second channel was added so that pipeline conductivity and temperature could be monitored. It had been noted that significant variation from sample to sample might be due to fluctuations in the pipeline itself.

Figure 1 is a block diagram of the instrumentation. The programmable logic controller (PLC) was used to facilitate data acquisition. In addition to programmability, the PLC is a low cost approach to signal conditioning that offers flexibility, ease of expansion, and industrial reliability. The PLC was fitted with four input/output (I/O) modules.

The first module, a 4-channel 4-20 mA current loop input module, was used to acquire conductivity data. The second module, a 4-channel RTD input module, was used to acquire the temperature data. The third module, a 4-channel 4-20 mA current loop output module, was used initially to output conditioned data to a pair of conventional dual-pen chart recorders. The fourth module, a 4-channel 24 Vdc discrete output module, was installed in anticipation of automated sample acquisition using solenoid valves; however, no automation was ever attempted.

The chart recorders shown in Figure 1 were abandoned when it was determined that more sophisticated data processing would be necessary than that possible from simple chart analysis. The laptop computer in the figure replaced the chart recorders. Software installed on the laptop computer included LabView from National Instruments, and Microsoft Excel. LabView provides powerful capabilities for data acquisition, and was used to communicate with the PLC, graphical presentation of data during a test, and preliminary data processing such as scaling, averaging, and logging. The data log file produced by LabView during a test was saved to disk for subsequent analysis using Excel. A block diagram depicting this sequence is shown in Figure 2.

Conductivity and Temperature Measurement

Initially, conductivity and temperature were measured with separate probes. Although in close proximity, there was a noticeable lag between the temperature and the conductivity. To reduce the lag time, and to ensure that temperature measurements were representative of the actual temperature near the conductivity sensor, the probe design was modified. Instead of a solid rod for the center electrode, an RTD was used so that temperature and conductivity could be sensed simultaneously on the same surface. The RTD was a fast response probe, 0.125" in diameter, containing a 100 Ω (at 0°C ±0.1 Ω) platinum element, manufactured by MINCO Products, Inc.

Conductivity signals were produced with the aid of a general purpose conductivity transducer, model CTC, manufactured by Sensor Development, Inc. The transducer combines several functions necessary for conductivity sensing. First, the transducer supplies the excitation needed to develop an electrical signal. The CTC incorporates a 50 kHz square wave oscillator and driver electronics for excitation purposes. The conductivity signal resulting from the excitation is sensed on the inner electrode which is connected to the CTC signal conditioning electronics. The signal is filtered, measured, and scaled in this part of the transducer. Finally, a 4-20 mA current loop signal is produced for input to the PLC. Figure 3 is a block diagram depicting the major functions of the conductivity transducer.

In operation, interference between probes was found when both conductivity probes were driven by their respective excitation circuits. To avoid the interference, it was necessary to drive both probes with the excitation source from only one CTC transducer. The signal conditioning circuits were monitored separately. This greatly reduced the cross-channel interference caused by dual excitation.

Recommended Improvements

Improvements in the instrumentation are recommended for future work. A newer laptop computer, with CPU clock speed of 200 MHz or greater, is strongly recommended. The laptop computer used in the field tests was a 20 MHz, circa 1991 vintage, PowerBook 160. It was barely adequate for LabView, and could only run a version of Excel several versions older than the current one.

Improvement of the conductivity transducers is also recommended. The model CTC transducers have dipswitches which must be changed manually to set the full-scale range for optimal resolution. Better access to the switches is an obvious improvement, but better still would be a method which changed ranges automatically. Another improvement which might also provide the automatic ranging feature, would be a controllable excitation system for the probes. Such a system could utilize the PLC to apply an initial excitation and sample the response. If a larger or smaller response is needed, the PLC could adjust the output of the excitation system accordingly. It could also be used to apply the excitation selectively, to one probe or the other, to avoid the interference that was found using both the CTC transducer sources at the same time.

A final area of improvement is the conductivity probe connections. Various means of attaching the leads to the stainless steel probe tubing were employed, including common alligator clips. The alligator clips performed well in the desert environment of Nevada and Southern California, but failed in the warm humidity of Costa Rica. Special clamps were fabricated in the field and proved to be successful. However, further improvement is warranted, since the field fabricated clamps were awkward and required tools to make or unmake a connection.

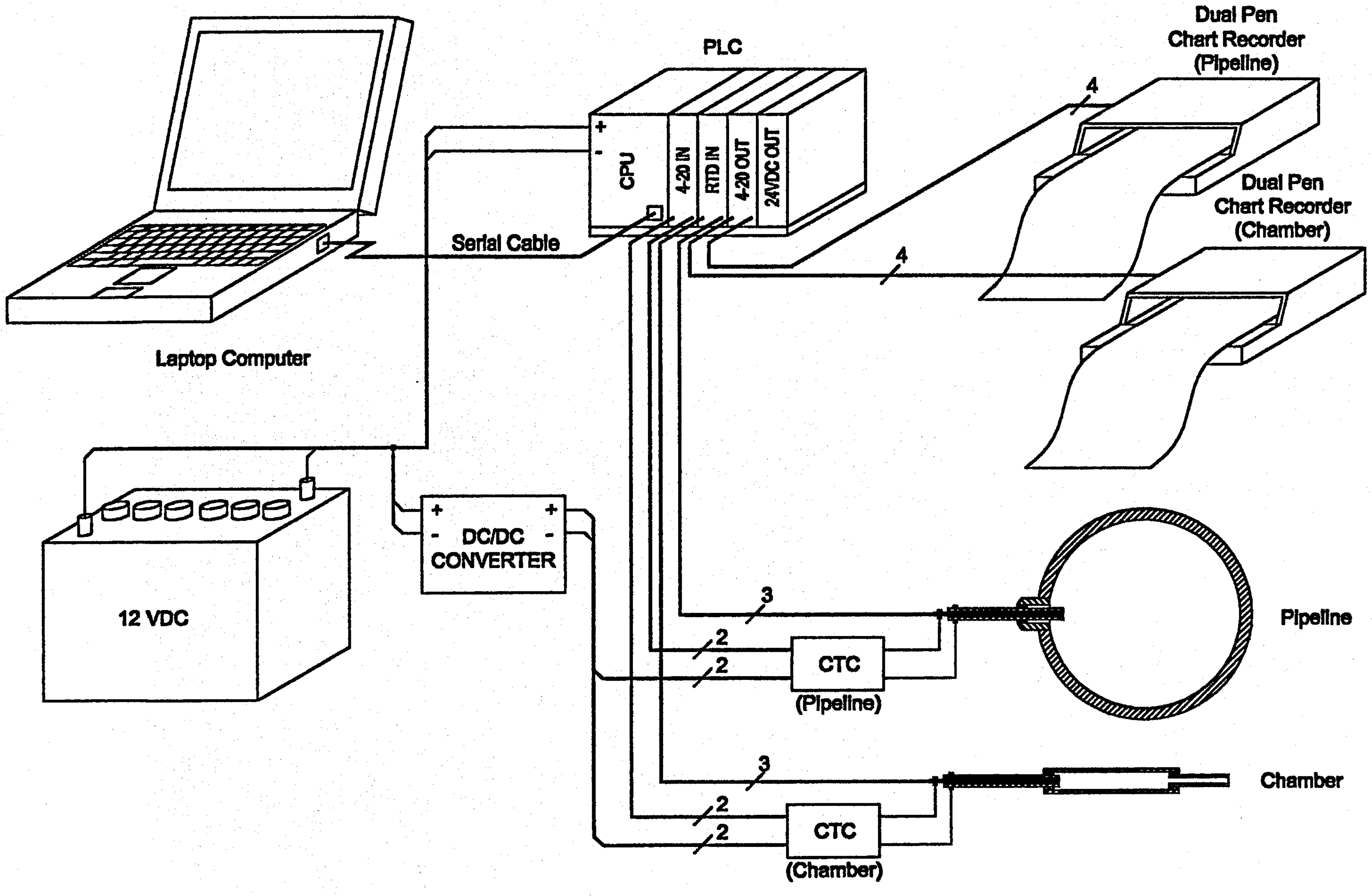


Figure 1: Instrumentation Block Diagram

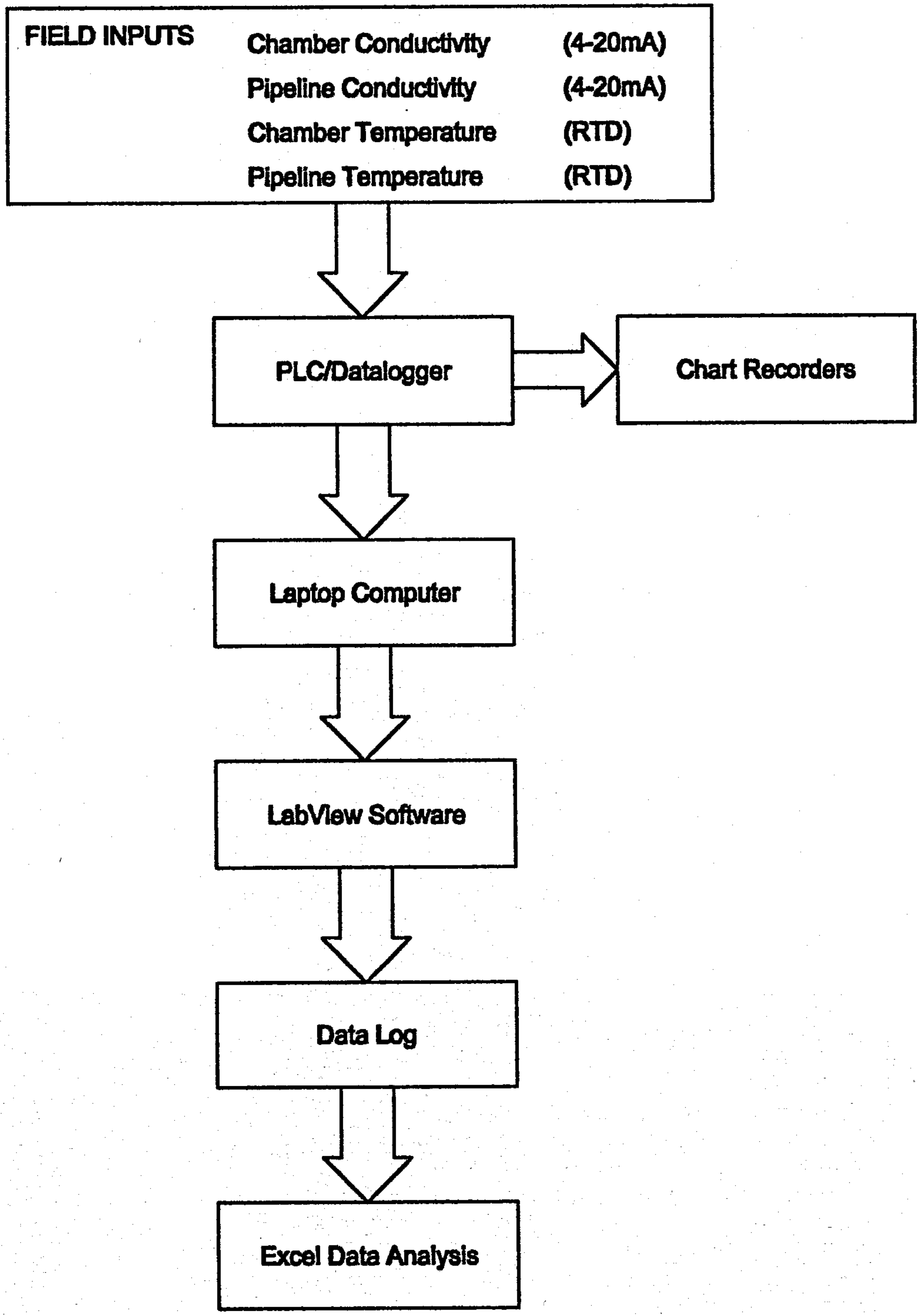


Figure 2: Data Acquisition and Analysis
Data Flow Block Diagram

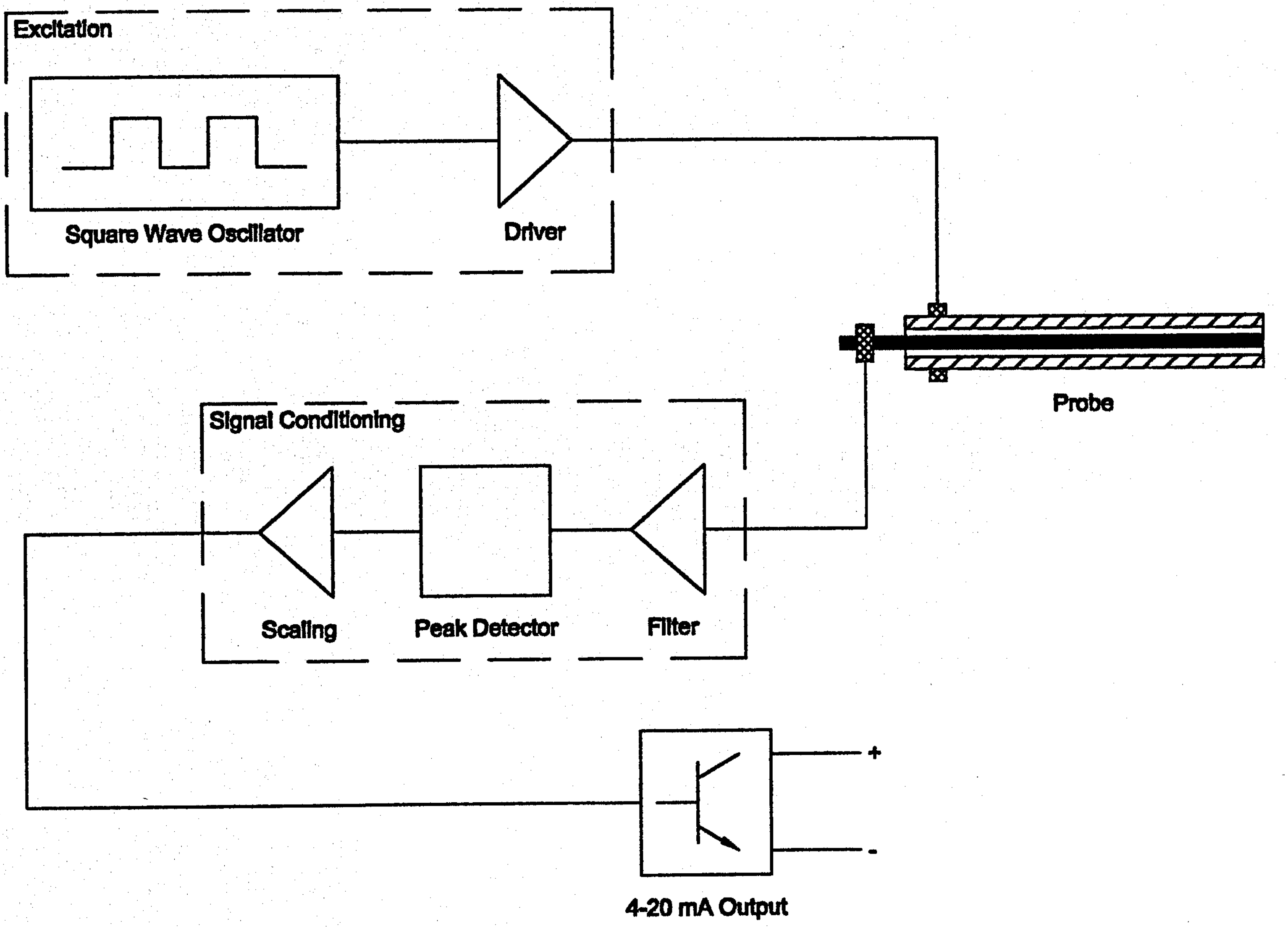


Figure 3: General Purpose Conductivity Transducer Block Diagram

APPENDIX F

DON MICHELS ASSOCIATES
P.O.Box 8652
Missoula, Montana 59807
Ph. 406/728-2578; FAX 406/721-7871

16 July 1999

Dr. Alfredo Mainieri Protti
Instituto Costarricense De Electricidad
P.O. Box 10032-1000
San Jose, Costa Rica

Subject: Silica Scaling Studies

Dear Alfredo:

The project to determine silica scale deposition rates and thresholds by monitoring apparent electrical conductivity, reached the end of its DOE funding term on June 20, 1999. Copies of our reports will be sent to you separately.

Overall, we were mostly successful in designing and constructing a system that appears to work in fundamental ways, but requires additional testing to attain statistical assurance. Unfortunately, we did not achieve all of our practical objectives, including the threshold which we believe is necessary to assist ICE in its selection of temperatures for the power plant bottoming cycle. Unfortunately, the data we obtained at Miravalles was not straight forward, it being negatively affected via instrumental malfunction or associated with real processes that were not readily determinable.

Martin and I want to thank you and all the others in ICE who worked with us so diligently on the project. Especially, I wish to thank Antonio Yock for the large amount of time and effort he used to help me while in Costa Rica.

The status of our work at Miravalles is certainly worth describing with some detail, considering the overall project results indicate we are close to achieving the project objectives. I'd like you to refer to the attached commentary.

It is our hope that the project results will be sufficient to encourage follow-on funding. In the not-to-distant future, we would like to be able to offer ICE this completed technique for use at Miravalles, as was originally anticipated.

Again, thank you and your associates at ICE for your abundant courtesies and efforts.

Respectfully,

Donald E. Michels

Approved: w/attachment

GMB/fc
G. Martin Booth, III
Project Manager
Geothermal Development Associates
Reno, Nevada

Dr. Alfredo Mainieri 16 July 1999 **Attachment 1**

Comments on Results at Miravalles

Dear Alfredo:

Please recall a few moments last December, when you were visiting my instrumentation setup at S-3. Among other subjects, one was greatly puzzling; the change in (apparent) electrical conductivity of liquid in the experimental chamber upon an impressed change of temperature (TC relationship). Normally, C is highly proportional to T, [$\log C = a + b/T_{abs}$] and sensors for T and C show an almost lock-step relationship. I expected to find small contrasts in successive TC relationships that could be interpreted in terms of silica deposition.

However, at S-3 we found a greatly different correlation between C and T when the experimental chamber was refilled with fresh pipeline liquid. Part way through the refilling, when T and C were both rising, the change in C reversed sharply. Then, after completion of the refill, when T began to fall, C began to rise. That rise in C during a smooth fall in T followed an irregular trace that was repeatable in successive trials. The magnitude of the C increase was greatly larger than could be accounted for by any reasonable suggestion about the changing concentrations of charge carriers in the liquid. Significantly, when the experimental chamber was simply heated (or cooled) by changing the heat exchanger settings <u>without</u> exchanging experimental liquid, a normal TC relationship was always observed. Thus, the cause of the unusual relationship appeared genuine, but how we might interpret it was obscure.

Later, during the evening of that day, I suggested to you that if a way to interpret that unusual TC relationship could not be found then we could not provide guidance to ICE about silica deposition temperatures that might be useful in the design of your power plant bottoming cycle. I even speculated, hopefully, that some ionic feature of the silica deposition reaction might be involved and we had stumbled on a means to detect it.

Subsequently, we made more field experiments in the USA. They suggested the unusual TC relationship was an artifact of the conductivity electrode. When using the same electrical and electronic setup in a California geothermal field as we used at S-3, specifically including the same electrode, an unusual TC relationship was observed. Although it had several similarities to the one observed at S-3 it also had several contrasts.

After those tests, that electrode was reconstructed at the California field site by replacing the Teflon insulator that filled the annulus between the outer sheath and the inner electrode. The reconstructed electrode, when put into the electrical and electronic setup in California, yielded the normal, proportional, TC relationship without reversals or irregularities.

Ordinarily, I would let the matter drop at this point -- seemingly an unfortunate instrument malfunction. However, three factors make me uneasy with that simple choice. Firstly, the unusual behavior at S-3 was reproducible and was substantially reproduced also at PGM-22, during my last day of field activity in Costa Rica. Furthermore, the TC relationship observed in California was also mainly reproducible, even though contrasting in several details with the S-3 relationship. Such repeatability suggests an attachment to a real physical phenomenon.

Secondly, the unusual TC relationship was only observed when the liquid was exchanged in the reactor; a normal TC relationship occurred when a simple temperature pulse of similar magnitude was impressed on the reactor.

Thirdly, differences between the Teflon insulators before and after reconstruction of the electrode do not seem large enough to explain the great changes in electrode behavior. Both Teflon insulators came from the same piece of manufactured tubing. The reconstructed electrode involved a single piece of Teflon whereas the other version had two pieces. The pieces were intended to touch, about 2.2 cm from the sensor end of the electrode. Although a gap between pieces of insulation would provide a conductive path between the outer sheath and inner electrode, it seems not reasonable to expect that gap, or conductive ions within it, to yield the several-fold changes in conductivity that were observed during temperature shifts. In no case can the metallic area presumably exposed by that gap be more than a small fraction of the area of the electrodes at the sensor end. Accordingly, I am suspicious that we have more, and significant, things to learn about detecting silica scale via measurements of electrical conductivity.