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Laboratory Investigation Of An Advanced Geothermal Primary Heat Exchanger (APEX)

Final Report 2146:08
Contract E(04-3)-1125
24 September 1976

Prepared For:
Energy Research And Development Administration
Division Of Geothermal Energy

Aerojet
Liquid Rocket
Company

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LABORATORY INVESTIGATION
OF AN ADVANCED GEOTHERMAL
PRIMARY HEAT EXCHANGER (APEX)

FINAL REPORT 2146:08,
30 June 1975 to 31 August 1976

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ABSTRACT

This report describes the research program conducted by Aerojet Liquid Rocket Company to investigate the feasibility of using a recirculating bed material, fluidized by geothermal brine, to reduce or eliminate fouling in an Advanced Geothermal Primary Heat Exchanger (APEX).

The research effort combined theoretical analyses and laboratory experimentation to evaluate and characterize the concept. Technical feasibility was established by testing the effectiveness of the bed material in preventing the fouling of a heat exchanger tube in which simulated geothermal fluid was circulated.

Economic feasibility was assessed through analysis in which potential cost savings resulting from the use of the APEX concept in a hypothetical 30 MW electrical power plant were determined in comparison with conventional tube-in-shell heat exchangers.

Detailed conclusions and recommendations are presented.

TABLE OF CONTENTS

	<u>Page</u>
1.0 Introduction	1
2.0 Technical Discussion	5
2.1 Task 1 - Analytical Design	5
2.1.1 Well Site and Plant Thermodynamic Power Cycle Selection	5
2.1.2 Primary Heat Exchanger Parametric Analysis	11
2.2 Task 2 - Laboratory Experiments	22
2.2.1 Beaker Tests	24
2.2.2 Preliminary Flow Tests	28
2.2.3 Main Test Setup	30
2.2.4 Entrainment and Separation Cold Flow Experiments	45
2.2.5 Baseline Heat Transfer Tests	47
2.2.6 Fluidized Bed Characterization	51
2.2.7 Baseline Fouling Tests	55
2.2.8 Fouling Tests	61
2.3 Task 3 - Concept Reevaluation and Design Update	77
2.3.1 Plant Conceptual Design and Economics	77
2.3.2 Heat Exchanger Conceptual Mechanical Design	87
2.3.3 Data Correlation	91
3.0 Conclusions and Recommendations	99
3.1 Conclusions	99
3.2 Recommendations	101
References	102

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
I	Imperial Valley Geothermal Fields	6
II	Niland Wells Chemistry, Temperature and Pressure	6
III	Brine and Working Fluid State Point Conditions (10 MWe Geothermal Power Plant)	8
IV	Primary Heat Exchanger Geothermal Side Heat and Mass Balance	12
V	30 MWe Power Plant Operating Conditions	79
VI	Reported Geothermal Brine Fouling Factors	81
VII	Comparison of APEX and Conventional Units	83
VIII	APEX Test Data	97

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1.	APEX Process Flow Schematic	3
2.	Flow Schematic for Power Cycle (10 MWe) with APEX	9
3.	Heat Exchanger Temperature Profile	10
4.	Comparison of Liquid Heat Transfer Characteristics	14
5.	Effect of Shell Side Velocity on Overall Heat Transfer Coefficient	16
6.	Influence of Tube Diameter on Heat Exchanger Design	17
7.	Effect of Tubeside Velocity on Heat Exchanger Design	18
8.	Effect of Shell Side Velocity on Heat Exchanger Design	20
9.	Effect of Shell Side Velocity on Heat Exchanger Pumping Power	21
10.	Test Sequence Logic Chart	23
11.	Laboratory Beaker Tests for Brine Simulant Selection	26
12.	Results of Laboratory Beaker Fouling Tests for Brine Simulant Evaluation	27
13.	APEX Cold Flow Test Setup	29
14.	Transparent Tube Showing Typical Bed Material Suspension Conditions	31
15.	APEX Experimental Evaluation Heat Exchanger Flow Schematic	32
16.	APEX Heat Exchanger Module	37
17.	APEX Brine Conditioning Module	38
18.	APEX Heat Rejection Module	39
19.	APEX Test Facility	40
20.	APEX Heat Exchanger Test Section - Horizontal Orientation	41
21.	APEX Heat Exchanger Test Section - Vertical Orientation	42
22.	APEX Control and Instrumentation Panel	44
23.	Laboratory Tests Entrainment and Separation Tests Typical Stratification Results	46
24.	Overall Heat Transfer Coefficient Less Tubewall Resistance as a Function of Brine Circuit Flowrate	49

LIST OF FIGURES (cont.)

<u>Figure No.</u>		<u>Page</u>
25.	Comparison of Shellside Heat Transfer Coefficient - Test Exchanger Against Flowrate	50
26.	Influence of Bed Material on Tubeside Heat Transfer Coefficient	53
27.	Stratification of Bed Materials After 10 ft of Travel	54
28.	Comparison of Fouling Rates with Saturated NaCl and KCl Brines	57
29.	Comparison of Tubeside Heat Transfer Coefficient vs Time 2.8/1 NaCl/KCl	58
30.	Influence of Salt Concentration on Tubeside Heat Transfer Coefficient	64
31.	Comparison of Fouling Resistance Rate 57 Mesh SiO ₂ Bed Material Against Time at Nominal Velocity of 10 ft/sec	66
32.	An Evaluation of 57 Mesh SiO ₂ Bed Material Against Time at Nominal Velocity 10 ft/sec	67
33.	Comparison of Fouling Characteristics of 100 Mesh Garnet Bed Material at a Velocity of 10 ft/sec	69
34.	Fouling Results of 120 Mesh SiO ₂ Bed Material at Nominal Brine Vel = 10 ft/sec	71
35.	Comparison of Fouling Rate in Hot and Cold Heat Exchangers With Salt Added at Five Minute Intervals	72
36.	Comparison of Fouling in 100 Mesh Garnet Bed Material at 10 ft/sec Nominal Velocity	74
37.	Comparison of Fouling in 100 Mesh Garnet Bed Vertical Exchanger Cold (Brine Downflow) at Velocities of 8 ft/sec and 5 ft/sec	76
38.	APEX Process Flow Schematic	78
39.	APEX Heat Exchanger Inlet Manifold Design Concept	88
40.	U-tube Exchanger with Internal Baffle Shellside	90
41.	Fixed Tubesheet Exchanger with Shellside Expansion Joint	90
42.	Single Pass Exchanger with Special APEX Channel and Floating Head	90

1.0 INTRODUCTION

Geothermal energy is found in dry steam and hot water reservoirs. Advanced studies are directed toward the utilization of hot dry rock, coastal geopressed brines, normal earth thermal gradient and magma intrusions. Power recovery from dry steam has reached a commercial stage of development; e.g., power production at the Geyser wells in northern California. Few well sites of this type have been discovered; the only other site where electricity is produced from dry steam is at Larderello, Italy. The recovery of energy from hot dry rock awaits a better technical understanding of the mechanics of in-situ heat transfer and the flow pattern when water is injected into the ground.

The recovery of energy from liquid dominated hydrothermal brines is much closer to realization and now depends mainly upon the development of process equipment to extract the available energy in an economical and socially acceptable manner. The Energy Research and Development Administration has published national goals of geothermal utilization for electrical power production as follows: 6000 Mw, 40,000 Mw and 140,000 Mw by calendar years 1985, 2000 and 2020 respectively. Non-electric applications are projected as 0.1 quad (10^{14} Btu), 1 quad and 8 quads at corresponding time periods.*

Difficulties have been encountered from hot water and brine flow in process equipment caused by dissolved solids coming out of solution during energy extraction.

The Advanced Geothermal Primary Heat Exchanger (APEX) concept is directed toward solving this fouling problem in a binary cycle system. Heat is transferred from the primary fluid to the secondary power conversion fluid,

*"Geothermal Energy RD&D Program Definition Report" ERDA-86, Oct. 1975.

1.0, Introduction (cont.)

passing counterflow, by forced convection. In the APEX concept, as illustrated in Figure 1, material such as fine sand is injected into the hot brine as it enters the heat exchanger. The passage of the solid abrasive material through the heat exchanger provides a scouring action which helps clean the exposed surface. Additionally, the suspended solids can provide precipitation sites for materials coming out of solution as the temperature and pressure of the geothermal well water drops. The brine mixture discharging from the heat exchanger passes through a disengagement unit where the sand and precipitated solid material is removed. The brine is then reinjected into the ground.

The work on this contract was divided into three major technical tasks. Task 1 was an analytical effort in which the size and conceptual design were developed and a sensitivity analysis performed. These analyses provided guidance such that the laboratory experiments conducted in Task 2 were applicable to a prototype design.

The Task 2 effort concentrated on laboratory experiments to investigate the technical feasibility of the APEX concept and to obtain the parametric data required for design of a demonstration size unit. The laboratory experiments included evaluation of the influence on fouling rate of bed composition and concentrations, brine velocities, and exchanger orientation. A simulated brine solution consisting of a saturated solution of sodium and potassium chloride was used for the experiments.

The Task 3 effort was an analytical assessment involving the reevaluation of the concept and a design update based upon the laboratory test results. This task includes an economic analysis showing the cost savings potential if the concept is employed in a 30 MW plant, an analytical extrapolation of Task 2 data to anticipated well site conditions, and possible heat exchanger conceptual design approaches.

Figure 1. APEX Process Flow Schematic

1.0, Introduction (cont.)

The conclusions reached are discussed, as well as the recommendations for further work. It was concluded that the concept is effective in significantly reducing the fouling rate. It is recommended that APEX testing be continued at a geothermal well site prior to prototype unit design.

This report covers the work performed under Contract E(04-3)-1125, from 30 June 1975 to 31 August 1976. The work described was conducted for the Utilization Technology Branch of the Division of Geothermal Energy, Energy Research and Development Administration. Clifton B. McFarland is the ERDA Program Manager. The program was conducted at the Aerojet Liquid Rocket Company facility at Sacramento, California.

The project activity at Aerojet included contributions from the following personnel:

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G. K. Olson	Systems Engineer
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Dr. E. M. Vanderwall	Manager of Chemical Processes
M. E. Bell	Data Manager

2.0 TECHNICAL DISCUSSION

The technical discussion is organized into three main sections paralleling the major program tasks. These three sections are (1) Analytical Design, (2) Laboratory Experiments, and (3) Concept Reevaluation and Design Update. Each section is divided according to program subtasks.

2.1 TASK 1 - ANALYTICAL DESIGN

The objective of Task 1 was to provide a preliminary design of an APEX heat exchanger in order to develop guidelines for the Task 2 laboratory experiments. This was accomplished by performing the initial design analysis of a heat exchanger for a 10 MW electric geothermal power plant.

The design analysis was conducted by (1) establishing a candidate well site for the APEX concept, (2) selecting a power cycle based on the well site water chemistry and properties and (3) performing a parametric design and sensitivity analysis of a heat exchanger for a 10 MW plant.

The following paragraphs describe the assumptions, results, and conclusions which lead to the choice of bed materials, operating conditions, and test exchanger design for the Task 2 experiments.

2.1.1 Well Site and Plant Thermodynamic Power Cycle Selection

Well sites at Heber, East Mesa, and Niland were reviewed as candidate geothermal water sources suitable for application of the APEX self-cleaning heat exchanger concept. These sites are all located in the Imperial Valley of California and are characterized by geothermal brines with relatively high concentrations of dissolved solids; (see Table I). The Niland field, having the typical composition listed in Table II was selected for use

TABLE I
IMPERIAL VALLEY GEOTHERMAL FIELDS

<u>Field</u>	<u>Temp (Well-Head)</u>	<u>Solids, mg/l</u>
Heber	300 - 350	14,000
East Mesa	300 - 350	1,000 to 19,000
Niland	375 - 385	216,000 to 240,000

TABLE II
NILAND WELLS CHEMISTRY, TEMPERATURE AND PRESSURE

<u>Constituent</u>	<u>mg/l</u>	<u>Constituent</u>	<u>mg/l</u>
Na	58,000	Al	180
K	11,000	Ba	800
Mg	100	Sr	533
Mn	160	Si	675
Fe	240	Cl	121,000
Cu	0.8	F	200
Zn	280	B	390
Pb	35	SO ₄	113
Ca	23,000	Sulfides	None Detected
Li	170	-	-

Total Solids 216886 mg/l

Flow	Temp	Press
0	464°F	330 psig
Rated	375 - 385	150 - 200

2.1, Task 1 - Analytical Design (cont.)

in this analytical effort because of its high water temperature and solids concentration. The very high solids concentration offers a worst case basis for the APEX concept while the higher temperatures offer the capabilities for higher cycle efficiencies and thus ultimately lower power generation costs.

The selection of a power cycle for the primary heat exchanger analysis was based on the data presented in References 1, 2 and 3. These study activities verified the superiority of a Binary Rankine cycle using an organic media as the working fluid.

A super critical cycle employing isobutane as a working fluid was selected. The geothermal and working fluid flow rates through the primary heat exchanger were obtained from the cycle study data presented in Reference 2. The geothermal fluid flow rates were increased approximately 25% to compensate for the lower specific heat of the high dissolved solid content water from the Niland wells as compared to the relatively clean water from East Mesa used in the reference cycle studies. Figure 2 shows the cycle flow schematic.

The preliminary design and sizing of the primary heat exchanger was based upon the brine and working fluid state point conditions provided in Table III for a Super Critical Isobutane Cycle.

The resultant counter flow temperature differentials through the heat exchanger for the indicated flow rates are shown in Figure 3, assuming 10% recirculating flow for bed material. The end point temperature differentials are 40°F and the pinch point temperature 15°F. This results in a log mean temperature difference of 25.5°F.

TABLE III

BRINE AND WORKING FLUID STATE POINT CONDITIONS
(10 MWe Geothermal Power Plant)

Brine

Well Head Temp at Rated Flow	380°F
Dilution due to Solids Recirculation (10%)	20°F
Heat Exchanger Inlet Temperature	360°F
Terminal Temperature Difference	40°F
Working Fluid at Turbine Inlet	320°F

Working Fluid - Isobutane

Inlet Temperature	105°F
Inlet Pressure	800 psia
Discharge Temperature	320°F
Discharge Pressure	750 psia
Flow Rate	1.75×10^6 lb/hr
Energy Transfer	176 Btu/lb, 3.08×10^8 Btu/hr

Figure 2. Flow Schematic for Power Cycle (10 MW_e) with APEX

Figure 3. Heat Exchanger Temperature Profile

2.1, Task 1 - Analytical Design (cont.)

2.1.2 Primary Heat Exchanger Parametric Analysis

The design analysis for the heat exchanger was based on a standard log mean temperature difference. The analysis considered the convection film resistances for flows internal and external to the tubes, the tube wall resistance and a standard fouling factor for the organic fluid side. It was assumed that the continuous recirculation of the particulate material on the brine side maintains a fouling free condition. Assumptions were also made relative to the particulate flow rate, supply temperature, heat capacity and carrier fluid at injection in order to complete the primary heat exchanger heat balance. These are presented in Table IV.

The addition of the solid material (up to 10 wt % assumed required) has only a slight effect on lowering the fluid temperature due to the low specific heat of the bed materials.

The design variables considered in the parametric analysis are listed below.

Brine Velocity - fps	5, 10 & 20
Isobutane Velocity - fps	5, 10 & 20
Tube Diameter - inches	1/2, 3/4 & 1.0

The preliminary study considered a single pass counter flow design with the brine-solids mixture flowing within the tubes and the super critical binary fluid flowing along the tube axis on the shell side.

Thermodynamic property data for the Niland brine were not available. The properties employed in computing the energy content and heat transfer coefficients were based on NaCl brine of equivalent total

TABLE IV

PRIMARY HEAT EXCHANGER GEOTHERMAL SIDE HEAT AND MASS BALANCE

Brine, from Well (TDS 217,000 mg/l $C_p = 0.8$ Btu/lb°F)

Flow	1.64×10^6 lb/hr
Temperature	380°F
Pressure	175 psig

Cleaning Media Injection

Solid $C_p = 0.23$ Btu/lb°F	0.20×10^6 lb/hr
Carrier Fluid C_p 0.8	0.10×10^6 lb/hr
Injection Temperature	145°F

Heat Exchanger Inlet

Total Flow	1.94×10^6 lb/hr
WT Percent Solids	10%

Heat Exchanger Discharge

Total Flow	1.94×10^6 lb/hr
Temperature	145°F

2.1, Task 1 - Analytical Design (cont.)

dissolved solids. These were obtained from Reference 4. NaCl properties were compared with CaCl (Reference 5) brine properties and found to be approximately the same. Since these two constituents comprise approximately 75% of the total dissolved solids, the approximation is believed to be reasonably accurate.

The properties of isobutane employed in the analysis were obtained from Reference 5. Properties of saturated liquid were used where specific data for the super critical state were unavailable.

2.1.2.1 Heat Transfer Coefficients

The heat transfer coefficients were calculated for the internal brine and external isobutane flow. In order to facilitate the analysis the constants and properties for each fluid were combined into a single term, which is plotted as a function of the fluid bulk temperature in Figure 4.

Comparison of these data provides insight into the theoretical heat transfer capabilities of fluids relative to each other and clean water. NaCl and CaCl brines have nearly identical heat transfer capabilities and are inferior to pure water. Saturated isobutane is a poorer heat transfer media than are the brines.

In the analysis all properties were evaluated at the mean bulk temperature of the respective fluid. The influences of the wall temperature and a correction for wall-to-bulk temperature ratio was small and neglected for the preliminary design.

The overall heat transfer coefficient U was calculated by:

Figure 4. Comparison of Liquid Heat Transfer Characteristics

2.1, Task 1 - Analytical Design (cont.)

$$U = \frac{1}{R_o + F + R_i + R_w}$$

R_o = Working fluid side convective film resistance

F = Working fluid side fouling resistance

R_w = Wall, resistance

R_i = Brine side (internal) convective film

A shell side fouling factor of $.0005 \frac{\text{Hr Ft}^2 \text{ } ^\circ\text{F}}{\text{Btu}}$ was assumed for F .

Figure 5 is a plot of U as a function of shell side velocity for various tube diameters at two different brine velocities. The shell side velocity is the major variable which controls the overall heat transfer rate with some additional benefit obtained by the use of smaller tube diameters. Increasing the brine velocity above that required for transporting the bed material shows little thermal advantage.

2.1.2.2 Heat Exchanger Design

The heat transfer surface required to transfer 3.08×10^8 BTU/Hr was computed parametrically as tube diameter and flow velocities were independently varied. Figure 6 shows the influence of tube diameter on the required surface and the resulting pressure drop for fixed flow velocities. The influence of smaller tube diameters on heat exchanger design is quite apparent, i.e., less pressure drop, shorter length and less surface. However, the use of the smaller diameter does require more tubes.

The effect of tubeside velocity on heat exchanger designs is shown in Figure 7. The optimum tubeside velocity appears to be in the 5-7 fps range.

Figure 5. Effect of Shell Side Velocity on Overall Heat Transfer Coefficient

Figure 6. Influence of Tube Diameter on Heat Exchanger Design

Figure 7. Effect of Tubeside Velocity on Heat Exchanger Design

2.1, Task 1 - Analytical Design (cont.)

Figure 8 shows the influence of shell side velocities for the optimum 1/2 in. tube diameter, considering tube side velocities of 5 and 10 fps. The maximum shell side velocity allowable (within the 50 psi pressure drop budget) is approximately 12 fps. This is nearly independent of tube side velocity in the 5 to 10 fps range.

The influence of shell side velocity on the total pumping power requirement is shown in Figure 9. A heat exchanger design optimized for minimum pumping power operates at a shell side velocity of 5 fps and is considerably larger than a minimum surface exchanger.

2.1.2.3 Solids Transport and Separation

The criteria for the selection of an appropriately sized cleaning media are as follows.

Particles should be sufficiently small to provide a large number of nucleation sites and to be transportable at velocities as low as 5 ft per sec without saltation (deposition). These particles should also be readily removable from the flow stream after passing through the heat exchanger in order to preclude plugging of the brine re-injection well. The smaller particle sizes are more difficult to separate. Thus, a selection criteria bounded by transport and separation limitation is required.

The range of possible saltation velocities were computed using a number of different correlating techniques, References 6 through 9. The Zenz parameter results in the highest saltation velocity predictions while the Durand and Zenz and Robinson data correlation result in much lower predictions.

Figure 8. Effect of Shell Side Velocity on Heat Exchanger Design

Figure 9. Effect of Shell Side Velocity on Heat Exchanger Pumping Power

2.1, Task 1 - Analytical Design (cont.)

The interim data correlations suggest that the maximum sand diameter employed for cleaning should not exceed 0.015-in. dia. The desired size range should probably be in the 0.002 in. to 0.005 in. dia range to insure saltation free flow within the heat exchanger tubing.

The results of these analysis provided the basis for selection of the following test parameter ranges in Task 2:

<u>Parameter</u>	<u>Test Range</u>
Bed Particle Size	24 Mesh thru 120 Mesh
Bed Material	Silica and Garnet
Brine Tube Diameter	1/2-inch
Brine Velocity	5 thru 10 ft/sec

2.2 TASK 2 - LABORATORY EXPERIMENTS

Task 2 of the program included the experimental effort required to establish APEX concept feasibility. This experimental effort encompassed laboratory beaker tests, cold flow experiments and elevated temperature heat transfer tests. Figure 10 illustrates the test sequence logic followed.

Design of the test setup for the heat transfer experiments was initiated as soon as sufficient data were available from the Task 1 analytical effort to define the design and operating conditions for the experiments. Completion of the test setup was dependent upon preliminary experimentation and verification of the suitability of the planned bed injection and separation techniques and beaker tests verifying the capability of fouling of the tubes with candidate brine simulants.

Figure 10. Test Sequence Logic Chart

2.2, Task 2 - Laboratory Experiments (cont.)

The first series of heat transfer tests were baseline tests conducted with clear water in both shellside and tubeside circuits. These tests were designed to checkout the system functionally and provide basic shellside and tubeside heat transfer data.

The second series of tests were performed with bed material added to the tubeside. These tests provided verification of the suitability and operating characteristics of the bed handling facilities, permitted determination of the influence of the bed material on the heat transfer coefficient, and were used for screening candidate bed makeup and correlating the bed makeup (material and particle size) with operating velocities required to maintain the bed in an unstratified condition within the test exchanger tube.

The third series of tests were the baseline fouling tests. These tests were conducted with simulated geothermal fluid in the tubes but without bed material. The baseline fouling tests were for the purpose of selecting a geothermal fluid simulant, demonstrating fouling capability and rate under various operating conditions, and establishing the heat transfer coefficients of the selected simulant.

The final test series conducted were the APEX non-fouling verification tests. These tests were performed to determine the influence of various bed makeups, concentrations, and operating conditions on the rate of tube fouling.

2.2.1 Beaker Tests

Laboratory beaker tests were begun during the test setup phase of the program to provide a preliminary evaluation of the fouling characteristics of various candidate geothermal fluid solutions.

2.2, Task 2 - Laboratory Experiments (cont.)

The requirements of the geothermal fluid simulant were: (1) that it provide a readily measureable amount of fouling in a single shift of test operation and (2) that some simple means exist for removing the fouling film. These requirements were basic to the program structure. A slower fouling fluid would be incompatible with the program testing schedule and funding. A permanent film would require multiple replacement exchangers.

Figure 11 illustrates a typical beaker test setup. A T-304 stainless steel tube 1/8-inch OD by 0.010-in. wall was suspended in a beaker containing a boiling saturated solution of the candidate simulant. Cooling water was flowed through the tube at a rate of 30 cc per minute. The solution level in the beaker was maintained by a makeup feed water supply activated by a level control switch. Water solutions of sodium metasilicate, potassium chloride, sodium chloride and potassium chloride plus iron and calcium chloride were evaluated. The calcium chloride would not deposit and the silica deposition rate was too slow to be useful. Deposition rates are tabulated below:

<u>Specimen No.</u>	<u>Solution</u>	<u>Exposure Time (hrs)</u>	<u>Deposition Rate (gms/hr)</u>
1	KCl	19.5	0.22
2	NaCl	23	0.15
3	KCl + Fe	24	0.24
4	(SiO ₂) _x	24	0.0018

The scale formation would generally start at the coolant inlet end of the tube and gradually extend downstream. Excessive undissolved salt in the solutions was found to cause rapid scaling. This scale appeared flakey and porous. With less undissolved salt, a dense hard scale was formed. A photograph of test specimens exposed to various saturated solutions is shown in Figure 12.

Figure 11. Laboratory Beaker Tests for Brine Simulant Selection

Figure 12. Results of Laboratory Beaker Fouling Tests for Brine Simulant Evaluation

2.2, Task 2 - Laboratory Experiments (cont.)

On the basis of these tests sodium chloride was selected as the first choice for use as a brine simulant because of the extensive amount of existing data on physical properties at various conditions of temperature and saturation. Potassium chloride was selected as an alternative material in the event that faster fouling was required.

2.2.2 Preliminary Flow Tests

The most critical portion of the test setup design is the bed injection and removal system. The selected design approach incorporated an educator for introducing the solids into the brine stream and a cyclone separator for removal of the solids from the brine stream. Preliminary verification of the concept and components was considered necessary before incorporating the concept in the final setup design.

Flow evaluation of the educator for solids reinjection and the solids separator was conducted in a bench test flow loop. Figure 13 is a photograph of the test setup. Facility water was introduced to drive the educator, simulating brine flow. The educator suction was connected to the separator solids discharge via a sight glass. The discharge was routed through two sight glasses in parallel to permit sampling of the educator discharge without shutdown of the experiment. The flow was then routed through a transparent U-tube to simulate the heat exchanger test section and to permit observation of the flow characteristics, i.e., uniformity, turbulence, and bed material settling. The discharge from the simulated exchanger was plumbed to a commercial uniclone (cyclone) separator. The discharge water stream from the separator was run through a settling tank to observe the solids carry-over.

The flow loop was used to determine: (1) the effectiveness of separating solid bed material from the heat exchanger effluent stream and

Figure 13. APEX Cold Flow Test Setup

2.2, Task 2 - Laboratory Experiments (cont.)

reinjecting the bed material at the heat exchanger inlet, (2) the solid concentration of the streams, and (3) the pressure losses in key components in the flow loop. Flow and pressure drop data on the components were obtained with water, and water/garnet bed mixtures.

The conclusions reached from this test series were as follows: (1) the cyclone separator achieved essentially 100% removal of solids from the pump suction stream, (2) the eductor tested was effective in reinjecting the solid material into the brine circuit, (3) at flows below 2-1/2 gpm (5-1/2 ft/sec heat exchanger velocity) the eductor pressure recovery was insufficient to overcome the test system pressure drop, indicating the need to switch to a modified eductor design should the process optimize at the lower flowrates, (4) particle stratification will occur with 100 mesh garnet bed material at flow velocities below 7 ft/sec, (5) solid concentrations in the eductor discharge (heat exchanger inlet) reach a maximum of 10 wt% at flow velocities of approximately 7 ft/sec.

Generalizing the results, the selected process and equipment were satisfactory for the higher flowrate ranges. The limiting minimum flowrate was established in subsequent testing.

Figure 14 is a photograph of the transparent tube at the outlet showing the typical bed material suspension conditions. The fluid velocity is 10 ft per second. The bed material is 100 mesh garnet.

2.2.3 Main Test Setup

The process design of the main test system was initiated as soon as sufficient analytical data from Task 1 were available to establish the operating and design conditions. Figure 15 is a schematic flow diagram of the final design.

Figure 14. Transparent Tube Showing Typical Bed Material Suspension Conditions

2.2, Task 2 - Laboratory Experiments (cont.)

The test setup was divided into three basic subassemblies as indicated by the dashed lines on the schematic. This division was made primarily for simplicity in fabrication and handling. The three subassemblies are the APEX heat exchanger circuit, the brine conditioning circuit, and the cooling water circuit.

2.2.3.1 Process Description

The APEX heat exchanger test section design, shown in the upper center of the flow diagram, consists of a pair of concentric tubes. The center tube which handles the brine-solid mixture is 1/2-inch stainless steel. The outer tube is 3/4-inch stainless steel. The annulus between the tubes provides the cooling jacket. Two 10-foot sections were used. These sections were joined at one end with a sample collection tube located at this junction. The exchanger was valved to permit cooling of one or both exchanger legs to provide flexibility in selection of the heat exchange surface during each experiment.

The brine-solids mix exits the heat exchanger and enters the separators. Two uniclone separators in parallel were used to provide the capability for handling both high and low flow rates effectively. The liquid leaves the separators at the top and is routed to the suction of the pump via a sight glass, a collection pot to remove any solids carried over, and a surge pot. The solids exit from the bottom of the separators through a sight glass to the suction of a water eductor.

The brine pump discharges into a 40 Kw electrical heater. The desired brine flowrate is routed to the mineral tank and the excess flow is bypassed to the suction of the pump. A bypass around the mineral tank is provided in the event that no salt addition is required in the brine solution. The clear brine solution is then used as the driving fluid in the eductor.

2.2, Task 2 - Laboratory Experiments (cont.)

The brine-solids mixture leaving the eductor passes through a sight glass and enters the heat exchanger. A bypass is provided around the heat exchanger to permit the system to come to steady-state before the exchanger is brought on-stream.

The cooling loop is used to simulate the working fluid. A pressurized system was used so that coolant temperatures in excess of 212°F are possible. A heat exchanger cooled by plant water was used to remove the heat. The cooling water temperature to the test section was maintained by controlling the plant water flowrate. A bypass from the pump discharge to the coolant surge tank provided for regulation of the coolant flowrate. There is an electrical heater located in this bypass to permit preconditioning of the coolant water to the desired temperature before placing the exchanger into service.

A nitrogen gas pressurizing system was provided for pressurizing the brine and cooling circuits to the desired level. Deionized water was plumbed to both the brine and water circuits to provide makeup water.

The particle loader permitted bed material to be added as desired during the experiments. The loader was in parallel with the eductor and valved such that it could be isolated to permit recharging during the course of a test.

2.2.3.2 Instrumentation

Flow measurements were provided on both the brine and cooling circuits. A conventional turbine type flowmeter located at the inlet to the heat exchanger was used for measuring coolant flowrate. The selection and location of the brine flowmeter presented some problems. A force deflection beam flowmeter was selected as being the best type flowmeter for corrosive

2.2, Task 2 - Laboratory Experiments (cont.)

service of those readily available and economically feasible. The flowmeter could not be located at the heat exchanger inlet because of the erosive characteristics of the bed material and was therefore located at the inlet to the eductor. This location did not provide the actual flowrate to the exchanger because the recirculation fluid from the separators was not measured. The method of determining brine flow to the exchanger is described below.

Chromel-Alumel thermocouples with an ice bath reference junction were used throughout. The temperatures measured were heat exchanger coolant and brine inlet and outlet, brine temperatures at the eductor inlet, outlet and suction, brine and coolant tank temperature and brine tubewall temperatures within the heat exchanger at various stations. The eductor inlet and outlet temperatures used were in an energy balance to calculate the recirculation flow needed to determine the total flow to the test exchanger. This calculation involves the subtraction of the two thermocouple readings which are only a few degrees apart and requires greater than normal TC accuracy to get meaningful data. Two thermocouples were made up and calibrated as a special set to provide the accuracy needed.

Special temperature instrumentation was required to obtain a direct meter readout of the overall heat transfer coefficient to facilitate control of the test. This was accomplished as follows: the overall Q was determined by measuring the cooling water ΔT , which is proportional to the heat transferred (assuming constant flowrates). The MTD was determined by averaging the ΔT between the brine and cooling water at each end of the exchanger. This closely approximates the log mean ΔT provided the ΔT 's at the extremes are not greatly different, which was the case. By dividing the Q reading by the ΔT reading, a value proportional to the overall U is obtained and the change in U with time can be monitored.

2.2, Task 2 - Laboratory Experiments (cont.)

Pressure data was provided through the use of strain gages. Pressures were recorded for both the brine and coolant circuits at the inlet and outlet to the heat exchanger sections, the pump discharge and the tanks. Pressures were also measured at the eductor suctions and the brine surge pot.

2.2.3.3 Fabrication

The test setup was constructed in three separate modules which were assembled on skids and interconnected at the test site.

Figures 16, 17, and 18 illustrate these three modules. Figure 19 is an overall view of the three interconnected modules.

The heat exchanger sections were fabricated from two different diameters of 10 ft long stainless steel tubing which were assembled concentrically. The center brine tube was 1/2-inch 0.035 wall T-316L tubing. The outer tube was 3/4-inch, 18 gauge. This provides an annulus width for the coolant water flow of 0.076-inches and a resultant flow area approximately equal to that of the brine tube. The center tube was spiral wrapped with 1/16-inch diameter wire, 1 turn every two feet, to provide support in maintaining the annulus and to improve the shellside heat transfer characteristics. Thermocouples were brazed to the outside of the center tube at specific stations and brought through the outer tube wall and brazed to the outer tube to form a seal. The tubes were assembled at each end using the equivalent of a heat exchanger swedgelok tee. A teflon ferrule was used at the aft end to permit differential thermal expansion. Figures 20 and 21 are photographs of the heat exchanger mounted in the horizontal and the vertical positions. Figure 20 also illustrates the sample collection system which was developed.

Figure 16. APEX Heat Exchanger Module

Figure 17. APEX Brine Conditioning Module

Figure 18. APEX Heat Rejection Module

Figure 19. APEX Test Facility

Figure 20. APEX Heat Exchanger Test Section - Horizontal Orientation

Figure 21. APEX Heat Exchanger Test Section - Vertical Orientation

2.2, Task 2 - Laboratory Experiments (cont.)

2.2.3.4 Data Collection and Recording Reduction

Data was recorded via an on-line Vidar digital system. A printed tape record was used for monitoring test parameters of a noncritical nature and a magnetic tape was employed for recording all data. The magnetic tape was transferred to the test area computer services periodically for processing of the raw data.

Data critical to the control of the experiment was also visually displayed at the control panel. Figure 22 illustrates the control panel data display.

The computer program requires the input of two parameters which were obtained by sampling. These are the fraction of bed material in the flow to the heat exchanger and the salt concentration. The required data were obtained by trapping a sample in a known volume container and then cooling and weighing it. The bed material was then removed from the sample and weighed separately. The fraction of bed material is the weight of bed material divided by the total sample weight. The density of the liquid portion of the sample was determined by subtracting the solids weight from the total sample weight and the solids volume from the sample volume and dividing the liquid weight by the liquid volume. Tables were used to convert density to salt concentration. The salt concentration calculated in this manner was spot checked for accuracy in the earlier testing by boiling down the sample and weighing the actual salt content. This time consuming boil-down procedure was later abandoned when the results of the simpler technique were found to be in close agreement with the boil-down results.

Figure 22. APEX Control & Instrumentation Panel

2.2, Task 2 - Laboratory Experiments (cont.)

2.2.4 Entrainment and Separation Cold Flow Experiments

The purpose of the entrainment and separation tests was two-fold: first, to complete the evaluation of the entrainment and separation parameters over the complete anticipated test range and second, to check out the test setup initially under cold flow conditions. The tests were performed using the brine module and the heat exchanger module. The actual heat exchanger was replaced by the transparent section used for previous entrainment and separation tests, Section 2.2.2. The coolant module was not activated nor were the system heaters. Nineteen tests were performed using three different mesh SiO_2 beds and one garnet bed as specified in the test plan. The tests were conducted at various velocities and bed-loading densities, in conformance with the test plan.

Stratification data from these tests were collected by photographing the transparent test section outlet using microflash photography. The 120 mesh SiO_2 bed material appeared homogeneously mixed at all test velocities (4.5 ft/sec was the minimum velocity tested). All other bed materials showed some stratification at the lower velocities. The coarse, 24 mesh SiO_2 material and the garnet also showed stratification at the intermediate velocities (6.9 ft/sec). The coarse bed material and the garnet material both showed a tendency to bridge across the eductor suction and stop flow. This bridging problem would probably not be significant on a full scale installation because of the larger passages. No other problems were experienced in these tests.

The 24 mesh SiO_2 was tentatively dropped from further consideration as a candidate bed material because of the stratification and bridging problems. Figure 23 illustrates typical photographic stratification data.

STRATIFIED
BED

57 MESH SiO_2
5.8 FT/SEC

UNIFORM
BED

120 MESH SiO_2
6.6 FT/SEC

Figure 23. Laboratory Tests Entrainment & Separation Tests
Typical Stratification Results

2.2, Task 2 - Laboratory Experiments (cont.)

2.2.5 Baseline Heat Transfer Tests

The purpose of these tests was to complete checkout of test components, to establish the clean heat transfer coefficients, to checkout and debug the data collection and reduction system, and to checkout the instrumentation. The baseline heat transfer tests were conducted using deionized water in place of the brine (tubeside) and the coolant (shellside).

The instrumented double pipe heat exchanger test section was installed (replacing the transparent cold flow unit) and the coolant module and heating system activated. Initial system activation disclosed some equipment deficiencies due to inadequate vendor quality control, i.e., bent pintle on the control valve, pump mechanical seal installation error, and separator inserts not seated. Following corrections to the equipment deficiencies, the mechanical system performed properly.

Ten baseline heat transfer tests were conducted over a range of brine side inlet temperatures and flowrates. The MTD of the 300°F tests was a nominal 40°F. The 80°F MTD planned could not be achieved under the existing condition of heat input, exchanger surface, and heat transfer coefficients because of heater power limitation. The higher MTD can be achieved by bypassing one section of the heat exchanger. The purpose of the high MTD is to promote more rapid fouling but was unnecessary during baseline testing. The exchanger bypass modification was made after completion of the baseline heat transfer test series.

The overall test results were satisfactory. Heat transfer coefficients agreed well with predicted levels, and the data collections and reduction system functioned satisfactorily. A discrepancy observed in the heat balance between the coolant and brine circuits was traced to inaccurate

2.2, Task 2 - Laboratory Experiments (cont.)

thermocouples in the eductor circuits. The error was eliminated after these thermocouples were removed and match calibrated, as described in Section 2.2.3. The coolant flowrate was used for all calculations of heat load because of its greater reliability.

The flowrates of the brine circuit and coolant circuit were set as close as possible to the same value so that meaningful data could be obtained by plotting overall heat transfer coefficients as a function of brine circuit mass flowrate. The flowrate adjustment was made by setting the coolant flowrate to a level which resulted in the same ΔT for both circuits. Figure 24 is a plot of the overall heat transfer, less tubewall resistance, for the three nominal brine circuit inlet temperatures. The data were calculated for the hot exchanger section and the cold exchanger section separately, but the operating temperature differences of the two exchangers was not great enough to differentiate the results. Data for both exchangers was therefore combined in this curve.

Calculation of the tubeside (brine circuit) heat transfer coefficient could be accomplished with reasonable expectations of a high degree of accuracy. The coefficient in the coolant annulus could not be calculated from theory with accuracy because of the uncertainty in annular area, the degree of leakage past the exchanger supports, and resulting velocity. The annular coefficient was required in subsequent calculations of fouling film resistance. The annular coefficient was determined by calculating the theoretical tubeside film resistance and subtracting the sum of the tube wall and tube film resistance from the overall resistance according to the equation:

$$\frac{1}{U_T} = \frac{1}{h_s} + \frac{1}{h_t} + R_{\text{tubewall}}.$$

Figure 25 presents the annular coefficient as a function of coolant flowrate resulting from these calculations.

Figure 24. Overall Heat Transfer Coefficient Less Tubewall Resistance as a Function of Brine Circuit Flowrate

Figure 25. Comparison of Shellside Heat Transfer Coefficient - Test Exchanger Against Flowrate

2.2, Task 2 - Laboratory Experiments (cont.)

2.2.6 Fluidized Bed Characterization

The fluidized bed characterization tests were conducted to determine the degree of influence the bed material would have on heat transfer coefficients and to evaluate the stratification characteristics over a greater horizontal length than in test series I (10 feet as compared to 3 feet).

Prior to initiating this test series, two modifications were made to the heat exchanger test loop. A bypass circuit was added around one leg of the heat exchanger to permit operation at higher temperature differences without exceeding the heat addition capabilities of the system. In addition a short transparent section was added to the exchanger at the brine outlet to observe the stratification characteristics of the candidate bed materials.

Tests were performed substantially as outlined in the test plan matrix. The baseline temperature point for comparison purposes was changed from the planned 300°F to 225°F. This lower temperature reduced the cooldown time required before personnel could enter the test bay and hence expedited the testing rate.

Variation in bed density was eliminated from the test matrix as an independent variable because of the excessive time required to achieve a specific weight percent. The tests were conducted under maximum bed loading conditions. The maximum loading is dependent on the eductor and separator characteristics at the particular operating conditions of temperature and flowrate.

Twelve tests were conducted using various bed makeups plus four tests without bed material to verify that no change had occurred in clean

2.2, Task 2 - Laboratory Experiments (cont.)

tube heat transfer coefficients. The tests were performed at two different velocities with each of three different bed makeups at a nominal 225°F temperature. A temperature-velocity test matrix was conducted with one bed makeup.

The conclusions from these tests were that the bed material had no noticeable influence on clean heat transfer coefficients. Figure 26 illustrates the influence of the bed material in tubeside heat transfer rates. The tubeside coefficients were calculated using the shellside resistance determined in the previous test series as well as the tube wall resistance. Tests without bed material were performed periodically through the test series to secure the comparative data. The data from tests without bed material fall within the data scatter of the data from tests with various bed materials and densities.

On the basis of observed solids stratification in the flowing stream the coarse bed material (24 mesh SiO_2) appears unacceptable at velocities as high as 10 ft per second. The garnet is acceptable at 10 ft per second but not at 5 ft per second. The fine (120 mesh) SiO_2 is suitable at all velocities tested. Figure 27 illustrates the bed distribution at the exchanger outlet for various operating conditions.

The results of the fluidized bed characterization tests suggest that future tests with the geothermal fluid simulant should concentrate on the higher velocity level to prevent too severe a restriction on acceptable bed makeup variations.

BRINE INLET 225 °F

Figure 26. Influence of Bed Material on Tubeside Heat Transfer Coefficient

120 MESH
 SiO_2
 2.3%
 SIEVE APERTURE - 0.0049

100 MESH
 GARNET
 3.1%
 0.0059

24 MESH
 SiO_2
 2.3%
 0.029

5
 FT/SEC

10
 FT/SEC

Figure 27. Stratification of Bed Materials After 10 ft of Travel

2.2, Task 2 - Laboratory Experiments (cont.)

2.2.7 Baseline Fouling Tests

The baseline fouling tests were performed using a geothermal fluid simulant on the tubeside without any bed material. The objective of these tests was to checkout the brine system, select the composition of the geothermal fluid simulant for future fouling tests, and establish a fouling rate under specific operating conditions which could later be duplicated using a fluidized bed for concept verification purposes. This last objective was later modified by combining the baseline and fluidized bed fouling tests.

Initial baseline fouling tests were conducted using a sodium chloride solution. A single leg of the test exchanger was used to permit a high MTD which should be most conducive to fouling. A nominal 10 ft/second brine velocity was used, based on the bed stratification data obtained in the previous test series. The test duration was established at four hours minimum or the maximum duration which could be achieved in a single work shift operation, whichever was greater.

The first two tests were performed at relatively low salt concentrations, 9.5 and 13.9%. No fouling was observed on either test. The salt concentration was increased to saturation for the next test and the system plugged with salt before any data could be secured. This was attributed to too rapid addition of salt.

The first successful test conducted at brine conditions near saturation was a four hour duration test. The brine inlet to the heat exchanger was maintained near 300°F. The salt content was held between 27.9 weight % and saturation (29.6 weight %). Some indication of progressive fouling was noted; however, the rate of scale buildup was not as great as desired. Scale resistance equaled $0.00003 \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$ after four hours. It was concluded

2.2, Task 2 - Laboratory Experiments (cont.)

that a solute with a steeper solubility curve was needed to achieve adequate fouling within the desired test duration. Potassium chloride was selected as the solute for the next test based on the results obtained in the earlier laboratory beaker tests.

One satisfactory fouling test was performed using KCl as the solute for the geothermal fluid simulant. The test duration was five hours. The fouling rate was somewhat higher with the KCl than with the NaCl; a scale resistance of $0.0005 \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$ was measured after five hours. Figure 28 illustrates the fouling results observed with NaCl and KCl.

The operation of the test system with the KCl brine was extremely difficult. The salt coming out of solution tended to form very large crystals which repeatedly plugged the test loop, requiring shutdown and flushing with a consequent loss of time. The plugging problems experienced with KCl overshadowed any advantage gained in fouling rate.

It was decided at this point to evaluate extended duration testing. Two long duration tests were conducted, one using NaCl and one using a mixture of NaCl and KCl in the proportions of 2.8 moles NaCl to 1 mole KCl. The later composition was selected in an attempt to secure the advantages of a steeper solubility curve without the disadvantages of the larger crystals formed with pure KCl.

The long duration test using NaCl was continued for 17 hours without evidence of fouling while the corresponding test using the NaCl/KCl mixture exhibited a cyclic behavior. Figure 29 illustrates the calculated tubeside heat transfer coefficient for the NaCl/KCl test as a function of time. Salt was added periodically to maintain the brine at saturated conditions during the day and swing shift. This procedure was not followed during the graveyard shift.

Figure 28. Comparison of Fouling Rates with Saturated NaCl and KCl Brines

Figure 29. Comparison of Tubeside Heat Transfer Coefficient vs Time 2.8/1 NaCl/KCl

2.2, Task 2 - Laboratory Experiments (cont.)

A strong correlation can be observed between salt additions and the heat transfer coefficient. The coefficient decreases each time there is salt addition. When no salt is added for an extended period the coefficient increases and when salt addition resumes the coefficient again decreases. These data demonstrate the difficulty of maintaining constant chemistry in a closed loop system and that the fouling film once formed dissolves readily unless salt is added periodically.

A reevaluation of the operating procedures and test schematic was made to determine what was causing the loss of fouling film and to devise methods of reducing the system sensitivity to plugging so that repeatable data could be secured. The following procedural and mechanical changes were made to the system.

1. The brine heater was rewired to keep one leg on continuously with the temperature controlled by switching power on and off to the other two legs. The temperature control element was relocated into the main stream from the previous well location. These changes were made to reduce the frequency and range of temperature cycling.

2. A faulty solenoid valve was discovered in the deionized water system which could permit leakage of water into the brine system. This would have diluted the brine and is thought to be the most probable cause of the loss of the fouling film with time.

3. The instrumentation was modified to provide for continuous monitoring of the overall heat transfer coefficient as discussed in Section 2.2.3.2.

2.2, Task 2 - Laboratory Experiments (cont.)

4. The operating procedure was changed to provide a saturated solution in the brine tank at a considerably higher temperature than the test conditions. The brine tank was set to operate at 300°F, which is its maximum design temperature. The heat exchanger brine inlet temperature was established at 212°F. This gives a large temperature differential so that when more salt is needed in the system, a super-saturated solution is introduced. This replaced the earlier technique of passing the brine through a solid salt bed which tended to contain solids and plug the system.

5. A procedural technique was derived whereby the 300°F saturated solution was added at regular intervals throughout the test (typically 15 seconds every 5 minutes) to insure that the solution in the brine system remained saturated.

6. The test plan was revised such that the baseline fouling tests and the fluidized bed tests were combined into single tests so that there was reasonable assurance that the operating conditions being compared were the same except for the presence or absence of the fluidized bed. This was accomplished by running without any bed material, measuring the fouling rate, and then adding bed material and, alternatively, running with a bed, measuring the fouling rate and then removing the bed and determining the fouling rate.

7. The geothermal fluid simulant selected for future testing was the 2.8/1 NaCl/KCl mixture. It is probable that the pure NaCl would have been adequate after the system and procedure modification described above were made, however, the mixture appears to work well in terms of both fouling rate and crystal size. No further experimentation with different salts was warranted.

2.2, Task 2 - Laboratory Experiments (cont.)

8. Preparations were made to evaluate a silica based geothermal fluid simulant in the heat transfer experimental setup. Discussions conducted with Oak Ridge National Laboratory concerning simulation of fouling of surfaces with silica in geothermal systems led to the preparation of a silica based fluid using Alexander's Method. Sodium metasilicate was dissolved in water and the PH was controlled at about 5. The beaker fouling tests indicated a fouling rate which was too slow to be feasible for the test program. As a result the silica based simulant was not tested in the heat exchanger equipment.

2.2.8 Fouling Tests

Fouling tests were initiated using the modified operating approach described in the previous section. The testing procedure was as follows. The bed loader was loaded with the selected bed material and the brine tank loaded with the proper proportions of NaCl and KCl. The brine and coolant tanks and system plumbing were then filled with deionized water. The brine tank was isolated from the system and the coolant water was brought to operating temperature using the brine heater and the test heat exchanger. This accomplished two purposes. First, it heated the coolant so that the operating conditions at the start of the test were the same as the steady state conditions. Second, it insured that any fouling film remaining on the exchanger was dissolved. When the coolant reaches the desired temperature, the heat exchanger was bypassed and the brine tank brought up to temperature (300°F) by circulating through the water (brine) heater and brine tank. Once the brine tank reached 300°F, the tank was isolated with the tank strip heaters maintaining the tank at 300°F. The brine heater was deactivated and the thermostat control reset for the test operating temperature, typically 212°F. Deionized water was added to the brine circuit to reduce the salt concentration to below saturation at operating conditions and to reduce the

2.2, Task 2 - Laboratory Experiments (cont.)

system temperature. The brine circuit was recirculated and water periodically added until the temperature and the salt concentration drop to the desired level. The salt concentration was determined by periodic sampling. A known volume sample was weighed to determine specific gravity and hence salt concentration.

When the recirculating brine temperature and concentration were reached, the brine heater was reactivated and the heat exchanger was cut into the circuit. Flowrates and temperatures were readjusted for the desired operating conditions and data accumulation begun. In the cases where bed material was added at the start of the test, this was accomplished in 4 second bursts until the separator discharge sight glass indicated a dense bed concentration.

Data was collected at the start of the test ($T = 0$) at the time when saturation is reached (if different from $T = 0$) and periodically through the test as determined by the heat transfer coefficient instrumentation. When the test plan called for bed addition after baseline fouling data were accumulated, the bed material was added before the ΔP across the exchanger changed materially. If the fouling built up to significantly increase the system ΔP the bed material could not be added because of eductor performance limitations. When the test plan called for removal of the bed after fouling, two procedures were used. One was to open the valve (VBHI) which increased the brine flow to the separators. This increased the system ΔP and caused the eductor suction to stop, thus eliminating the recirculating loop. A second method of removing the circulating solids and the method most frequently used was to physically blow the bed material out of the circuit by briefly opening the eductor bypass, VBEB. This caused backflow through the eductor and separator and blew the bed material overhead into the collection pot. A third uncontrolled method occurred on occasion. This was failure of the eductor through plugging or erosion which again eliminated the bed by blocking the recirculation loop.

2.2, Task 2 - Laboratory Experiments (cont.)

The results from the fouling tests were compared on the basis of the buildup of the tubeside scale resistance over the testing time period. The tubeside scale resistance was calculated for each sample period in the following manner. First the overall heat transfer coefficient was determined from the test data using the computer program as described in Section 2.2.3.4. Then the analytically derived tubewall and shellside resistances were backed out of the overall coefficient, leaving the basic tubeside coefficient as described in Section 2.2.5. If saturated conditions did not exist in the brine at the time of the sample the experimental tubeside coefficient was corrected to a theoretical coefficient for a saturated solution using the curve shown in Figure 30. The value computed at the start of the test was considered to be the clean tubeside coefficient. Tubeside coefficients for subsequent data points were corrected for flowrate differences by multiplying the calculated coefficient by the ratio of the flowrates to the 0.8 power. The clean tubeside resistance was subtracted from the resistance calculated at subsequent time periods to determine the fouling resistance.

The fouling resistance data were plotted against time for each fouling test to observe the rate of fouling under various operating conditions. It was noted that the addition of bed material always reduced the rate of fouling. Alternatively, the removal of bed material always increased the rate of fouling depending on the test sequence. The rate of fouling was lowest when the garnet bed material was used, which is the denser of the two candidate minerals tested. The coarser mesh sand (57 mesh) was more effective in reducing fouling than the fine (120 mesh) sand. Typical test results follow.

The first fouling test, Test 117, was conducted using 57 mesh SiO_2 as the bed material at a nominal brine velocity of 10 ft/second. The baseline data with no bed material was collected first. The first hour

Figure 30. Influence of Salt Concentration on Tubeside Heat Transfer Coefficient

2.2, Task 2 - Laboratory Experiments (cont.)

of the test was spent in raising the brine solution to saturation. The fouling buildup was relatively slow during this period. Data collection was initiated before the brine had reached saturation. Figure 31 is a plot of the fouling resistance measured as a function of time. The fouling rate increased rapidly once saturation was reached. Bed material was added when the scale resistance reached $37 \times 10^{-5} \text{ hr-ft}^2\text{°F/Btu}$ which is equivalent to an average scale thickness of 0.010 inches.

The first data point taken after bed addition indicated a decrease in scale resistance and a bed concentration of 1.0 weight percent. The addition of bed material appears to smooth off the high points of the scale buildup, thus reducing the overall resistance. The bed concentration was increased to 3.3 weight percent for the remainder of the test. Two additional data points were recorded. These data indicated a progressive increase in scale resistance but a fouling rate only one-ninth that measured without any bed material.

Test 118 was conducted under identical operating conditions as 117 to verify the extent of repeatability and to evaluate the influence of higher bed loading. A plot of the test results is shown in Figure 32. The initial baseline portion of the test was similar to that observed in Test 117. No appreciable fouling was noted until saturation was reached. Rapid fouling occurred after saturation. The same characteristic reduction in scale resistance was observed during the bed addition phases of the test. The remainder of the test contains conflicting data. If all data points are valid it would indicate a fairly rapid increase in fouling rate after the bed addition followed by a gradual reduction in scale resistance. The gradual reduction in resistance is believable since the bed loading of >10% was much higher than on the previous tests but the increase cannot be accounted for. If the data point at 3 hours and 15 minutes is considered to be invalid, a gradual fouling

TEST 117

Figure 31. Comparison of Fouling Resistance Rate
57 Mesh SiO_2 Bed Material Against Time
at Nominal Velocity of 10 ft/sec

Figure 32. An Evaluation of 57 Mesh SiO_2 Bed Material Against Time at Nominal Velocity 10 ft/sec

2.2, Task 2 - Laboratory Experiments (cont.)

increase would be observed which essentially duplicates the results of Test 117. This is believed to be the most valid interpretation of the test data.

Tests 119 and 120 were performed at the same operating conditions but with 100 mesh garnet sand bed material in place of the 57 mesh SiO_2 . Test 120 was performed with the bed material added at the start of the test as contrasted to the previous tests where fouling was started before bed material was added. The purpose of this reversal was to verify that the reduction in fouling rate observed with the fluidized bed was not simply a function of some limiting scale thickness. Figure 33 shows the fouling characteristics observed on these two tests plotted together for comparative purposes.

Test 119 exhibits essentially identical characteristics as previously observed. No fouling occurs until the brine is saturated, then rapid fouling takes place until the bed is added. The characteristic drop in fouling with bed addition is observed followed by gradual fouling at a rate about 1/12 that observed without bed material.

Test 120 exhibits no fouling with the bed added at the beginning of the test. The test was run with saturated brine for 45 minutes, which was more than three times the duration required to foul in Test 119 without bed material. The bed material was then removed and the system fouled at about the same rate as observed for Test 119 under the no bed conditions.

Test 121 was performed in the same manner as Test 120 except that 120 mesh SiO_2 was substituted for the garnet bed material. The purpose of this test was to evaluate the influence of bed material on fouling.

Figure 33. Comparison of Fouling Characteristics of 100 Mesh Garnet Bed Material at a Velocity of 10 ft/sec

2.2, Task 2 - Laboratory Experiments (cont.)

Figure 34 is a plot of the fouling results of this test. The exchanger fouls at a more rapid rate than observed with either the garnet or the coarser SiO_2 , but still significantly slower than when the bed material is removed.

The brine velocity was reduced for Tests 122 and 123 to evaluate the influence of this parameter. A nominal 7 ft/sec velocity was selected. Both sections of the test heat exchanger were used. The 120 mesh SiO_2 was retained for bed material for Test 122. No bed material was used in Test 123. Test 123 was a baseline fouling test at the lower velocity. Baseline conditions could not be established in Test 122 because of difficulty in removing all of the fine light bed material.

Figure 35 is a plot of the fouling results obtained for these tests. The data are plotted separately for the two exchanger sections. It is of interest to note that the rate of fouling is about the same for both the hot and cold exchanger sections both with and without bed material. It can be noted that the rate of fouling is a little lower at this lower velocity when no bed material is used. This may be because less excess salt is added at the lower velocity although the injector time was increased from 15 seconds to 30 seconds every 5 minutes to compensate for the lower velocity. The exchanger fouled in one hour without bed material but negligible fouling was observed after 100 minutes with the bed. The bed concentration was reduced from 62% to 12% at the 100 minute data point. The fouling rate then increased to a rate about half the value observed without bed material.

Test 124 was designed to duplicate the conditions of Test 122 except that 57 mesh SiO_2 was substituted for the 120 mesh SiO_2 . Quantitative results from this test are questionable because control of the salt addition rate was lost when the brine tank developed a small steam leak. The loss of heat in the brine tank ultimately required running continuously

TEST 121
120 MESH SiO_2 BED MATERIAL
NOMINAL BRINE VEL = 10'/SEC

Test 121

Figure 34. Fouling Results of 120 Mesh SiO_2 Bed Material
at Nominal Brine Vel = 10 ft/sec

TEST 122 & 123
 120 MESH SiO_2 BED $\sim 7'$ /SEC
 NOM. VELOCITY

Figure 35. Comparison of Fouling Rate in Hot and Cold Heat Exchangers With Salt Added at Five Minute Intervals

2.2, Task 2 - Laboratory Experiments (cont.)

through the tank to maintain saturated conditions. Qualitative results were as observed previously with garnet. No fouling was observed until the bed was removed at which point rapid fouling occurred.

Tests 125, 127 and 128 were performed using the garnet bed material at a brine velocity of 10 ft/second. These conditions appeared to be the best of those tested. The tests were designed to demonstrate repeatability and to provide added information on the influence of bed concentration. Figure 36 is a plot of the fouling data from these tests. As can be seen, the baseline fouling results are essentially identical to those previously observed. The calculated fouling rate is $65 \times 10^{-5} \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$. The tests with 3.4 weight % bed material, Test 128, exhibited essentially no fouling over the two hour test period. (The actual calculated fouling rate was $2.5 \times 10^{-5} \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$.) This test fouled as soon as the bed material was removed. Test 125, with 4.8 weight % bed material, initially exhibited a zero fouling rate. This test was continued for 3-1/2 hours. Unfortunately the brine tank began to cool down significantly after the first two hours so that the data in the final 1-1/2 hours may not be valid.

At this point in the program the results had been shown to be repeatable and the higher specific gravity bed material (garnet) was found to provide superior anti-fouling behavior. There was still one question concerning the data which had to be resolved. Previous tests indicated stratification occurred with the garnet bed material at velocities below 10 ft/second. The Task 1 analysis on the other hand indicated the optimum brine velocity for overall plant efficiency to be in the 5 ft/second range. These conflicting requirements could be reconciled if the exchanger were vertical instead of horizontal because stratification would no longer be a problem and the lower velocity would be acceptable.

TESTS 125, 127, 128
100 MESH GARNET BED MATERIAL 10'/SEC
NOMINAL VELOCITY

To = SATURATION TIME

Figure 36. Comparison of Fouling in 100 Mesh Garnet Bed Material at 10 ft/sec Nominal Velocity

2.2, Task 2 - Laboratory Experiments (cont.)

To answer this question the exchanger was reoriented to the vertical position for the remainder of the test program. Two successful tests were performed in this position, one at a brine velocity of 5 ft/second and one at 8 ft/second. Figure 37 is a plot of the fouling data obtained on these two tests. The hot (upflow) exchanger leg and the cold (downflow) exchanger leg are plotted separately. There is no significant difference in fouling rate between the upflow and downflow units. The fouling rate appears to be velocity sensitive with the lower velocities resulting in the higher fouling rates. The 8 ft/second test fouls at a rate of $3 \times 10^{-5} \frac{\text{hr-ft}^2\text{-}^\circ\text{F}}{\text{Btu}}$ per hour, about double the rate previously observed at 10 ft/second. The test at 5 ft/second fouls at a rate of $16 \times 10^{-5} \text{ hr-ft}^2\text{-}^\circ\text{F/Btu}$.

The vertical orientation tests concluded the fouling rate experiments. The fouling test results obtained were totally consistent in establishing the technical feasibility of the APEX concept. The data invariably showed a marked reduction in fouling rate when bed material was being circulated as compared with no bed material circulation. This was true regardless of the testing procedures, or operating conditions. Consistent trends were also observed which indicated that, over the range tested, the fouling rate was reduced with (1) denser bed material, (2) higher velocity and (3) coarser bed material. The minimum bed weight percent requirements appear to be in the 3% range. Quantitative data on the influence of the various parameters on fouling rates should be verified in the field. These data, as well as erosion rate data are needed to effectively complete a prototype heat exchanger design.

Figure 37. Comparison of Fouling in 100 Mesh Garnet Bed Vertical Exchanger Cold (Brine Downflow) at Velocities of 8 ft/sec and 5 ft/sec

2.0, Technical Discussion (cont.)

2.3 TASK 3 - CONCEPT REEVALUATION AND DESIGN UPDATE

The purpose of the Task 3 design update effort was to evaluate the potential of the APEX concept based on the experimental data from Task 2. The evaluation was in the areas of (1) plant conceptual design and economics, (2) exchanger conceptual designs, and (3) analytical extrapolation of Task 2 data to anticipated well site conditions.

2.3.1 Plant Conceptual Design and Economics

An APEX conceptual design and economics study was conducted to preliminarily establish the equipment required for a typical APEX installation (Figure 38) and to verify that the concept will be economically feasible.

The initial step in the analysis was to establish typical design and operating conditions. Table V details the conditions selected for a 30 MWe binary cycle isobutane plant with 350°F inlet brine.

The analysis was performed in three steps. First, the size and cost of the heat exchangers were calculated. The other special capital equipment required for APEX was then identified and costed. Finally, the operating cost, energy supply and brine disposal cost differentials were determined. These costs were totaled and compared on a yearly operating cost basis as well as on a capital equipment cost basis. The study does not include comparative figures for installation costs. It was assumed that the special equipment installation costs required for the APEX approach would be offset by reduced exchanger installation costs due to smaller size.

Figure 38. APEX Process Flow Schematic

TABLE V

30 MWe POWER PLANT OPERATING CONDITIONS

1.0 Brine Parameters

Plant inlet temperature, °F	350
Plant inlet pressure, psia	150
Plant outlet temperature, °F	185
Total dissolved solid, ppm	20,000
Brine flow rate, gpm	10,900
Brine flow rate, lb/hr	5.44×10^6

2.0 Plant Parameters

Gross power output, MW	37
Net power output, MW	30
Working fluid flow rate, lb/hr	5.11×10^6
Cooling water temperature	80°F
Condensing temperature	110°F

3.0 Heat Exchanger Parameters

Shell side pressure (R-600a) psia	600
Tube side pressure (brine), psia	150
Working fluid inlet temperature, °F	115
Working fluid outlet temperature, °F	300
Brine inlet temperature, °F	350
Brine outlet temperature, °F	185
Heat flow rate, Btu/hr	9.0×10^8

2.3, Concept Reevaluation and Design Update (cont.)

2.3.1.1 Heat Exchanger Size and Cost

Heat exchanger size and costs were compared assuming bare tubes would be used for both the conventional tube-in-shell and the APEX approach. An alternative comparison was made in which extended surface (finned) tubes were assumed for the APEX concept. Extended surface exchangers are not practical for the conventional units because of the low brine side heat transfer coefficient when fouled.

The major differences in the surface requirements of the conventional and APEX units is a result of the difference in fouling factor. It is essential that realistic values be assumed for the fouling factors if the comparison is to be meaningful. A standard fouling factor of 0.0005 was assumed for APEX and conventional designs for the clean isobutane shellside. No fouling was allowed for the tubeside. A factor of 0.003 was used for the conventional unit. This value was selected after comparison of factors used in various geothermal plant studies as presented in Table VI.

Another significant difference between the APEX and the conventional design is the log mean temperature difference (MTD). The recirculation of approximately 5% of the total brine flow rate drops the inlet brine temperature to the APEX heat exchanger approximately 10°F. For this application this decreases the MTD by about 8%.

A third difference occurs as a result of the higher tube-side velocity assumed for the APEX unit. This is needed to assure adequate suspension of the bed material. The higher velocity does not have a major influence on the heat exchanger size or cost but does influence the comparison when pump operating costs are considered.

TABLE VI
REPORTED GEOTHERMAL BRINE FOULING FACTORS

1. List of Fouling Factors from Geothermal Plant Studies

<u>Study/Organization</u>	<u>Site</u>	<u>TDS</u>	<u>Fouling Factor</u>	<u>Ref.</u>
10 MWe Isobutane Plant/Bechtel	Heber	14,000 ppm	0.002	10
10 MW Isobutane/ANC	Raft River	2,000	0.003	11
10 MW Isobutane/LBL	Northern Nevada	2,250	0.007	12
10 MW Isobutane/TRW	East Mesa	3000-20,000	None Specified	13
Susanville/AECC	Susanville	2000-10,000	0.003	14

2. Data from SG&E Tests at Heber Wells (Reference 15)

<u>Operating Time (days)</u>	<u>Fouling Factor</u>	<u>Time Difference Between 0.001 Change in Fouling (days)</u>
0	0	0
92	0.001	92
184	0.002	92
234	0.003	50
267	0.004	33
292	0.005	25
309	0.006	17
323	0.007	14
335	0.008	12

2.3, Concept Reevaluation and Design Update (cont.)

The finned tube unit was sized assuming integral spiral fins, 19 fins per inch with a nominal fin height of 0.0625 inches. The surface area is $0.514 \text{ ft}^2/\text{ft}$ as compared with $0.1964 \text{ ft}^2/\text{ft}$ for the bare tubes. The design heat transfer coefficient was reduced from 330 to 280 due to the conversion of the tubeside heat transfer coefficient to the larger shellside heat transfer surface. The tubeside ΔP is lower because of the reduced tube length required.

Table VII summarizes the results of the comparison of the conventional and APEX heat exchangers. The bare tube APEX exchanger would cost about \$1,250,000 less in 1976 dollars than the conventional exchanger. The cost of the APEX can be reduced further by the use of finned tubes. The savings of finned tubes over bare tubes is \$650,000. The finned tube exchanger cost was derived by using the cost per linear foot of tube determined for the bare tube units increased by 10% to cover the added cost of finned tubes.

2.3.1.2 APEX Special Equipment Costs

For a comparison of the equipment costs of the APEX, a preliminary design was made of the solids separation and recirculation system. This system could be a closed pressurized system or an atmospheric system. In the latter case, the effluent brine is at ambient pressure; e.g., solids separation occurs in an unpressurized settling tank. The atmospheric system would be economically competitive only if reinjection can be achieved by gravity flow. Normally reinjection must be done under pressure. For the system discussed herein, the heat exchanger inlet pressure is 150 psia, and the APEX pressure loss (bare tube) is 65 psi. For a pressurized system, the exit pressure is 85 psia; therefore, for an atmospheric system, 70 psi (85-14.7) must be recovered assuming the reinjection pressure exceeds 85 psia. The pump power costs associated with this pressure rise exceed capital cost savings which could be attributed to the unpressurized system.

TABLE VII

COMPARISON OF APEX AND CONVENTIONAL UNITS

	<u>Conventional</u>	<u>Bare APEX</u>	<u>Finned APEX</u>
Heat Flow, Btu/hr	9.0×10^8	9.0×10^8	9.0×10^8
Design Coefficient, Btu/ft ² -hr-°F	150	330	280
Design Fouling Factor, ft ² -hr-°F/Btu	0.003	0.0005	0.0005
Mean Temperature Difference, °F	36.8	33.8	33.8
Area, ft ²	1.63×10^5	0.81×10^5	0.95×10^5
Tubeside ΔP, psi	20	65	30
Tube, Outside Diameter	0.75	0.75	0.75
Tube Velocity, ft/sec	5	10	10
Total Flow Area, ft ²	4.85	2.42	2.42
Number of Tubes	2300	1150	1150
Total Tube Length, ft	8.3×10^5	4.15×10^5	1.85×10^5
Design Shell Side Pressure, psia	720	720	720
Design Tube Side Pressure, psia	180	180	180
Cost of Exchanger*, \$/ft ²	15.5	15.5	6.5
Cost (1976 \$)	2.53×10^6	1.26×10^6	0.62×10^6

*Cost per square ft of shell side surface area.

2.3, Concept Reevaluation and Design Update (cont.)

2.3.1.3 Operating Costs

A major difference in system operating costs using the different types of heat exchangers occurs due to the difference in heat exchanger pressure drop. The higher APEX pressure drop produced an operating cost penalty. The bare tube APEX pressure drop is 65 psia which is equivalent to an operating cost of \$70,000 per year for a 65% efficient boost pump and electric motor. The conventional exchanger pressure drop is only 20 psia, therefore, an operating cost penalty of 45/65 times \$70,000, or \$48,500 per year should be charged against the bare tube APEX for its higher pressure drop. The pressure drop for the finned tube APEX results in annual operating costs of \$11,000.

The conventional heat exchanger is predicted to require cleaning for this application every 6,000 to 7,000 hours (Reference 15). The cost of cleaning the heat exchanger is estimated to be \$20,000 and requires 5 to 7 days. The annual cleaning cost would be approximately \$29,000.

The APEX heat exchanger also has operating costs associated with the solids separation and recirculation system. A comparison of operating costs is as follows:

	Comparison of Geothermal Heat Exchanger Annual Operating Costs		
	Conventional	Bare Tube APEX	Finned Tube APEX
Cleaning Costs	\$29,000	\$ -	\$ -
Increased HX Press. Drop	-	48,500	11,000
Solids Separation	-	19,000	19,000
Solids Recirculation	-	7,000	7,000
Total	\$29,000	\$74,500	\$37,000

2.3, Concept Reevaluation and Design Update (cont.)

The energy supply and disposal costs increase as brine utilization (power/flow) decreases. For this application, the utilization would decrease from 5.50 with a conventional unit to 5.45 watt-hr/lb brine with the bare tube APEX due to the small increase in the required brine recirculation flow rate of 54,000 lb/hr. Added pumping costs due to the additional flow would be less than \$1,000 annually for the bare tube APEX and insignificant for the finned tube unit.

2.3.1.4 Impact on Annual Plant Operating Costs

The APEX and conventional heat exchanger systems are best compared on a plant yearly cost basis because of the important operating costs associated with both units. The plant capital equipment cost is converted to a yearly basis by using the fixed charge rate of 0.178 for an investor-owned utility. The yearly cost comparison is as follows:

<u>Yearly Cost Items</u>	<u>Conventional</u>	<u>(1976\$)</u>	
		<u>Bare Tube APEX</u>	<u>Finned Tube APEX</u>
Heat Exchanger	450,000	225,000	110,000
Solid Separation and Recirculation	-	31,300	31,300
Operating Costs	29,000	74,500	37,000
Added Energy Supply Costs	-	1,000	500
	479,000	331,800	178,800

The yearly cost difference subtracted from the cost of power production is about \$150,000, or 0.67 mills/kwh for the bare tube APEX and \$300,000 or 1.34 mills/kwh for the finned tube approach.

2.3 Concept Reevaluation and Design Update (cont.)

The comparison of the capital equipment costs are as follows:

<u>Cost Items</u>	<u>Conventional</u>	<u>(1976 \$)</u>	
		<u>Bare Tube APEX</u>	<u>Finned Tube APEX</u>
Basic Heat Exchanger	2,530,000	1,260,000	620,000
Solids Separation and Recirculation	<u>-</u>	<u>176,000</u>	<u>176,000</u>
	2,530,000	1,436,000	796,000

On either a yearly cost basis or a capital equipment cost basis, the APEX heat exchanger concept shows the potential for substantial cost savings in a typical geothermal power plant application.

2.3, Concept Reevaluation and Design Update (cont.)

2.3.2 Heat Exchanger Conceptual Mechanical Design

The mechanical design of the heat exchanger for a binary cycle geothermal power plant using isobutane as the working fluid is restricted by several considerations. Some of these considerations are characteristics of the operating conditions; others are unique to the APEX concept. The exchanger design approach for a particular plant will be dependent on the operating condition and economic considerations of that specific plant. However, some generalized approaches to the design can be outlined which will be applicable to most installations.

One of the major design requirements for any APEX exchanger will be to eliminate sharp turns, low velocity areas, and internal configurations which could cause maldistribution of the bed material, settling, or erosion. This can be readily controlled within the exchanger by locating the bed material on the tubeside and maintaining the velocity in a range which will keep the bed material in suspension. The manifolding of the exchanger from the feed pipe to the tubes will require a departure from conventional design. Figure 39 illustrates a possible approach to this problem. The tubes are rolled into the tubesheet with a small portion of the tube projecting. Plastic tubes are inserted over the exchanger tubes. The tube feed manifold is then positioned with the plastic tubes passing through the pipe connection flange end of the manifold. The interstitial passages between the plastic tubes and the manifold are filled with a castible material which is compatible with the brine chemistry and temperature. The plastic tubing can then be chemically dissolved away or left in place as desired.

A second consideration for both APEX and conventional exchangers is the large temperature crossover. This temperature crossover requires that the flow be countercurrent or nearly so. If true countercurrent

Figure 39. APEX Heat Exchanger Inlet Manifold Design Concept

2.3, Concept Reevaluation and Design Update (cont.)

flow is not used, at least six shells in series will be required to provide a reasonable MTD correction factor based on the typical operating conditions given in Table XIII. The problem with true countercurrent flow is that the exchanger length becomes excessive increasing both tubeside and shellside pressure drop. This problem can be minimized by (1) reducing the tubeside velocity, (2) reducing tube diameter and (3) going to finned tube construction. The first alternative is practical only for conventional exchangers and then only within limits since reduced heat transfer coefficients will begin to adversely influence the design. Reduced tube diameter and finned tube construction are both techniques for increasing the surface to area ratio. Neither can be effectively used for conventional exchangers because of tubeside fouling. Both approaches are suitable for APEX concepts hence the countercurrent flow restriction is a greater limitation on conventional exchangers than on APEX units.

Figures 40, 41, and 42 illustrate possible approaches to the countercurrent flow requirements. Figure 40 is a U-tube design with an internal baffle. This design has advantages in construction costs, solves differential expansion problems, and provides a removable tubebundle for servicing. It has the disadvantages of leakage across the baffle and eliminating the potential for mechanical cleaning of the tubes. The U-bend would have some limiting radius from an erosion standpoint.

Figure 42 illustrates a straight tube concept with a removable tubebundle. This concept contains a floatinghead and expansion bellows to provide for differential expansion. This concept would be appreciably more expensive than the U-tube approach because of the floating head, added flanges, and bellows. The tubes can be mechanically cleaned and the tube bends, which may be areas where erosion problems occur, are eliminated. Figure 41 illustrates a fixed tubesheet concept. Expansion is provided

CONCEPTUAL APEX EXCHANGERS

Figure 40. U-tube Exchanger with Internal Baffle Shellside

Figure 41. Fixed Tubesheet Exchanger with Shellside Expansion Joint

Figure 42. Single Pass Exchanger with Special APEX Channel and Floating Head

2.3, Concept Reevaluation and Design Update (cont.)

by the bellows in the shell. The tubebundle is not removable. This approach is the most economical from an initial cost standpoint and may be practical with the clean shellside fluid. Retubing requires cutting away the shell.

Many other variations are possible depending on (1) the actual operating conditions at the plant, (2) experience factors relating to service life and maintenance requirements and (3) economic considerations relating capital and operating costs.

2.3.3 Data Correlation

The physical and chemical processes controlling scale deposition and subsequent partial or total removal in an APEX heat exchanger are complex. To date no analytical model exists in the published literature which addresses the operation of an APEX heat exchanger. Even the published analyses and correlations which address the component processes of scale deposition and the erosion of surfaces by impinging particles are best classified as semi-empirical and approximate.

The development of an analytical model was not part of the current program. However, an empirical relationship based on the physical processes occurring in an APEX heat exchanger has been developed. This correlation provides a means for presenting the data in the generalized format necessary for engineering design as well as giving some physical insight into what is occurring within the APEX heat exchanger. Development of this empirical relationship is presented in the following discussion.

If the primary mechanism of APEX cleaning is considered to be mechanical abrasion, then the rate of scale buildup in an APEX heat exchanger can be viewed as the net result of a deposition process and a removal process.

2.3, Concept Reevaluation and Design Update (cont.)

$$\frac{d\delta}{d\theta} = D - R \quad (1)$$

δ = scale thickness

θ = time

D = rate of scale deposition

R = rate of scale removal

If the scale growth is viewed as a crystal deposition process, then the deposition rate can be given as¹⁶

$$D = \frac{C - C'}{1/K_d + 1/K_r} \quad (2)$$

C = concentration of solution

C' = equilibrium concentration

K_d = coefficient of mass transfer by diffusion

K_r = rate constant for molecular lattice integration

It should be noted that "D" is equal to the rate of scale buildup when no solids are circulating in the system. "D" is primarily a function of the chemistry of the system and will be considered essentially independent of bed conditions. Exactly the opposite is true of "R". "R" is determined primarily by the bed conditions and is not primarily a chemical factor.

The rate of removal "R" is known to be dependent upon a large number of parameters. Included are such items as the hardness and

2.3, Concept Reevaluation and Design Update (cont.)

strength of the scale layer, the hardness, strength, and sharpness of the impinging particles, the angle at which the particles strike the surface, the number and size of the impacting particles, and the velocity of impingement.

Studies of surface erosion by impinging particles have indicated the surface erosion is related to the kinetic energy of the impinging particles. However, it is also recognized that there is some threshold particle kinetic energy below which negligible damage will be done to the surface. This threshold energy might be viewed as constituting the energy which the material can absorb without damage and also reflects the fact that high energy particles from the free stream dissipate part of their energy in traversing the lower velocity fluid in the boundary layer prior to striking the surface.

Another factor which affects the rate of scale removal is the amount of scale present. Kern¹⁶ notes that the net rate of scale buildup in fouling heat exchangers decreases as the scale layer thickens. He attributes this to the increasing number of defects and low strength areas within the scale layer which make it more subject to break-off and failure. The rate of scale removal should then increase as the scale layer thickens and decrease as the scale layer gets thin.

The above factors can be combined to give a relationship for the scale removal rate "R".

2.3, Concept Reevaluation and Design Update (cont.)

$$\frac{R}{N} = D \left(\frac{1}{2g} m V^2 - T \right) (1 + K\delta) \quad (3)$$

where

N = number of particles hitting the surface

D = a constant

m = mass of an individual particle

V = particle velocity

T = threshold kinetic energy

K = a constant

The number of particles "N" can be given by:

$$N = \frac{E V_{\infty} \times S}{4/3 \pi d^3 \rho} \quad (4)$$

S = solids concentration by mass

E = a constant

V_{∞} = free stream velocity

d = particle diameter

ρ = particle density

$$\text{Or, } N = \frac{F V_{\infty} S}{\rho d^3} \quad (5)$$

The constant "F" in Equation (5) compensates or accounts for many assumptions. For example, the particles are generally not spherical, the particle velocity normally would not equal the free stream velocity V_{∞} , etc. However, the necessary correction factors can all be combined and lumped in "F".

2.3, Concept Reevaluation and Design Update (cont.)

The mass "m" of the individual particles in Equation (3) can be given by

$$m = \frac{4\pi}{3} d^3 \rho \quad (6)$$

Combining (3), (5), and (6) gives

$$R = G \left(\frac{V_{\infty} S}{\rho d^3} \right) (\rho d^3 V_{\infty}^2 - T) (1 + K\delta) \quad (7)$$

The constant "G" in (7) again accounts for many factors. For somewhat similar systems in terms of scale and bed materials the factor "G" will include hardness, strength, and roughness effects, particle size distribution effects, fluid viscosity effects, etc. The value of "G" for a given system is determined experimentally.

Equations (7) and (1) can now be combined to give

$$\frac{d\delta}{d\theta} = D - G \left(\frac{V_{\infty} S}{\rho d^3} \right) (\rho d^3 V_{\infty}^2 - T) (1 + K\delta) \quad (8)$$

This equation can be simplified for the condition of a nearly clean surface as encountered in the APEX testing since $\delta \approx 0$. Thus Equation (8) becomes

$$\frac{d\delta}{d\theta} = D - G \frac{V_{\infty} S}{\rho d^3} (\rho d^3 V_{\infty}^2 - T) \quad (9)$$

Application of Equation (9) to the APEX test results is made easier if the scale resistance "P" is substituted for the scale thickness δ since "P" is actually measured during testing.

2.3, Concept Reevaluation and Design Update (cont.)

$$\frac{dP}{d\theta} = D - G \left(\frac{V_{\infty} S}{\rho d^3} \right) (\rho d^3 V_{\infty}^2 - T) \quad (10)$$

To use this equation it is necessary that the values of D, G and T be determined. When there is no bed material in the system, $S = 0$, and

$$\frac{dP}{d\theta} = D \quad (11)$$

Thus the value of "D" is simply the rate of fouling of the heat exchanger when no bed material is present and is readily obtained from the test data. The values of "G" and "T" can be obtained by simply solving data from two test data points simultaneously. The resulting values should be generally applicable to a given data set and allow the influence of various operating parameters to be established.

Equation (10) indicates the scale removal action depends on the velocity between the 2nd and 3rd power. This agrees with data from other sources which give the same dependence. The cleaning action also is shown to be directly proportional to the solids concentration (as expected) and, for a given mass loading, to show a weak inverse proportionality, to particle size and density. This latter result is somewhat surprising since it does not appear to be in agreement with the general test results which indicate both increased particle size and particle density to be favorable for increased cleaning. What is likely is that the normally anticipated size and density effects are buried in the threshold energy "T" and that assuming T to be constant is valid only over small ranges of particle size and density.

The data obtained in the laboratory tests are given in Table VIII in terms of the factors of Equation 10. Values of D, the fouling rate without bed material, are obtained for seven different tests and are also given.

TABLE VIII
APEX TEST DATA

<u>Test</u>	<u>V_{∞} (ft/sec)</u>	<u>S (wt %)</u>	<u>d (in.)</u>	$\times 10^5$ (ft ² °F/Btu ²) <u>$\frac{dP}{d\theta}$</u>	<u>ρ</u> (lb/ft ³)
117	10	1.0	0.0104	7.2	163
	10	3.3	0.0104	2.5	163
	10	0	-	76	-
118	10	0	-	70	-
	10	>10	0.0104	-2	163
119	10	0	-	250	-
120	10	3.3	-	113	-
	10	3.3	0.0059	-2	237
121	10	0	-	65	-
	10	6.6	0.0049	27	163
122	7	0	-	63	-
123	7	6.2	0.0049	2	163
	7	1.2	0.0049	20	163
125	10	0	-	68	-
128	5	3.3	0.0059	16	237
131	8	3.0	0.0059	3	237

<u>Test</u>	<u>D (hr ft²°F/Btu hr)</u>
117	76
118	70
119	250
120	113
121	65
122	63
125	68

2.3, Concept Reevaluation and Design Update (cont.)

Although there is significant scatter in the data, an average value of nominally 70 seems valid for use in data reduction.

Additional correlation of the data on a test by test basis using Equation 10 has been attempted. The results have shown the values of G (which should be a constant) and T (the threshold kinetic energy) to vary significantly from one set of test data points to another. There are several likely causes for this occurring. The deviation of the equation constitutes a simplistic approach to what is a physically very complex problem. It is unlikely, for example, that the threshold kinetic energy T as defined, is independent of particle size and density and that the entire process is independent of pipe diameter and boundary layer effects. Also, the rate of scale deposition is likely to influence the ease of scale removal with a very slow net scale buildup being more difficult to remove than a rapid buildup. There are probably inadequacies in the data itself arising from the difficulty of precisely controlling the experimental variables such as the degree of saturation of the brine. This is reflected in the values of "D" listed previously in which 5 out of the 7 data points fit within a $\pm 10\%$ data scatter and the other 2 data points show deviation of 61% and 257% respectively.

From the above comments it is apparent that additional work is required in analytical model development. However, Equation (10) as developed here does constitute an easily used equation which properly identified the major factors in APEX design and as such is useful as a preliminary design tool.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

The conclusions reached as a result of the analysis and testing, and the specific data and logic which led to each conclusion are described in this section.

3.1.1 The APEX concept technical feasibility was established using simulated geothermal fluids. The test results showed a reduction in fouling rate when the solid particle bed material was in the exchanger. This was true regardless of the bed material used or the sequence of the testing comparison, i.e., bed material added at the start of the test and subsequently removed or added after the fouling had occurred on the exchanger walls.

3.1.2 The denser bed materials were more effective in preventing fouling. The garnet bed material was much more effective in reducing the fouling rate than the silica sand at approximately the same particle diameter.

3.1.3 Brine velocity requirements for bed material suspension are within acceptable limits. Test data indicated velocities of 10 ft per second were effective in suspending the bed material and controlling the fouling. The economic analysis establishing APEX feasibility was performed assuming 10 ft/sec was required. Lower velocities may prove to be technically acceptable in which case the superiority of the APEX concept will be enhanced.

3.1.4 Higher brine velocities were more effective in reducing the fouling rate. Tests conducted with a given bed material and loading over a range of velocities resulted in the greatest fouling rate at five feet per second, intermediate fouling at eight feet per second, and the lowest rate at 10 feet per second.

3.1, Conclusions (cont.)

3.1.5 The mechanism for scale prevention was primarily scrubbing. The fine mesh sand had a greater fouling rate than the coarse mesh sand at nearly equal loadings. The fine mesh sand with the far larger number of particles for nucleation sites would be expected to be more effective if fouling were prevented by crystal growth on the bed material. Further, the garnet bed material of similar mesh to the silica was more effective than the silica sand. The significant difference between the two bed materials is the particle weight, implying the higher kinetic energy of the garnet particles make them more effective for scale control. Finally, it was observed that higher velocities were most effective at reducing the fouling rate. This is again a particle energy parameter which would be expected to be significant only for the scrubbing mechanism.

3.1.6 Bed loading concentration of 3 to 5 weight percent is required for scale control. The data did not show a significant variation in fouling rate at bed loadings of 5% and greater. Tests conducted with garnet concentrations as low as 3% were effective. However, tests conducted below 2 weight % bed material showed a loss of effectiveness. The 3 to 5 weight percent spread is considered a conservative estimate allowing for variation in velocity and bed material. It is possible that an optimized bed can be selected which will require less than 3 weight percent.

3.1.7 A preliminary analytical model was developed which properly identifies the major factors in the APEX design and will be a useful preliminary design tool for future work.

3.1.8 The APEX concept is economically practical. This conclusion was based on a cost comparison analysis conducted as part of the program. The key assumption in the analysis is the fouling rate of a conventional exchanger.

3.1, Conclusions (cont.)

3.1.9 The APEX concept could make the use of finned tubes feasible in the primary heat exchanger. If essentially zero scale buildup occurs on the brine side, the binary fluid film coefficient becomes important and can be reduced by means of extended surface application.

3.1.10 The control of the salinity of a small volume recirculating brine system is difficult when salt is continuously being removed. A small volume closed loop system is not recommended for long duration tests.

3.2 RECOMMENDATIONS

The following work is recommended to carry the APEX concept to the application stage:

3.2.1 Verify the concept feasibility at an actual well site using parallel single tube exchangers for comparison. This will demonstrate fouling control and durability over an extended operating period.

3.2.2 Perform a parametric study at several well sites using the single tube exchangers. The parameters which need to be evaluated include:

1. velocity
2. bed loading
3. duty cycle including intermittent bed flow
4. particle parameters; size, shape, hardness, and density

Testing at different well sites would permit evaluation of the influence of brine chemistry on operating ranges and limitations.

3.2.3 Design a full scale primary heat exchanger to permit detailed evaluation of the economics associated with application of the APEX system.

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