Geothermal Heat Exchanger Test at Heber, California

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Prepared by
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Pasadena, California

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Geothermal Heat Exchanger Test at Heber, California

ER-572
Research Project 846-1

Final Report, August 1978

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ABSTRACT

A tube-in-shell counterflow heat exchanger, having four sections in series, was tested for approximately 2000 hours under field conditions. The objective of the test was to measure long term corrosion and fouling rates for use in commercial plant design. The geothermal brine used in the test was produced from the Nowlin No. 1 well at the Heber geothermal field in California. Alternate sections of the heat exchanger were tubed with steel and titanium. The purpose of two material types was to facilitate data on both from a single test. Heat transfer degradation was calculated throughout the test. At the conclusion of the test, the tubes were removed, sectioned, and analyzed. Heat transfer coefficients, fouling factors, corrosion rate and scale characteristics are reported.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This is the final report for the Geothermal Heat Exchanger Test at Heber, California under Research Project 846-1 which investigated the corrosion effects of the Heber-type geothermal fluid on mild carbon steel and the scaling effects on carbon steel and titanium. Prior data of this type was based on short intermittent tests and had limited application. Previous tests at this site had indicated severe pitting corrosion on carbon steel heat exchanger tubing, while there was some evidence from other sources, although meager, that pitting should not be as severe as observed. As a result of bits and pieces of information from different sites, the role of exposure to oxygen in the air due to operating conditions was not clear, but was a prime suspect. It was speculated that if exposure to oxygen were reduced, the pitting would also be reduced.

PROJECT OBJECTIVES

In contrast to earlier heat exchanger work, the goal of this project was to develop corrosion and scaling data by means of continuous, near steady state tests for at least 2000 hours. Further objectives were to investigate corrosion rates (both uniform and pit growth) for carbon steel, scaling rates for both carbon steel and titanium and scale characteristics such as thickness, density, thermal conductivity and composition. Care was taken to limit exposure of the heat exchanger tubes to air.

CONCLUSIONS AND RECOMMENDATIONS

The uniform corrosion rate for the mild carbon steel was reported to be equivalent to about 0.3 mils/year, not particularly severe. The investigators reported no pitting or crevice corrosion as noted in earlier tests at the same site, RP376-1, thus suggesting that intermittent exposure to oxygen may have a more detrimental effect than long term steady state exposure to this particular geothermal brine.

An independent laboratory also analyzed the tube samples. They concluded there was evidence of pit growth, but that the rate of growth was probably not greater than 0.3 mils per year.

The results of this work suggest that the use of carbon steel tubes can be considered for service at Heber, if precautions are taken to prevent excessive exposure to air during start-up, shutdown and maintenance operations.

Vasel Roberts

Fossil Fuel and Advanced Systems

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Section 1

SUMMARY

In 1976 the Electric Power Research Institute commissioned The Ben Holt Co. to study the heat transfer characteristics of a shell-and-tube exchanger in geothermal brine service. The Heat Exchanger Test Unit (HETU) used in this test had been previously used by San Diego Gas & Electric Company in 1975 in a preliminary series of tests. The objective of the current program was to test both steel and titanium tubes for 2,000 hours in geothermal brine service to obtain reliable information on corrosion of heat exchanger tubes and exchanger fouling that could be used to design a commercial plant.

The HETU is made up of four 20-foot long exchanger sections connected in series. Each section contains four 3/4-inch, 16 gauge tubes. The unit operates by exchanging heat from the incoming brine to a recirculated stream of treated water. The exchanger sections are arranged as follows:

<u>Section</u>	<u>Description</u>	<u>Material</u>	<u>ASTM Specification</u>
E-1	Brine inlet	Steel	A-179
E-2	Second in series	Titanium	B-338
E-3	Third in series	Steel	A-179
E-4	Brine outlet	Titanium	B-338

The HETU was cleaned and instruments and controls were overhauled prior to startup of the test program.

The test was started 1 November 1976 and continued for 2,034 hours operation with only minor shutdowns such as for power failure. During the test, brine

and treated water temperatures were recorded continuously at the inlet and outlet of each heat exchanger section. Heat transfer coefficients were calculated at two-hour intervals for each section. These data have been plotted, and equations derived to describe the change in the coefficients.

At the completion of the test the tubes were removed from the HETU, and examined using a scanning electron microscope. Photomicrographs of the scale were taken which showed the structure and thickness of the scale. Analyses of the scale were obtained using the scanning electron microscope in conjunction with an X-ray analyzer. The photomicrographs and the X-ray analyses of the scale are presented in the report.

Chemical analyses of the Nowlin No. 1 well brine and the noncondensable gases present in the brine are also presented in this report.

Overall heat transfer coefficients were calculated as follows:

<u>HEAT TRANSFER COEFFICIENT, Btu/(hr)(ft²)(F)</u>		
<u>Section</u>	<u>Clean Tube Coefficient</u>	<u>365 Day Coefficient</u>
E-1	890	569
E-2	639	542
E-3	741	395
E-4	553	402

The following fouling factors were calculated for the exchangers:

<u>Section</u>	<u>365 Day Fouling Factor, (F)(ft²)(hr)/Btu</u>
E-1	.000576
E-2	.000280
E-3	.001182
E-4	.00679

The thermal conductivity of the scale was also calculated.

<u>Section</u>	<u>Conductivity, Btu/(hr)(ft)(F)</u>
E-1	0.490
E-2	0.160
E-3	0.345
E-4	0.143

No pitting or crevice corrosion was observed on either the steel or the titanium tubes. The scale deposits on the steel tubes contained about 30 percent iron whereas the deposits on the titanium tubes contained no iron. If this iron is a corrosion product from the tube wall, the corrosion rate would be 0.3 mils/year, which rate would be acceptable in a commercial plant.

An analysis of the uncertainty of the data and the calculated results are presented in the report.

The conclusions reached in this study are as follows:

1. Either steel tubes or titanium tubes could be used in a commercial geothermal plant. Scale deposition would be more rapid on the steel tubes.
2. The scale deposited on the steel tubes contains silicon, iron, antimony, arsenic, and sulfur. The scale is brittle and can be easily scraped from the tube surface.
3. The scale deposited on the titanium tubes is primarily antimony sulfide. This scale is a loose amorphous deposit which can be easily scraped from the tube surface.
4. An analysis of the noncondensable gases in the Heber brine showed that the gas constitutes only .0049 weight percent of the brine. The gas contains 0.36 mol percent hydrogen sulfide.

The study "Geothermal Energy Conversion and Economics - Case Studies", EPRI Report No. ER-301 prepared by Holt/Procon in November, 1976 recommends that the Heber Reservoir be selected as the site of the Geothermal Demonstration Plant, and that an energy conversion plant be constructed there with a capacity of 50 MWe. This heat exchanger study provides additional data which confirm that the recommended plant would be feasible to build and operate.

The test results show that the Heber brines are not severely corrosive, and that scale deposition as a result of cooling the brine will not seriously reduce the plant operating efficiency. These characteristics of the brine give credence to the economic studies in the November report which were made assuming that the energy conversion plant could operate with an 85 percent availability factor.

The study further defined the chemical quality of the constituents present in the brine. The high salinity of the brine necessitates reinjection into the reservoir. The analysis of the noncondensable gases present in the brine confirms that hydrogen sulfide is present in the brine in such a low concentration that it would not constitute a hazard if a brine spill should occur.

Section 2

INTRODUCTION

In June 1976, the Electric Power Research Institute (EPRI) commissioned The Ben Holt Co. (Holt) to perform a test program to measure the performance characteristics of a shell-and-tube heat exchanger in geothermal brine service. The test program was designed to simulate conditions in a binary cycle geothermal conversion plant using brine from the Heber geothermal reservoir.

The Heat Exchanger Test Unit (HETU) used in this test was designed and built by Holt for San Diego Gas & Electric Company (SDG&E). In 1974 and early 1975, SDG&E used the HETU to study heat exchange between the effluent of Chevron Oil Company's Nowlin No. 1 well and treated cooling water in a closed cycle. Tests were conducted using steel, stainless steel and titanium tubes in the HETU. The duration of individual tests varied from 200 to 560 hours. The results of that work were presented in a report prepared by SDG&E for EPRI titled "Test and Evaluation of a Geothermal Heat Exchanger, at Heber, California", RP-376, September 15, 1975.

The duration of the SDG&E tests was insufficient for a detailed examination of tube corrosion. Operating periods were too short to develop an adequate layer of scale for analysis or for prediction of long range heat transfer coefficients. The prediction of heat exchanger performance for operating periods up to a year's duration based on these data, would have a significant element of uncertainty.

The current test program extended the test duration to 2,000 hours to provide an adequate period in which to observe the precipitation of scale on exchanger surfaces and to measure any corrosion of the exchanger tubes that might occur.

The project was jointly funded by EPRI and the California State Energy Resources Conservation and Development Commission (ERCDC).

The specified objectives of the test program were:

1. Measure the fouling characteristics of the Heber Geothermal Brine from Chevron's Nowlin No. 1 well in contact with titanium and steel heat exchanger tubes.
2. Determine the uniform and localized corrosion rate of carbon steel heat exchanger tubes induced by Heber geothermal brine, and from the results estimate the useful life of the tubes.
3. Determine the uniform and localized corrosion rate of titanium in the same service and estimate its useful life.
4. Determine the scaling rates of both carbon steel and titanium tubes and estimate the required frequency of cleanouts for scale removal.
5. Analyze the scale for physical properties, thermal conductivity, and chemical composition.
6. Determine whether there are any step functions in scaling rate and evaluate them if found.
7. Determine the chemical composition and pH of the brine, and the amount and composition of noncondensables that may be dissolved in it.

The results of this investigation are contained in this report.

Section 3

TEST EQUIPMENT

The Heat Exchanger Test Unit (HETU) is made up of four 20-foot long exchanger sections connected in series. Each section was tested and analyzed separately to identify the effect that brine temperature has on scale deposition, fouling factor, corrosion, etc.

Each section has four parallel 3/4-inch, 16 gauge tubes. Each tube is installed concentrically within a 1-inch Schedule 40 steel pipe. Geothermal brine was circulated in the tubes and treated water was circulated in the annulus in countercurrent flow. The treated water flows from the HETU to an exchanger which removes the sensible heat by exchange with cooling water. The treated water is then recycled back through the HETU. The spent brine is re-injected into the geothermal reservoir at the Holtz No. 2 well.

The testing of both steel and titanium tubes in geothermal brine service presented the following technical and budgeting problems: (1) The HETU could not be modified for parallel testing of the two tube materials without extensive alterations. (2) Budgeting limitations prevented our testing the two tube materials in consecutive 2,000 hour tests. (3) If mixed tubes (steel and titanium) were used in a single heat exchange section, the difference in the scale deposits could result in interaction between the tubes and a possible imbalance of flow.

To resolve these problems EPRI decided that steel and titanium tubes would be used in alternate sections of the exchanger. The exchanger sections were assembled in the sequence listed below:

<u>Section</u>	<u>Description</u>	<u>Material</u>
E-1	Brine inlet section	Steel
E-2	Second in series	Titanium
E-3	Third in series	Steel
E-4	Brine outlet section	Titanium

Figures 3.1 and 3.2 show two different views of the HETU. Drawing 7331-D-1301 shows the mechanical details of one of the exchanger sections and the general arrangement of the four sections. Drawing No. 7616-E-3202 is a piping and instrumentation diagram of the skid-mounted HETU.

After SDG&E concluded their tests in 1975, the HETU remained idle at the site of Nowlin No. 1 well for more than a year. During this period, some instruments and other equipment from the HETU were removed for use in other operations. It was therefore necessary to give the HETU a thorough overhaul and to replace missing equipment. Because of the lack of local specialized labor and facilities in the Heber area, the HETU was shipped from the test site to Holt's laboratory in Long Beach, California for repairs. To rehabilitate the HETU the following actions were taken:

1. The HETU piping network was thoroughly cleaned by flushing with water, and hydrostatically tested at 150 psig and ambient temperature.
2. All instruments left by SDG&E on the unit were removed and sent to Instrument Specialists Company of Long Beach, California, for reconditioning and calibration.
3. Pumps P-1, P-2 and P-3 were sent to Ingersoll-Rand's Western Service Center in Los Angeles for overhauling.
4. New instruments and auxiliaries were ordered to replace those that had been removed from the HETU.

5. The treated water cooler was severely plugged. All attempts to repair it by physical and chemical means failed. It was necessary to retube the exchanger completely.
6. All new and reconditioned instruments and equipment were installed on the HETU at the Holt laboratory, and the refurbished unit was shipped back to the Nowlin No. 1 well site.

The Cooling Tower CT-1 was cleaned and the fan and motor were reconditioned at the site. A package unit for addition of chemicals and control of cooling water quality was purchased from Water Chemists, Inc. and installed.

At the test site some piping sections and valves had been removed for use in other operations. To operate Nowlin No. 1 well for the Holt test, the piping network had to be reconditioned and modified. Drawing 7616-C-3201 is a piping and instrument diagram of the subject facilities. Dotted lines indicate missing items. To prepare Nowlin No. 1 well for operation, the following actions were taken:

1. Flow Recorder FR-201, Flow Element FE-201, Pressure Recorder Controller PRC-202, two 6-inch check valves, and the relief valves on V-201 and at the discharge of the Booster Pump P-202A, were shipped to Long Beach, California for repair, reconditioning, and recalibration as required.
2. To accommodate the much lower flow rate attending self-flowing of Nowlin No. 1 well, the meter run on flow element FE-201 was changed from 6" to 3".
3. Two water storage tanks were installed; one for storage of cooling water, and one for storage of cooling tower blowdown and any other plant effluents.
4. An air compressor and dryer were rented and installed to supply instrument air for operation of instruments at the well and at the HETU.

5. A high-head pump P-202A was installed for injecting Nowlin No. 1 brine into the injection line to Holtz No. 2 well. This pump was rated to deliver Nowlin No. 1 brine at 500 psig to the point of junction with the Holtz No. 2 injection line. This pressure was required, according to Chevron data, when Jackson No. 1 well was discharging into the injection line at the expected maximum rate.
6. Pressure Controller PC-202 was located upstream of P-202A to maintain a positive pressure in the HETU system. This change was necessary to prevent flashing in the Nowlin No. 1 system when the injection line pressure dropped to a low level because of curtailed or interrupted operation of Jackson No. 1 well.
7. Blowdown Pump, P-201 was reconditioned at the site. A line from the pump discharge to T-201 was added to recirculate the tank contents and thus effect mixing of chemicals added before disposal by injection to Holtz No. 2 well.
8. A gate valve was installed on the 6-inch outlet line of V-201, and two 3-inch branch lines with valves were installed just up and downstream of the 6-inch valve. The arrangement was requested by EPRI to serve in work contemplated by SDG&E.
9. All other lines and valves shown dotted in Drawing 7616-C-3201 were installed.
10. The assembled piping network was thoroughly flushed with water, and instrument lines were blown with air to remove scale and debris.
11. The HETU was connected to the 6-inch Nowlin No. 1 brine line between the Sand Separator V-201 and Booster Pump P-202A so that the Nowlin No. 1 production over and above that required by the HETU would bypass the HETU.

Figure 3-1 East Side of HETU
with Pumps and Instrumentation in Foreground

Figure 3-2 View of HETU from Southwest
Showing Exchanger Sections and Electrical Controls

Figure 3-3 Brine Test Exchanger

Figure 3-4 Brine Test Exchanger

Section 4

TEST PROCEDURE

The heat exchanger test project involved three phases. Phase I consisted of preparatory tasks and system shakedown. Phase II involved data logging of the brine flow through the HETU. Phase III was the termination of the test and preparation of the exchanger tubes for analysis.

PHASE I

Reconditioning of the test site started 9 September 1976 and continued up to the start up of the test unit. Several days were devoted to field repairs of the piping and instrumentation. Piping repairs were given top priority so that the flow of brine could be initiated as soon as possible. These repairs involved dismantling of entire strings of pipe to replace corroded fittings and valves, and installation of control valves with associated pneumatic equipment.

When the end of the piping repairs was in sight, brine production from Nowlin No. 1 was initiated to stabilize flow and preheat the piping system. The HETU was bypassed and the brine was reinjected at Holtz No. 2.

After three days of stable flow the piping repairs were completed and flow was started through the HETU on 1 November 1976. Several more problems surfaced and seven more days of downtime were required to cope with these new problems. The major difficulty was pump failure. New bearings, unions and seals were installed on two pumps. One pump had a cracked outlet flange. It was repaired by field fabrication of a backup brace. When the system

finally could contain fluids without leaks, the brine and treated water were allowed to flow and work on the instruments was started.

The pneumatic control system was found to be contaminated, and further cleaning of the lines and instruments was required. Some instruments required complete dismantling for cleaning.

The Brown-Honeywell temperature recorder was found to be out of order. The unit performed erratically, and several weeks were required to correct the defect. During this time, data obtained had to be critically evaluated to prevent inclusion in the record of incorrect information. Local repair services were not familiar with the machine, and Honeywell Company did not have an area representative. Repair was finally accomplished by Holt personnel. During the interim that the temperature recorder was not in service, a laboratory potentiometer was used to record the temperature of the brine through the various exchangers. During this period it was discovered that some thermocouples used to sense the temperatures of the brine and treated water in and out of each exchanger section were short-circuited within the thermowells causing erroneous readings. Thereafter, the thermocouples themselves were checked for accuracy by comparison with a calibrated mercury thermometer on at least a weekly basis.

Phase I was completed when all the recording equipment was made operable.

PHASE II

Continuous logging of data began 12 November 1976. Almost immediately, the differential pressure cells (DP cells) and the flow meter transmitters failed. The DP cells were repaired, but within two days, failed again. Pressure differences observed were below the range of the recording equipment and it was apparent that no pressure difference would develop until a significant deposit of scale had accumulated in the tubes. Henceforth, differential pressures were obtained by observing inlet and outlet pressures on gauges.

The flow meters could not be repaired without prolonged system shutdown. Consequently, a Fischer-Porter rotameter was purchased and installed on the brine flow. This could be done without shutdown. No flow meter was installed on the treated water loop because shutdown of the HETU would have been required. Flow rates for the treated water were calculated using the brine flow rate together with a heat balance across each exchanger section.

Brine flow was set at $4.09 \text{ M}^3/\text{hr}$ (18 gpm) which corresponds to a liquid velocity of about 1.5 m/s (5 fps) in the exchanger tubes. The flow of treated water in the HETU was set to produce a temperature drop of about 99 C (210 F). This condition resulted in a fluid velocity of about 2 m/s (7 fps) on the outside surface of the tubes.

Except for a 20-hour interruption forced by the failure of the air compressor control mechanism after about 1,030 hours of operation, a few minor interruptions of one hour or less caused by a power failure and Chevron operations at Jackson No. 1 well, the HETU was operated continuously for 2,034 hours.

Brine and treated water inlet and outlet temperatures were recorded during the test. Every two hours the temperature for each thermocouple was read for calculation of heat transfer coefficients. Readings were taken by Holt Company personnel 24 hours a day. Staffing for nights and weekends was accomplished by hiring local residents.

As part of this test, weekly brine samples were taken. An initial sample had a complete analysis of all chemical constituents. Table 5-4 shows two typical analyses. Weekly samples were analyzed for total dissolved solids (TDS). If a change in amount was observed week-to-week, then another complete analysis would be made. The TDS remained constant at approximately 13,500 ppm during the course of this experiment so no additional complete analysis was necessary.

Testing was concluded 24 January 1977.

PHASE III

At the conclusion of the experiment, the brine flow through HETU was terminated. The HETU was allowed to cool, but Nowlin No. 1 well continued to flow as part of a test conducted by Chevron Research. The cooling water and treated water loops were shut down. The exchanger sections were opened sequentially starting with E-1. Each tube was sealed with rubber stoppers as it was removed to prevent oxidation corrosion of the interior tube surface. The tubes were marked to show orientation and location within the exchanger, and removed. They were wrapped in protective material and shipped to the Holt laboratory for analysis.

The Honeywell recorder was removed from the HETU, wrapped in protective material and stored on-site. All other instrumentation was left on the test skid.

The exchanger shells were reassembled following tube removal to prevent loss of parts and to protect against the environment.

The treated water cooler, E-5, was disassembled, examined and reassembled. No scaling or fouling from cooling water occurred and heat transfer through this unit was both excellent and constant during the course of the test.

CHEMICAL ANALYSES

The preparation of samples from the heat exchanger tubes and analysis by electron microscopy were all performed by Holt personnel. Samples were prepared and taken to the materials laboratory at the University of Southern California where they were examined and analyzed with a scanning electron microscope.

Sample Preparation

The exchanger tubes were plugged as soon as the HETU was opened to prevent oxidation that would occur if the tubes were allowed to dry in the air. All subsequent work was done on wet tubes.

The tubes were labeled east top, east bottom, west top, and west bottom in each exchanger. Samples from the inlet, middle and outlet of one tube in each of the exchangers E-1 through E-4 were taken. An identically located tube from each exchanger was studied.

The samples were prepared by cutting one-foot segments from each end and from the middle of the exchanger tubes. A fresh cut was made 1 inch below the stopper at the proximal end of each segment. This was to obtain a surface free from abrasion by the stopper. From each segment, 3/4-inch long samples were taken for analysis. The samples were immediately rinsed with acetone to dry them.

Samples from each segment were sawed longitudinally to obtain specimens for surface characterization and analysis. In each instance, sawing was terminated when it became possible to manually break apart the two halves of the specimens. This procedure was used to obtain fracture surfaces which would expose pitting or crevice corrosion in the base metal. This mode of preparation enabled these samples to be used for thickness determination as well. To obtain material for the elemental analysis, scale was scraped from the tubes and cold mounted in a plastic base.

Analytical Procedure

The scale samples were analyzed using a Cambridge Stereoscan S4-10 Scanning Electron Microscope equipped with a Tracor-Northern NS-880 X-ray analysis system. Figure 4.1, "X-ray Analysis System" is a schematic diagram of the system.

The secondary electron mode of X-ray analysis, or "Energy Dispersive Analysis" as it is titled, was used. Secondary electrons are those which emanate from within the sample as a consequence of the primary beam of electrons impinging upon the sample and exciting electrons from it. These electrons are less energetic than the 20 kv primary electron beam, but they arise from the

"excited volume" in large enough numbers to enable the production of clear, sharp images on a cathode ray viewing screen and semi-quantitative analysis of the sample being examined. Electron photomicrographs and in situ compositional analyses were done sequentially on the samples so that observed surface manifestations could be immediately correlated to chemical composition.

Elements were initially identified by manually aligning an energy level indicator (the "cursor") to the spectral peaks. The cursor is calibrated such that when it overlies a given point along the X-axis of a cathode ray image of the X-ray spectra, the element correlating to that energy level is displayed on the image. See representative spectra in Appendix C. The cursor may be moved rapidly and independently of the remainder of the image. It creates a means of identifying spectral peaks by their alignment with the cursor.

This procedure is, however, regarded as semi-quantitative because of the possibility of incorrect positioning of the cursor by the researchers. Consequently, it is regarded as a first approach and a means to evaluate what elemental standards (i.e., pure elements) should be employed for accurate, weight percentage analysis. The analyses in Tables 5-1 and 5-2 were prepared using this procedure.

Examination of the first analyses showed that in situ study of the scale had inconsistencies due to contamination by the background metal tube. For a more precise analysis, scale samples were removed from the metal substrate and compared with internally stored elemental standards. This technique provides quantitative data regarding elemental composition of the scale. Table 5-3 shows the weight percentage composition of the scale obtained using elemental standards.

Representative spectra for each exchanger section are presented in Appendix C. Each peak is identified by the symbol of the element it represents.

Figure 4-1 X-ray Analysis System Using Secondary Electrons

Section 5

TEST RESULTS

OVERALL HEAT TRANSFER COEFFICIENT

The experimental temperatures recorded during the test program and the calculated values of the overall heat transfer coefficient are tabulated in Appendix A. These data are plotted in this section on Figures 5.1 to 5.4 for the four heat exchanger sections. The heat transfer coefficients plotted in these curves are the daily average values described in Section 7.

SCANNING ELECTRON PHOTOMICROGRAPHS

The scanning electron microscope was used to examine the heat exchanger tubes before and after exposure to the Heber brine. It was also used to study the thickness and type of scale deposited on the different tubes. The pictorial results of these studies are presented on Figures 5.5 to 5.10. A description of individual photographs is included in Section 6.

In a few cases stereoscope pictures were made of the scale to emphasize the difference between the scale deposited on iron tubes and that deposited on titanium tubes. Figure 5.11 shows four stereo views of scale deposits.

CHEMICAL ANALYSES

X-ray analyses were made of the scale that accumulated on the tubes. At first the analyses were made with the scale still attached to the tube material. The results of these analyses are presented in Tables 5-1 and 5-2. In cases where the scale was thin such as E-2 inlet and where the X-ray was directed at the cross section of the tube, the analysis included the metal of the tube wall.

Typical spectra from which these analyses were made are presented in Appendix B. Figures B-1 and B-2 show the difference in the composition of scale at the inlet and outlet of Section E-1; Figure B-3 shows the scale at the outlet of E-2; Figure B-4 shows the scale at the outlet of E-3; and Figures B-5 and B-6 show the scale in and out of E-4. To obtain a more accurate analysis of the scale a second series of tests were made using scale that had been separated from the tube wall. These analyses are shown in Table 5-3.

Two analyses of the brine from Nowlin No. 1 well are presented in Table 5-4.

Table 5-5 presents an analysis of the noncondensable gases present in the brine. This analysis was obtained from Chevron Oil Company. The gas constitutes only .0049 weight percent of the brine (49 ppm) and contains 0.36 mol percent hydrogen sulfide.

Table 5-1

ANALYSES OF SCALE ON STEEL TUBES

	<u>As</u>	<u>Si</u>	<u>S</u>	<u>Sb</u>	<u>Fe</u>	<u>Cu</u>	<u>Zn</u>
<u>E-1 In</u>							
Surface, %	11.2	1.6	18.5	33.4	30.3	2.1	2.8
X-Section, %	6.5	6.2	32.0	8.4	42.1	0.6	4.2
<u>E-1 Out</u>							
Surface, % (Hi)	-	6.1	24.4	5.0	61.8	0.4	2.3
Surface, % (Low)	-	15.4	31.7	20.0	25.2	1.1	6.6
X-Section, %	8.6	1.9	27.7	7.5	53.9	0.3	-
<u>E-3 In</u>							
Surface, %	-	20.7	14.9	35.4	25.7	-	3.3
X-Section, %	-	14.1	40.8	-	45.1	-	-
<u>E-3 Out</u>							
Surface, %	-	15.2	31.4	34.9	18.0	-	0.5
X-Section, %	19.0	9.2	20.1	2.7	47.4	0.8	0.8

Table 5-2

ANALYSES OF SCALE ON TITANIUM TUBES

	<u>As</u>	<u>Si</u>	<u>S</u>	<u>Sb</u>	<u>Fe</u>	<u>Ti</u>	<u>Cu</u>	<u>Zn</u>
<u>E-2 In</u>								
Surface, %	-	11.3	21.4	15.4	3.8	46	1.3	0.7
<u>E-2 Out</u>								
Surface, %	3.9	3.4	20.2	48.2	0.8	22.5	1.0	-
X-Section, %	2.9	3.1	15.3	62.8	-	15.9		-
<u>E-4 In</u>								
Surface, %	0.8	7.7	40.5	48.9	0.7	1.5	-	-
X-Section, %	5.0	6.7	17.3	66.2	-	4.2	0.6	-
<u>E-4 Out</u>								
Surface, %	0.8	2.3	44.5	50.1	0.7	1.4	-	0.3
X-Section, %	0.8	0.9	42.9	52.8	0.5	1.0	-	-

Table 5-3

ANALYSES OF SCALE SCRAPED FROM TUBE WALL

STEEL TUBES

Constituent Element, Weight Percent

	<u>S</u>	<u>Zn</u>	<u>Si</u>	<u>Fe</u>	<u>Cu</u>	<u>Ni</u>	<u>Cr</u>	<u>As</u>	<u>Sb</u>	<u>Other*</u>
<u>E-1</u>										
IN	5.8	2.1 ^a	13.2	34.9	1.1	0.5	0.4	9.0	1.0	30.3
OUT	8.6	-	14.0	37.4	0.9	0.4	0.2	-	-	38.4
<u>E-3</u>										
IN	4.9	4.8 ^a	16.2	30.9	0.2	0.3	0.3	-	2.0	51.3
OUT	6.7	-	10.5	24.4	3.0	1.2	2.8	0.5	-	50.0

TITANIUM TUBES

	<u>S</u>	<u>Zn</u>	<u>Si</u>	<u>Fe</u>	<u>Cu</u>	<u>Ni</u>	<u>Cr</u>	<u>As</u>	<u>Sb</u>	<u>Other*</u>
<u>E-2</u>	INSUFFICIENT MATERIAL OBTAINED									
<u>E-4</u>										
IN	19.0	1.7 ^a	1.6	0.8	2.6	-	0.2 ^a	2.5	55.0	17.9
OUT	12.7	-	0.4	-	0.5	-	-	2.5	41.2	42.8

* This value is obtained by difference. It represents constituents with a molecular weight less than 23, such as carbon or oxygen.

^a Not universally detected.

Table 5-4

ANALYSES OF CONSTITUENTS OF BRINE IN NOWLIN #1 WELL

<u>ELEMENT</u>	<u>11/1/76</u> <u>mg/l</u>	<u>11/2/76</u> <u>mg/l</u>
Sodium	3,900	3,500
Potassium	375	510
Calcium	850	945
Magnesium	5	5
Chloride	8,100	7,500
Iron	19	65
Manganese	3.5	5.0
Lead	NO	NO
Copper	0.02	0.05
Zinc	0.5	0.6
Barium	3.8	4.2
Silicon	105	100
Strontium	38	36
Lithium	7	6
Ammoniacal-Nitrogen	13	6.5
Sulfate	64	50
pH	6.45	6.57
eH, mv	-23	-46
Conductivity, mhos	25,600	24,400
TOTAL DISSOLVED SOLIDS	13,500	12,900

Table 5-5

NONCONDENSABLE GASES IN NOWLIN NO. 1 BRINE*

<u>COMPONENT</u>	<u>Mol %</u>
He	2.10
Air	2.12
H ₂	1.32
N ₂	23.64
CO ₂	63.75
C ₁	6.92
C ₂	0.13
C ₃	0.01
C ₇	0.01
Other Hydrocarbons	trace
H ₂ S	0.36

*Noncondensable gases constitute 0.004914 weight percent of the brine.

Figure 5-1 E-1 Heat Transfer Coefficient as Function of Time

Figure 5-2 E-2 Heat Transfer Coefficient as Function of Time

Figure 5-3 E-3 Heat Transfer Coefficient as Function of Time

Figure 5-4 E-4 Heat Transfer Coefficient as Function of Time

FIG. 5.10.1

FIG. 5.10.2

FIG. 5.10.3

FIG. 5.10.4

Section 6

DATA ANALYSIS

FUNDAMENTALS

In this section the data obtained in the 2,000 hour HETU experiment are analyzed to obtain information on the effect of scaling on the heat transfer coefficients of the individual exchanger sections. These results can be directly applied to predict heat exchanger coefficients and fouling factors for the brine/hydrocarbon exchanger in a commercial geothermal conversion plant.

The overall heat transfer coefficient of a shell-and-tube exchanger is defined by the equation

$$U = \frac{Q}{A\Delta t_m} \quad (1)$$

where

U = heat transfer coefficient

Q = heat transferred

A = area of exchanger

Δt_m = logarithmic mean temperature difference

The heat transferred (Q) was calculated from the relation

$$Q = (\Delta t_b)(\dot{m})(C_p) \quad (2)$$

where

Δt_b = brine temperature difference between
exchanger inlet and outlet

$\dot{m}$ = mass flow rate

C_p = specific heat of fluid

The overall heat transfer coefficient is a measure of the combined resistances to heat transfer from one fluid to another. It is made up of the resistance of the brine film, the resistance of the working fluid film, the resistance of the tube wall, and the resistance of any scale that might deposit on the tube wall. For this experiment the working fluid was treated to prevent scale formation so that the only scale that could form would be on the brine side of the heat exchanger tubes. The relation between U and the individual resistances is as follows:

$$\frac{1}{U_{\text{overall}}} = \frac{1}{U_b} + \frac{1}{U_{wf}} + \frac{t_w}{K_w} + \frac{t_s}{K_s} \quad (3)$$

where

U_b = film coefficient of brine, Btu/(hr)(ft²)(F)

U_{wf} = film coefficient of working fluid, Btu/(hr)(ft²)(F)

t_w = thickness of tube wall, ft

K_w = thermal conductivity of tube wall, Btu/(hr)(ft)(F)

t_s = thickness of scale, ft

K_s = thermal conductivity of scale, Btu/(hr)(ft)(F)

The last term of this equation is the brine fouling factor (f):

$$f = \frac{t_s}{K_s} \quad (4)$$

The units of f are (hr)(ft²)(F)/Btu.

The fouling factor is a measure of the degree of scaling that has occurred on a tube. For a given exchanger that is tested when clean and when fouled at the same conditions of flow rate and temperature, the fouling factor can be calculated from the relation:

$$f = \frac{U_1 - U_2}{(U_1)(U_2)} \quad (5)$$

Each of the four heat exchanger sections transfers heat energy at a different rate from the flowing brine to a secondary circulating fluid. This

rate depends upon the temperature difference of the two fluids, the amount of scale in the exchanger, and the type of metal in the exchanger tube.

The rate of scale deposition varies as a function of brine temperature and as a function of the type of metal in the tube wall. Consequently, each of the four sections of the exchanger will have a different overall heat transfer coefficient and a different fouling factor. Fouling factors have been calculated for the period of the test run and then extrapolated to a period of one year.

TEMPERATURE

The temperature values which are tabulated in the Appendix were analyzed to confirm that the data recorded were consistent. Figure 6.1 shows a plot of fluid temperature vs change in temperature of the brine. Since the heat capacity of the fluids remain essentially constant in the temperature range investigated, the graph is essentially a plot of temperature vs enthalpy.

The brine temperature and the working fluid temperatures are both straight lines indicating that the temperatures recorded are consistent. Any deviation from a straight line correlation would indicate that one of the temperature points was giving an erroneous reading.

Figure 6.1 shows that the temperature range of the brine in the HETU simulates the proposed operating range of the Geothermal Demonstration Plant, i.e., from 176 C (350 F) to 54 C (130 F). The outlet temperature of the treated water was controlled at 205 F. The water is heated from 43 C (110 F) to 96 C (205 F), whereas the plant design calls for heating the hydrocarbon to 149 C (300 F). The temperature changes shown create a temperature pinch (minimum approach) at the coldest part of the exchanger. Most of the heat is transferred in the hottest section of the exchanger.

The temperature control sensor for the treated water was located at the outlet of the exchanger in the region where the greatest temperature change occurred.

The outlet temperature was controlled by adjusting the inlet temperature of the treated water. Unfortunately this system requires a large temperature change at the inlet to make any significant change to the outlet temperature. As a result, the temperatures recorded for section E-1 were severely affected by ambient temperature changes. The temperatures in the other three sections were reasonably stable and the heat transfer coefficients calculated from the data could be correlated readily.

OVERALL HEAT TRANSFER COEFFICIENTS

Because of the erratic operation of the temperature recorder during Phase I, the data taken during that period have been rejected. The data taken during Phase II are the basis of this analysis.

Overall heat transfer coefficients were calculated for each of the data points that were recorded by the plant operator. These coefficients have been reviewed, and inconsistent values have been rejected as described in Section 7. The remaining values are tabulated in Appendix A. Daily averages of these coefficients are plotted in Figures 5.1 to 5.4.

It is necessary to have a value for the heat transfer coefficient of each exchanger section when free of scale to accurately describe the change in the heat transfer coefficient as a function of time. Clean heat transfer coefficients can be calculated for the exchanger and these values are more accurate than values obtained by extrapolating the test data back to the start of the test. Overall clean heat transfer coefficients were calculated for the four exchanger sections using the McAdams equation to calculate the film transfer coefficients.

$$N_{Nu} = 0.023(N_{Re})^{0.8}(N_{Pr})^{0.4} \quad (6)$$

where N_{Nu} is the Nusselt number = $\frac{hD}{k}$
 N_{Re} is the Reynolds number = $DV\rho/\mu$
 N_{Pr} is the Prandtl number = $C_p\mu/k$

<u>Section</u>	<u>Clean Heat Transfer Coefficient Btu/(hr) (F) (ft²)</u>
E-1	890
E-2	639
E-3	741
E-4	553

The thermal conductivity of steel is approximately three times that of titanium in this temperature range, which accounts for the difference in coefficients between the steel tubes and the titanium tubes.

To predict the effect of scale deposition on the overall heat transfer coefficients, we assumed that the velocity and temperatures of the two fluids remain constant. The two film coefficients will remain constant also, and the equation defining the overall heat transfer coefficient can then be written in the form

$$\frac{1}{U} = K_1 + K_2 + K_3 + f \quad (7)$$

$$= K_4 + f \quad (8)$$

where K_1 and K_2 represent inverse liquid film coefficients, K_3 represents the resistance of the tube wall and K_4 is the sum of K_1 , K_2 and K_3 . The inverse of K_4 is the clean tube coefficient.

The inverted form of equation (8) is

$$U = \frac{1}{K_4 + f} \quad (9)$$

Differentiating this equation with respect to f we get

$$\frac{dU}{df} = - \frac{1}{(K_4 + f)^2} \quad (10)$$

This equation shows that the rate of change of U with respect to f is a function with a negative slope. The slope will be greatest when the tube is clean and $f = 0$. As f increases in value the numerical value of the slope will decrease. Thus, the rate of change of U with respect to f will decrease as f increases in value.

Calculated heat transfer coefficients for clean tubes were used in combination with the experimental data to calculate the equations that describe the change of heat transfer coefficient as a function of time. A variety of curves were fitted to these data to determine the best equation to describe the change of the coefficient as a function of time. These correlations are tabulated in Appendix C. The equations which fit the data best are tabulated below.

<u>Item</u>	<u>Equation</u>	
E-1	$U = x / (.00184 x - .0363)$	(11)
E-2	$U = x / (.0019 x - 0.0268)$	(12)
E-3	$U = x / (.0028 x - 0.1203)$	(13)
E-4	$U = x / (.0027 x - 0.0881)$	(14)

where $x = (n + 86)$ days

These equations are similar in form to the simplified equation which defines the overall heat transfer coefficient, equation (9). Graphs of these equations are superimposed on the experimental data in Figures 5.1 to 5.4.

Using these equations it is possible to predict the overall heat transfer coefficient for each section of the exchanger after an operating period of one year. Two methods of predicting this value were considered. One value was estimated assuming that the change of coefficient was a lineal function of time. The best lineal equation for the experimental data was extrapolated to 365 days operation. The second value was calculated using equations (11) to (14) as shown on Figures 5.1 to 5.4. The value of the coefficient was calculated for 365 days of operation. The results of these calculations are as follows:

Extrapolated Coefficient at 365 Days, Btu/(hr)(F)(ft²)

<u>Exchanger</u>	<u>Lineal</u>	<u>Value from Curve</u>
E-1	459	569
E-2	438	542
E-3	118	395
E-4	180	402

The values for E-1 and E-3 are predicted for steel tubes and the values for E-2 and E-4 are for titanium tubes in brine service. The type of scale deposited on the steel tubes was different from the scale deposited on the titanium tubes. Also, the amount of scale deposition is affected by the temperature of the brine. The heat transfer data from the steel tubes should be used to predict fouling factors for steel tubed exchangers only, and the data for titanium tubes should be used for exchangers with titanium tubes only.

Since the correlation of U with f is not lineal we have used equations (11) through (14) to predict values of U in the following discussion.

FOULING FACTORS

Fouling factors were calculated for each of the four exchanger sections using the calculated clean heat transfer coefficient and a value of U at 365 days obtained from the equations listed. The following values were obtained:

<u>Exchanger</u>	<u>Brine Temperature Range, F</u>	<u>Fouling Factor, (F)(ft²)(hr)/Btu</u>	
		<u>Test</u>	<u>365 Day</u>
E-1	350-235	0.000484	0.000576
E-2	235-180	0.000174	0.000280
E-3	180-145	0.000760	0.001182
E-4	145-130	0.000389	0.000679

These values reflect the difference in scale deposition which occurred on the exchanger tubes. Deposition was higher on the steel tubes than on the titanium tubes, and significantly more material was deposited on the cooler tubes. The predicted 365 day fouling factors for both steel and titanium tubes are in the range of values normally used in heat exchanger design. With this degree of fouling, an annual cleanout of the exchangers would provide satisfactory service.

In a similar manner fouling factors were developed from the data obtained by SDG&E in the earlier HETU tests.

<u>Exchanger</u>	<u>Fouling Factors from SDG&E Test*</u>	
	<u>Brine Temperature Range, F</u>	<u>365 Day</u>
E-1	350-235	.0001
E-2	235-180	.0011
E-3	180-145	.0011
E-4	145-130	.0033

The fouling factors predicted from the SDG&E data are quite close to the values obtained for steel tubes in this investigation. However, because of the short duration of the SDG&E tests we recommend using the results obtained from the 2,000 hour test.

THERMAL CONDUCTIVITY

The calculated thermal conductivity of the scale is not a critical factor in this study, but it can be used to demonstrate the consistency of the calculated values of U and f. The following values of thermal conductivity were calculated using the average thickness of scale and the calculated fouling factors.

*Steel tubes were used in each exchanger section in this test.

<u>Exchanger</u>	<u>Conductivity, Btu/(hr)(ft)(F)</u>
E-1	0.490
E-2	0.160
E-3	0.345
E-4	0.143

These values are consistant with conductivities reported for similar materials, i.e.,

<u>Substance</u>	<u>Conductivity*, Btu/(hr)(ft)(F)</u>
Boiler Scale, Sulfate	0.34 - 1.34
Gypsum Board	0.25
Magnesia Powder	0.35
Water @ 250 F	0.396
Dry Sand	0.19 - 0.22

SCALE DEPOSITION

The photographs in Section 5 provide useful information on the structure and rate of growth of the scale deposits.

Figure 5.5 shows the following views of scale deposits on the steel tube, E-1: Numbers in parentheses show magnification of the photograph.

5.5.1 E-1 Inlet (500X)

The scale in the inlet of Exchanger 1 was friable. The scale is in the left half of the picture and the bare metal is in the right half. Pitting is conspicuous by its absence. The texture of the scale is different from the outlet of E-1, shown in Figure 5.6.3.

*Reference "Engineering Heat Transfer", S. T. Hsu Van Nostrand, New York, N.Y., 1963.

5.5.2 E-1 Inlet (2,000X)

A rosette growth has been enlarged. Its composition is iron and chloride indicating corrosion has occurred. Since it is on the metal surface, which only became clear of scale after the HETU tubes were removed for analysis, it could be caused by drops of brine left on the tube surface.

5.5.3 E-1 Outlet Surface (50X)

At 50X magnification the surface is observed to have topography not unlike high altitude photographs of planets. Rills and valleys were very much in evidence.

5.5.4 E-1 Outlet (500X)

The caked surface of the scale gives evidence that drying and shrinking has occurred.

Figure 5.6 shows additional views of the scale on E-1.

5.6.1 E-1 Inlet (600X)

This cross section of scale has a thickness of 52 microns. The scale has a solidity that is not characteristic of the scale deposited downstream. Scale at this point was more adherent than at other locations in the tube.

5.6.2 E-1 Middle of Tube (500X)

This section of the scale is more open than at the inlet, and could be easily scraped.

5.6.3 E-1 Outlet (220X)

View of scale at outlet of tube showing a porous structure similar to that at the middle.

5.6.4 E-1 Outlet (550X)

Enlarged view of scale at tube outlet.

Figure 5.7 shows views of the scale deposited on the titanium tube, E-2.

5.7.1 E-2 Inlet (2,000X)

Cross section of scale shows a thickness of about 5 microns. The substance is very porous and fragile. X-ray analysis of the substance shows it to be primarily antimony sulfide.

5.7.2 E-2 Middle of Tube (500X)

Scale at middle of tube shows a heavier deposit that has the structure and composition of scale at the tube inlet.

5.7.3 E-2 Outlet (1,000X)

The outlet of E-2 differs from the inlet in quantity of scale. The scale thickness shown in this photograph is 12 microns, which is about twice the thickness at the inlet.

5.7.4 E-2 Outlet (500X)

The scale is thicker than at the inlet and gives the appearance of a blanket of scale.

Figure 5.8 shows the scale deposits occurring on the steel exchanger tube E-3.

5.8.1 E-3 Inlet (600X)

Scale thickness is 48 microns. The only difference of note between E-3 and E-1 was the fact that the scale in E-3 tended to flake from the surface of the steel tubes. In E-1 the scale flaked off underlying harder scale. In this figure the scale has lifted off the metal surface.

5.8.2 E-3 Middle of Tube (500X)

This scale is similar to that at the inlet of the tube, but the thickness has increased to 96 microns.

5.8.3 E-3 Surface (50X)

Surface of scale appears smooth except for a few particulate deposits.

5.8.4 E-3 Outlet (200X)

Cross section shows two layers of scale.

Figure 5.9 shows the scale deposits occurring on the titanium exchanger E-4.

5.9.1 E-4 Inlet (1,100X)

Scale structure and composition is similar to that on E-2. The scale thickness is 11.8 microns as shown. Material in the background is scale rising on the curvature of the tube wall.

5.9.2 E-4 Surface (2,000X)

Enlarged view of scale shows porous structure of deposit.

5.9.3 E-4 Middle of Tube (500X)

Scale deposit is comparable to that at the tube outlet. Thickness is 26 microns.

5.9.4 E-4 Outlet (1,000X)

The only difference between the inlet and outlet of E-4 is the scale thickness. Here it is 22 microns.

Figure 5.10 compares samples of clean tubes with tubes that have been exposed to brine for 2,000 hours.

5.10.1 New Steel Tube (50X)

The surface of the tube is smooth except for minor particles on the surface.

5.10.2 E-3 Inlet (50X)

E-3, as a representative sample of steel tubes, was cleaned by scraping with a wooden rod followed by an ultrasonic ethanol bath. The majority of the scale was removed, and no pitting corrosion was found. The discontinuity on the surface is a weld line.

5.10.3 New Titanium Tube (50X)

The surface of the titanium tube is smooth except for a few particles on the surface.

5.10.4 E-4 Inlet (50X)

This tube was cleaned in an ultrasonic ethanol bath but was not scraped. Some particles can be seen clinging to the titanium wall. No corrosion is evident on the tube wall.

Figure 5.11 shows stereoscopic views of scale surfaces.

5.11.1 E-1 Outlet (580X)

A cross section stereo picture of E-1 outlet makes the scale plates appear three dimensional. The flaking off of these plates as a consequence of the shearing action of the flowing brine is an expected result of their morphology. Note the porosity of the scale.

5.11.2 E-2 Surface (2,000X)

To elucidate the structure of the scale in E-2, stereo views were taken at 2,000X. At this magnification, the individual granules comprising the scale can be recognized. It is this granular composition that causes the scale to be so weak.

5.11.3 E-3 Surface (100X)

At the outlet of E-3, the scale was thick enough to "chunk" off, and new deposits have occurred on the fracture surfaces. Two layers of the same type of scale are visible.

5.11.4 E-1 Outlet (200X)

Stereo view of E-1 surface at 200X emphasizes the plate-like structure of the scale and its butte-like contours. This view is an enlargement of the area below center right in Figure 5.5.3.

The algorithm employed to determine the scale thickness (t) from the photographic image is:

$$t = \frac{y \times 10^4}{\text{Magnification}} \quad (15)$$

where t = thickness of scale, microns

y = measured thickness of scale on photographic image, cm.

Measurement of the photographs of deposited scale yielded the following scale thicknesses in the exchanger sections.

<u>Exchanger</u>	<u>Scale Thickness, Microns*</u>		
	<u>Inlet</u>	<u>Middle</u>	<u>Outlet</u>
E-1	51.7	92	93.1
E-2	5	8	12
E-3	48	96	110
E-4	12	26	24

These thicknesses are plotted as a function of brine temperature in Figure 6.2. This figure emphasizes the fact that the thickness of the scale deposited on the iron tubes (E-1 and E-3) was much greater than was deposited on the titanium tubes (E-2 and E-4).

In all cases the scale deposited at the inlet of the tube was less than that deposited at the outlet of the tube. Figure 6.2 shows that scale deposition

*Average estimated thickness, variation $\pm 10\%$.

is not linear along the length of the tube. The explanation may be that the fluid entering the tube is in laminar flow at the entrance. Under these conditions the film heat transfer coefficient is reduced. The fluid must flow some distance into each tube before turbulent flow is established, with accompanying higher local heat transfer coefficients which cause the liquid to cool more rapidly. The Reynold's Number of the brine varied from about 127,000 at the inlet of the HETU to 43,000 at the outlet.

There is a distinct difference in the characteristics of the scale deposited at different sites. At the inlet to E-1 the scale appears to be homogenous. However, the scale at the outlet of E-1 as well as at the inlet and outlet of E-3 appears to be made up of nonhomogenous plates with ridges. It is mechanically brittle and can be easily broken and crumbled. New deposits can be seen growing on the edges where plates have apparently broken away.

Figures 5.7 and 5.9 show the scale deposition on the two titanium tubes. All pictures of this scale show it to be an amorphous open assembly of particles. It is fragile and readily subject to breakage. The thickness of the samples shown in these pictures averages 8 to 18 microns for brine flowing 2,000 hours at a velocity of 5 feet per second.

The initial test performed by San Diego Gas & Electric Company measured a scale thickness of 15 to 18 microns after 300 hours of operation at a velocity of 10 feet per second. The similarity of scale thickness between the two tests indicates that the scale deposited on titanium tubes must reach a stable thickness at some point, after which, additional scale deposits will be broken off from the tube, and entrained in the flowing brine. If this assumption is true, then the titanium tube heat transfer coefficients measured at the end of the 2,000 hour run would remain essentially constant for the remainder of the year, and it would not be necessary to schedule regular tube cleanout.

No step functions were observed in the scaling rate on either steel or titanium.

CORROSION

The electron photomicrographs showing the tube cross sections do not show any visible evidence of corrosion in either the steel or the titanium tube sections. The tube wall surfaces are free of pits or crevices. Figure 5.10.1 shows the surface of an unused steel tube and 5.10.2 shows the cleaned surface of a steel tube exposed to brine for 2,000 hours. The discontinuity across this figure is the weld line. No corrosion is evident on the tube even in the vicinity of the weld.

Figure 5.10.3 shows the surface of an unused titanium tube. Figure 5.10.4 shows the surface of a tube from E-4. The tube from E-4 was cleaned in an ultrasonic bath but some particles still cling to the surface of the tube. These particles can be readily scraped off the tube. Corrosion of the titanium tube is not evident. Corrosion should not be a factor affecting the service life of titanium tubes.

There is some evidence that corrosion of the steel tubes was occurring. The analyses on Tables 5-1 and 5-3 show relatively high iron concentrations in the scale that formed on the iron tubes. In Table 5-2 almost no iron appears in the scale formed on the titanium tubes. If the iron scale that was found had originated in another part of the system, then iron would appear in the scale of both the iron and the titanium tubes. Consequently, it was concluded that the iron present in the scale represented a corrosion product of the steel tubes.

The density of the scale was calculated based on weighed scale samples and calculated volumes. The results of this calculation follow:

<u>Unit</u>	<u>Density grams/cc</u>
E-1 in	0.366
E-1 out	0.526
E-2 out	0.186
E-3 out	0.516
E-4 out	0.198

These figures are consistent for E-1 out and E-3 out, and for E-2 and E-4. The lower value for E-1 in could be due to the apparent difference in the scale structure, or it could be the result of not totally removing the scale from the tube sample.

Using an iron concentration in the scale of 30 percent by weight, and the density reported above at the outlet of E-1 and E-3, we calculated that the rate of loss of iron from the tube was 0.47%/year or 0.3 mils/year. This rate of weight loss would result in a 15 percent loss of metal from the tubes in 30 years time. The allowable working pressure of the tubes would be reduced to 2,400 psi which value exceeds the design pressure of the heat exchanger by a factor of about 3.5. This is a minimal corrosion rate which would be acceptable in a commercial plant.

Figure 6-1 HETU Temperature Enthalpy Diagram

Figure 6-2 Exchanger Scale Thickness

Section 7

UNCERTAINTY ANALYSIS

The temperature instruments used in this test program have the following accuracies:

	<u>Accuracy</u>
Iron constantan thermocouples (ANSI standard)	± 4 F
Brown Electronik multipoint recorder	± 1 F
Chart graduation	2 F
Calibrated laboratory glass thermometer	± 0.5 F

The accuracy of the temperature recordings without calibration would have been ± 4 F, but because these temperatures were checked with a calibrated thermometer a higher accuracy can be assumed. Because the temperature chart had a 2 degree graduation the accuracy of these readings is taken to be ± 1 F.

The Fischer-Porter rotameter used to measure brine flow was calibrated by the manufacturer to have an accuracy of ± 2 percent. Pressure gauges used in the experiment have a standard accuracy of ± 1 percent. These instruments were calibrated to ± 1 percent of actual readings.

The temperature of the treated water was controlled by a feed-forward system. The temperature sensor was located on the shell side of exchanger 1 while the mixing valve was located ahead of the treated water flow into exchanger 4. Minor fluctuations in the ambient temperature, the brine flow rate, or the brine temperature caused a major correction response to be made by the temperature controller. Control was being attempted at the pinch point of the exchanger, while the region of greatest temperature difference was used

as the control point. Temperature fluctuations due to ambient effects occurred so rapidly that equilibrium at the hot end of the HETU was rarely attained.

When the temperature controller sensed a low temperature in the treated water outlet it opened the control valve which bypassed the treated water cooler, E-5, effectively raising the temperature of treated water to E-4. The time required for the brine to flow through the HETU was approximately one minute. Consequently, the slug of cooled brine originally prompting the response did not reach the end of the process until a significant time-lag had occurred with reference to the temperature controller.

The treated water flowed through the system in about 45 seconds, and response time for the temperature element (capillary bulb) and valve was about 30 seconds. By the time the temperature controller responded, about 75 seconds had passed.

Diurnal temperature changes of 16 C to 22 C (20 F to 40 F) were common during the course of the experiment. Heat loss from the brine supply line was also significantly affected by local wind conditions. These factors caused the brine inlet temperature to vary, and the temperature control was constantly adjusting the bypass flow to stabilize the treated water outlet temperature.

This instability complicated the analysis of the recorded data. The procedure adopted to evaluate the heat transfer coefficients involved rejecting most extreme values. To accomplish this, we rejected any heat transfer coefficient for the given exchanger that differed by more than $10 \text{ Btu}/(\text{hr})(\text{ft}^2)(\text{F})$ from the preceding calculation. A procedure was thus established which forced heat transfer coefficients to be similar for at least four hours before they were accepted as valid.

The remaining heat transfer coefficient values were averaged for each day to obtain the most probable value of the coefficient. The average values were plotted vs time, for each exchanger. These plots were further examined for

eccentric variation and the remaining values were computer analyzed to determine the type curve which would best fit the data.

Five curve types were examined. They included polynomials (to 4th degree), hyperbolic, inverse, exponential curves and power equations. The program determines the least square values of the unknown constants A and B for each curve type using linear regression and provides a "goodness-of-fit" index called the index of determination. This index allows the user to determine which curve type best represents the input data.

The equation $Y = X/(AX + B)$ provides the best fit when compared to the original heat transfer coefficients. Eighty percent confidence limits were used in evaluating the data. The index of determination (goodness-of-fit) was:

<u>Exchanger</u>	<u>Index of Determination</u>
E-1	0.5147409
E-2	0.8393144
E-3	0.9440604
E-4	0.8922477

The closer the index approaches 1.00, the more accurate the predicted curve. The low index for Exchanger E-1 results from the wide variation in values of heat transfer coefficient experienced in this exchanger.

The heat transfer values predicted by these equations are most inexact at the start of the experiment where the greatest change was occurring, and when no data were available. However, the calculated values are reasonably close to the predicted clean heat transfer coefficients as shown below:

<u>Exchanger</u>	<u>Calculated Clean Heat Transfer Coefficient</u>	<u>Value from Computer Curve</u>	<u>Ratio of Values</u>
E-1	890	704	0.79
E-2	639	627	0.98
E-3	742	704	0.95
E-4	554	598	1.08

Extrapolation of the values to an operating period of one year appears to be a valid procedure.

The overall heat transfer coefficient is calculated from the equation

$$U = \frac{\dot{m} \Delta t_b}{A \Delta t_m} \quad (16)$$

The following uncertainties are used for the experimental values.

<u>VARIABLE</u>	<u>SYMBOL</u>	<u>UNCERTAINTY, %</u>	<u>UNCERTAINTY, UNITS</u>
Flow rate	$\dot{m}$	± 2	$\pm 480 \text{ \#/hr}$
Temperature	t	$\pm .3$	$\pm 1 \text{ F}$
Area	A	± 4	$\pm .6 \text{ ft}^2$

The uncertainty of U was calculated using these values and the relation:

$$\Delta U = \left[\left(\frac{\partial U}{\partial \dot{m}} \Delta \dot{m} \right)^2 + \left(\frac{\partial U}{\partial \Delta t_b} \Delta \Delta t_b \right)^2 + \left(\frac{\partial U}{\partial A} \Delta A \right)^2 + \left(\frac{\partial U}{\partial \Delta t_m} \Delta \Delta t_m \right)^2 \right]^{\frac{1}{2}} \quad (17)$$

For E-1 the following values are obtained:

$$\begin{aligned} \Delta U &= [(33)^2 + (9)^2 + (27)^2 + (12)^2]^{\frac{1}{2}} \\ &= 46 \end{aligned}$$

The major sources of error are the uncertainty attributed to flow rate and to the effective tube area. The flow uncertainty is a characteristic of the flow

meter. The velocity of the treated water is reduced at both ends of the tube, resulting in a reduced coefficient in that region. As a result the effective tube area is slightly less than the total tube area.

Temperature has little effect on ΔU . Consequently, the above value of ΔU can be used for each of the four sections of the HETU.

The uncertainty of the fouling factor was calculated with equation (18)

$$\Delta f = \left[\left(\frac{\partial f}{\partial (\Delta U)} \Delta \Delta U \right)^2 + \left(\frac{\partial f}{\partial U_1} \Delta U_1 \right)^2 + \left(\frac{\partial f}{\partial U_2} \Delta U_2 \right)^2 \right]^{\frac{1}{2}} \quad (18)$$

and the following values obtained:

<u>EXCHANGER</u>	<u>365 Day Fouling Factor</u>
E-1	.00057 $\pm$.00014
E-2	.00028 $\pm$.00004
E-3	.00118 $\pm$.00026
E-4	.00068 $\pm$.00030

This procedure establishes the uncertainty of the fouling factor at 365 days of operation. For a conservative design this uncertainty should be included with the fouling factor.

Scale densities were obtained by calculating the volume of a weighed sample of scale. Scale thicknesses were obtained by measurement of photomicrograph images. Thicknesses could be read with an accuracy of about ± 1 micron. The length of the tube sample from which the scale came was measured with a micrometer to the nearest 64th of an inch. The balance was accurate to 0.01 mg. It was found that the two iron scale samples which had a similar appearance had similar densities. The two titanium scale samples also had similar values. The mean deviations of these values are listed below:

	<u>Deviation</u>
density of scale on iron tubes	0.9%
density of scale on titanium tubes	3.12%

Section 8

CONCLUSIONS AND RECOMMENDATIONS

The study "Geothermal Energy Conversion and Economics - Case Studies", EPRI Report No. ER-301 prepared by Holt/Procon in November, 1976 recommends that the Heber Reservoir be selected as the site of the Geothermal Demonstration Plant, and that an energy conversion plant be constructed there with a capacity of 50 MWe. This heat exchanger study provides additional data which confirm that the recommended plant would be feasible to build and operate.

As a result of this test program the following conclusions have been reached:

1. Heat transfer coefficients have been measured over a 2,000 hour test period. From these figures the following fouling factors have been calculated for heat exchangers operating for a 365 day period in Heber geothermal brine service:

<u>TUBE MATERIAL</u>	<u>BRINE TEMPERATURE RANGE, F</u>	<u>FOULING FACTOR, (hr)(F)/Btu</u>
Steel	350 - 235	0.000576
Titanium	235 - 180	0.000280
Steel	180 - 145	0.001182
Titanium	145 - 130	0.000679

Based on these numbers either steel or titanium tubes would be suitable for a geothermal brine/hydrocarbon heat exchanger at Heber.

2. Analyses of scale deposited on steel tubes show that it contains silicon, iron, antimony, arsenic and sulfur. The scale is brittle and can be mechanically scraped from the tube surface.

3. Analyses of scale deposited on titanium tubes show that it is primarily antimony sulfide. This scale is an amorphous deposit of particles that can be readily scraped from the tube surface. Comparison of this scale deposit with deposits from the San Diego Gas & Electric 300 hour test program showed that the thickness of the deposit was the same in both cases. This fact indicates that there is a maximum thickness of scale that would accumulate on titanium tubes.
4. An analysis of the noncondensable gases present in the Heber brine showed that the gas constitutes only .0049 weight percent of the brine. The gas contains 0.36 mol percent hydrogen sulfide.
5. No pitting or crevice corrosion was observed on the steel tubes. However, the presence of iron in the scale on the steel tubes, while there was no iron in the scale deposited on the titanium tubes, could indicate that corrosion of the surface of the metal was occurring. The weight loss from the tubes was calculated to be 0.47 percent per year or 0.3 mils/year.
6. No corrosion of the titanium tubes was observed.
7. The thermal conductivity and density of the scale was calculated with the following results:

<u>Exchanger</u>	<u>Conductivity Btu/(hr)(ft)(F)</u>	<u>Density grams/cc</u>
E-1	0.490	0.526
E-2	0.160	0.186
E-3	0.343	0.516
E-4	0.143	0.198

8. The results listed above indicate that either steel or titanium tubes would be suitable for service with the Heber geothermal brine.

The tests results show that the Heber brines are not severely corrosive, and that scale deposition as a result of cooling the brine will not seriously reduce the plant operating efficiency. These characteristics of the brine give credence to the economic studies in the November report which were made assuming that the energy conversion plant could operate with an 85 percent availability factor.

The study further defined the chemical quality of the constituents present in the brine. The high salinity of the brine necessitates reinjection into the reservoir. The analysis of the noncondensable gases present in the brine confirms that hydrogen sulfide is present in the brine in such a low concentration that it would not constitute a hazard if a brine spill should occur.

Appendix A

TABULAR DATA

Heat transfer coefficients were calculated for each data set logged regardless of the believed accuracy of the data. At the conclusion of the experiment, the statistically questionable heat transfer coefficients were discarded in a manner explained in the error analysis section. Data presented are daily averages of the data obtained at two-hour intervals from 12 November 1976 to 24 January 1977. Temperatures corresponding to the retained heat transfer coefficients were averaged in like manner to produce the data summary of Table A-1.

The following symbols are used in the table:

- U_1 - Overall heat transfer coefficient, Exchanger E-1
- U_2 - Overall heat transfer coefficient, Exchanger E-2
- U_3 - Overall heat transfer coefficient, Exchanger E-3
- U_4 - Overall heat transfer coefficient, Exchanger E-4
- B_{in} - temperature of brine in, F
- B_{out} - temperature of brine out, F
- W_{in} - temperature of treated water in, F
- W_{out} - temperature of treated water out, F

TABLE A-1

HETU AVERAGED DATA
 FLOW RATE CONSTANT AT 18 gpm
 TEMPERATURES IN F, HEAT TRANSFER COEFFICIENT $U = \text{Btu}/(\text{hr})(\text{F})(\text{ft}^2)$

DATE	E-1					E-2					E-3					E-4				
	U_1	Bin	Bout	Win	Wout	U_2	Bin	Bout	Win	Wout	U_3	Bin	Bout	Win	Wout	U_4	Bin	Bout	Win	Wout
11/12	713	336	226	158	200	669	226	173	138	158	692	173	145	127	138	---	145	132	---	127
13	677	334	231	162	205	638	231	178	139	162	633	178	148	126	139	603	148	132	120	126
14	662	328	231	162	205	604	231	180	138	162	621	180	149	124	138	555	149	132	116	124
15	655	336	236	164	208	614	236	182	139	164	611	182	151	124	139	573	151	133	117	124
16	657	338	239	167	210	612	239	185	142	167	610	185	153	127	142	558	153	134	118	127
17	650	339	239	166	210	607	239	185	141	166	608	185	153	126	141	553	153	134	118	126
18	648	339	238	165	209	600	238	184	140	165	607	184	152	125	140	552	152	134	114	125
19	642	340	240	167	211	599	240	186	142	167	584	186	153	127	142	558	153	134	117	127
20	648	339	239	164	208	603	239	186	139	164	585	186	154	122	139	535	154	133	115	122
21	646	338	239	166	209	598	239	185	141	166	586	185	153	126	141	531	153	136	118	126
22	633	341	242	168	212	599	242	187	143	168	589	187	155	128	143	509	153	138	120	128
23	648	340	241	170	213	568	241	188	142	170	572	188	155	127	142	500	155	137	118	127
24	630	341	242	167	211	602	242	186	141	167	572	186	153	126	141	548	153	134	116	126
25	631	340	240	166	210	607	240	183	140	166	568	183	150	125	140	538	150	131	113	125
26	636	339	240	165	210	604	240	185	140	165	561	185	154	124	140	522	154	133	115	124
27	650	335	233	160	206	593	233	179	135	160	568	179	147	119	135	521	147	129	111	119
28	647	337	234	159	206	589	234	178	132	159	561	178	144	116	132	508	144	127	108	116
29	649	339	235	157	205	595	235	179	131	157	561	179	147	115	131	510	147	127	108	115
30	643	340	234	159	206	589	234	178	134	159	558	178	146	119	134	507	146	127	109	119
12/1	643	340	234	157	204	591	234	178	132	157	534	178	147	117	132	506	147	127	109	117
2	651	340	237	163	209	598	237	181	137	163	551	181	148	120	137	518	148	129	111	120
3	680	341	234	160	209	588	234	179	134	160	563	189	148	119	134	518	148	132	113	119
4	669	341	235	162	210	606	235	180	136	162	530	180	150	120	136	518	150	129	112	120
5	669	340	236	161	209	606	236	181	135	161	545	181	150	120	135	521	150	132	115	120
6	662	339	235	160	208	609	235	179	134	160	543	179	148	119	134	500	148	131	112	119
7	665	338	233	160	207	595	233	178	134	160	537	178	147	119	134	512	147	131	113	119
8	660	339	244	164	223	644	244	188	138	164	522	188	155	124	138	496	155	124	103	124
9	631	338	239	161	213	585	239	182	132	161	516	182	148	113	132	475	148	125	97	113
10	624	335	238	161	211	572	238	182	131	161	512	182	148	113	131	472	148	127	102	113
11	622	336	240	162	213	567	240	183	131	162	513	183	148	112	131	460	148	126	101	112
12	616	338	243	164	215	560	243	186	133	164	511	186	151	114	133	408	151	128	103	114
13	631	342	244	167	219	576	244	187	136	167	524	187	152	118	136	491	152	129	104	118
14	622	342	245	166	218	570	245	188	135	166	507	188	153	116	135	476	153	130	104	116
15	627	342	244	165	217	583	244	186	134	165	513	186	151	115	134	478	151	129	104	115

TABLE A-1 Continued

DATE	E-1					E-2					E-3					E-4				
	U ₁	Bin	Bout	Win	Wout	U ₂	Bin	Bout	Win	Wout	U ₃	Bin	Bout	Win	Wout	U ₄	Bin	Bout	Win	Wout
12/16	630	341	244	165	217	585	244	186	133	165	517	186	151	114	133	491	151	129	104	114
17	626	342	244	166	217	592	244	185	134	166	526	185	150	113	134	490	150	127	102	113
18	632	343	244	166	218	583	244	186	135	166	513	186	152	114	135	488	152	129	105	114
19	633	342	244	167	219	578	244	187	137	167	521	187	153	118	137	493	153	137	107	118
20	637	342	243	165	217	575	243	186	134	165	509	186	152	115	134	487	152	129	104	115
21	630	341	241	162	214	578	241	183	132	162	509	183	149	113	132	476	149	127	102	113
22	627	339	240	162	213	585	240	183	132	162	506	183	150	112	132	479	150	124	101	112
23	630	335	235	167	207	580	235	178	137	167	507	178	145	120	137	494	145	122	99	120
24	629	341	241	161	214	571	241	183	130	161	510	183	148	111	130	477	148	124	99	111
25	626	341	242	161	214	565	242	184	129	161	501	184	148	109	129	469	148	125	98	109
26	627	341	241	162	214	568	241	183	130	162	501	183	148	110	130	476	148	125	99	110
27	629	341	240	160	212	573	240	182	126	160	501	182	147	107	126	475	147	123	98	107
28	644	342	237	159	210	583	237	179	130	159	500	179	146	113	130	504	146	125	103	113
29	637	342	239	159	210	578	239	181	130	159	503	181	148	113	130	479	148	127	104	113
30	646	340	237	158	209	582	237	180	130	158	504	180	148	114	130	482	148	127	104	114
31	643	343	241	164	213	576	241	184	136	164	514	184	151	119	136	476	151	132	109	119
1/1	640	343	241	164	213	588	241	184	135	164	505	184	152	119	135	484	152	131	109	119
2	641	342	240	163	212	584	240	183	135	163	499	183	151	119	135	486	151	130	107	119
3	644	333	234	160	207	581	234	179	133	160	502	179	148	118	133	480	148	126	107	118
4	638	328	230	156	202	573	230	176	129	156	502	176	145	114	129	471	145	125	103	114
5	638	341	239	162	211	584	239	182	133	162	499	182	150	117	133	470	150	129	107	117
6	633	342	240	161	212	581	240	183	133	161	505	183	151	117	133	478	151	131	108	117
7	629	342	241	163	211	588	241	183	134	163	503	183	151	118	134	485	151	130	108	118
8	626	340	240	161	210	594	240	182	133	161	501	182	150	117	133	488	150	129	107	117
9	622	341	239	159	208	587	239	180	129	159	492	180	148	113	129	471	148	127	103	113
10	623	335	234	155	204	583	234	176	127	155	493	176	144	111	127	463	144	124	99	111
11	620	339	239	160	209	575	239	181	130	160	497	181	148	113	130	468	148	128	104	113
12	613	344	244	163	213	579	244	185	132	163	482	185	152	115	132	470	152	130	105	115
13	614	343	243	163	213	575	243	185	133	163	483	185	152	116	133	469	152	129	104	116
14	618	343	243	163	213	573	243	185	133	163	485	185	152	116	133	461	152	130	105	116
15	617	343	242	162	212	573	242	183	132	162	473	183	150	115	132	456	150	129	104	115
16	620	342	242	161	211	574	242	183	131	161	477	183	150	114	131	460	150	128	103	114
17	616	340	240	160	210	570	240	182	131	160	477	182	150	115	131	466	150	127	103	115
18	620	341	242	162	212	571	242	185	133	162	475	185	153	116	133	462	153	130	105	116
19	621	343	244	164	214	572	244	186	134	164	484	186	154	117	134	454	154	133	108	117
20	619	343	244	165	214	576	244	186	136	165	487	186	154	119	136	460	154	133	109	119
21	623	343	245	167	216	569	245	189	138	167	485	189	157	122	138	464	157	130	110	122
22	620	343	244	167	216	576	244	187	138	167	478	187	155	121	138	467	155	135	110	121
23	620	343	244	166	215	574	244	187	137	166	478	187	155	121	137	458	155	134	110	121
24	622	342	242	163	212	575	242	184	133	163	474	184	152	116	133	455	152	131	107	116

Appendix B

SCALE SPECTRA

This section presents typical X-ray spectra from which the chemical analysis of the scale was determined.

Figure B-1 and B-2 show the difference in the composition of the scale at the inlet and outlet of E-1 (steel tube).

Figure B-3 shows the spectrum of scale at the outlet of E-2 (titanium tube).

Figure B-4 shows the spectrum of scale at the outlet of E-3 (steel tube).

Figures B-5 and B-6 show spectra of scale at the inlet and outlet of E-4 (titanium tube).

D4418 5677HETU TUBES
 PHA11 ADD .010KEY/CH 100. SECS
 BUG= .480KEY, 0.

Figure B-1 Spectrum of Scale at Inlet to E-1

D7534 6177HETU E1OUT
 PHA11 ADD .010KEY/CH 100. SECS
 BUG= .590KEY, 0.

Figure B-2 Spectrum of Scale at Outlet of E-1

D3833 6777 E2 OUT
 PHA11 ADD .010KEY/CH 100. SECS
 BUG= 1.020KEY, 74.

Figure B-3 Spectrum of Scale Outlet of E-2

D4126 6777 E3 OUT
 PHA11 ADD .010KEY/CH 100. SECS
 BUG= .520KEY, 0:

Figure B-4 Spectrum of Scale at Outlet of E-3

D6912 6177 HETU E4
 PHA11 ADD .010KEY/CH 100. SECS
 BUG= 8.350KEY, 17.

Figure B-5 Spectrum of Scale at Inlet to E-4

D5116 6777 E4 OUT
 PHA11 ADD .010KEY/CH 100. SECS
 BUG= .970KEY, 57.

Figure B-6 Spectrum of Scale at Outlet of E-4

Appendix C

COMPUTER PROGRAM DATA

The following four data pages show the results for the computer program used to determine the equation that best fits the experimental heat transfer coefficients. The first 10 lines list the data used to calculate the curve.

The name of the program is "Sixcur" and is in the computer program library of Remote Computing Corporation.

After entering all data, the program is used to calculate the best fit for the six curves listed, as shown. The index is the degree of fit, with 1.000 being the best fit possible. Details for the desired curve are available and were obtained for $Y = X/(AX + B)$, which had the highest index of determination. At the 80 percent confidence limits, the extreme values for coefficients A and B are shown.

Confidence limits of 90 percent, 95 percent or 99 percent were not chosen because the scatter in the data was too great to warrant closer statistical tolerance.

Exchanger One
Curve-fitting Print Out
Correlation To Best Of Six Curves

LOAD CURD1

#WORKFILE CURD1: SEQ, 10 RECORDS, SAVED

P

50 87,890,

100 102,677,103,662,104,655,105,657,106,650,107,648,108,642,109,

200 648,110,646,112,648,116,650,117,647,118,649,119,643,120,643,

300 121,651,128,631,129,624,130,622,132,631,133,622,134,627,135,

400 630,136,626,137,632,138,633,140,630,141,627,142,630,143,629,

500 144,626,145,627,146,629,147,644,148,637,149,646,150,643,151,

600 640,152,641,153,644,154,638,155,638,156,633,157,629,158,626,

700 159,622,160,623,161,620,162,613,163,614,164,618,165,617,166,

800 620,167,616,168,620,169,621,170,619,171,623,172,620,173,620,

900 174,622

*

RUN LIB/SIXCUR

#RUNNING 0578

ENTER FILE NUMBER (1-9)-1

ENTER NUMBER OF DATA POINTS- 62

ENTER 1=50% 2=80% 3=90% 4=95% 5=99% CONFIDENCE- 2

NUMBER	CURVE	INDEX	A	B
1.	$Y=A+B \cdot X$	0.3202839	761.4081781	-0.8811767
2.	$Y=A \cdot \exp(B \cdot X)$	0.3613762	761.8661820	-0.0012759
3.	$Y=A \cdot (X \cdot B)$	0.4128496	1557.6617875	-0.1813703
4.	$Y=A + (B/X)$	0.4311433	508.8232945	17586.6503328
5.	$Y=1/(A+B \cdot X)$	0.4038057	0.0013094	0.0000019
6.	$Y=X/(A \cdot X+B)$	0.5147409	0.0018375	-0.0362855

WHICH CURVE ARE DETAILS DESIRED (NUMBER)? 6

	EXPECTED VALUE	80% CONFIDENCE LIMIT	
A	0.001838	0.001810	0.001865
B	-0.036285	-0.040016	-0.032555
X-MEAN	140.177419		
Y-MEAN	637.887097		

Exchanger Two
Curve-fitting Print Out
Correlation To Best Of Six Curves

```
LOAD CURD _3
#WORKFILE CURD3: SEQ, 9 RECORDS, SAVED
P
50 87.639,
100 103.608,104.614,105.612,106.607,107.600,108.599,109.603,110.598,
200 111.599,113.608,114.607,115.604,116.593,117.589,118.595,119.589,
300 120.591,121.598,122.588,126.595,128.585,134.583,135.585,136.592,
400 137.583,138.578,139.575,140.578,141.585,142.580,143.571,146.573,
500 147.583,148.578,149.582,150.576,151.588,152.584,153.581,154.573,
600 155.584,156.581,157.588,159.587,160.583,161.575,162.579,163.575,
700 164.573,165.573,166.574,167.570,168.571,169.572,170.576,171.569,
800 172.576,173.574,174.575
#
RUN LIB/SIXCUR
#RUNNING 0592
ENTER FILE NUMBER (1-9)-3
ENTER NUMBER OF DATA POINTS- 60
ENTER 1=50% 2=80% 3=90% 4=95% 5=99% CONFIDENCE- 2
```

NUMBER	CURVE	INDEX	A	B
1.	$Y=A+B \cdot X$	0.7626181	658.9962719	-0.5195035
2.	$Y=A \cdot \text{EXP}(B \cdot X)$	0.7677521	662.6518352	-0.0008767
3.	$Y=A \cdot (X \cdot B)$	0.8064056	1058.5768103	-0.1199736
4.	$Y=A \cdot (B/X)$	0.8370934	516.7752019	9449.2489657
5.	$Y=1/(A+B \cdot X)$	0.7723113	0.0014994	0.0000015
6.	$Y=X/(A+B \cdot X)$	0.8393144	0.0019036	-0.0267888

WHICH CURVE ARE DETAILS DESIRED (NUMBER)? 6

	EXPECTED VALUE	80% CONFIDENCE LIMIT	
A	0.001904	0.001894	0.001913
B	-0.026789	-0.028052	-0.025526
X-MEAN	139.100000		
Y-MEAN	586.733333		

Exchanger Three
Curve-fitting Print Out
Correlation To Best Of Six Curves

LOAD CURD4
#WORKFILE CURD4: SEQ, 10 RECORDS, SAVED

P

50 87,742,
100 103,621,104,611,105,610,106,608,107,607,108,584,109,585,110,586,
200 111,599,112,572,113,572,114,568,115,561,116,568,117,561,118,561,
300 119,558,120,591,121,551,122,563,123,530,124,545,125,543,126,537,
400 127,522,128,516,129,512,130,513,131,511,132,524,133,507,134,513,
500 135,517,136,526,137,513,138,521,139,509,140,509,141,506,142,507,
600 143,510,144,501,145,501,146,501,147,500,148,503,149,504,150,514,
700 151,505,152,499,153,502,154,502,155,499,156,505,157,503,158,501,
800 159,492,160,493,161,497,162,482,163,483,164,485,165,473,166,477,
900 167,477,168,475,169,484,170,487,171,485,172,478,173,478,174,474

#

RUN LIB/SIXCUR

#RUNNING 0601

ENTER FILE NUMBER (1-9)-4

ENTER NUMBER OF DATA POINTS- 72

ENTER 1=50% 2=80% 3=90% 4=95% 5=99% CONFIDENCE- 2

NUMBER	CURVE	INDEX	A	B
1.	$Y=A+B \cdot X$	0.8141877	802.0278191	-1.9919072
2.	$Y=A \cdot \exp(B \cdot X)$	0.8519609	867.6160065	-0.0036362
3.	$Y=A \cdot (X \cdot B)$	0.8962571	6074.5476950	-0.4980575
4.	$Y=A + (B/X)$	0.9110627	255.1274838	36605.7721314
5.	$Y=1/(A+B \cdot X)$	0.8808786	0.0009869	0.0000067
6.	$Y=X/(A+B \cdot X)$	0.9440604	0.0028038	-0.1203049

WHICH CURVE ARE DETAILS DESIRED (NUMBER)? 6

	EXPECTED VALUE	80% CONFIDENCE LIMIT	
A	0.002804	0.002782	0.002826
B	-0.120305	-0.123167	-0.117443
X-MEAN	137.291667		
Y-MEAN	528.555556		

Exchanger Four
Curve-fitting Print Out
Correlation To Best Of Six Curves

LOAD CURDS

#WORKFILE CURDS: SEQ, 10 RECORDS, SAVED

P

50 87,554,
100 103,555,105,548,106,553,107,552,108,558,109,535,110,531,111,509,
200 113,548,114,538,115,522,116,521,117,508,118,510,119,507,120,506,
300 121,518,122,518,123,518,124,521,125,500,126,512,127,496,131,508,
400 132,491,133,476,134,478,135,491,136,490,137,488,138,493,139,487,
500 140,476,141,479,142,494,143,477,144,469,145,476,146,475,148,479,
600 149,482,150,476,151,484,152,486,153,480,154,471,155,470,156,478,
700 157,485,159,471,160,463,161,468,162,470,163,469,164,461,165,456,
800 166,460,167,466,168,462,169,454,170,460,171,464,172,467,173,458,
900 174,455

#

RUN LIB/SIXCUR

#SCHED 0605

#RUNNING 0605

ENTER FILE NUMBER (1-9)-5

ENTER NUMBER OF DATA POINTS- 66

ENTER 1=50% 2=80% 3=90% 4=95% 5=99% CONFIDENCE- 2

NUMBER	CURVE	INDEX	A	B
1.	$Y=A+B \cdot X$	0.8691433	667.0206201	-1.2503946
2.	$Y=A \cdot \exp(B \cdot X)$	0.8782927	696.9535874	-0.0024997
3.	$Y=A \cdot (X \cdot B)$	0.8929268	2602.9695684	-0.3383242
4.	$Y=A + (B/X)$	0.8892811	329.4636120	22177.5163973
5.	$Y=1/(A+B \cdot X)$	0.8860987	0.0013381	0.0000050
6.	$Y=X/(A+X+B)$	0.8922477	0.0026849	-0.0881248

WHICH CURVE ARE DETAILS DESIRED (NUMBER)? 6

	EXPECTED VALUE	80% CONFIDENCE LIMIT	
A	0.002685	0.002661	0.002708
B	-0.088125	-0.091260	-0.084989
X-MEAN	138.651515		
Y-MEAN	493.651515		