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**DETAILED TEST PROGRAM
FOR THE
NILAND GEOTHERMAL TEST FACILITY
FINAL REPORT**

**SUBMITTED TO
SAN DIEGO GAS & ELECTRIC COMPANY
SAN DIEGO, CALIFORNIA**

**PREPARED BY
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P.O. GTF-00049

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ABSTRACT

This report presents a test program for the Niland Geothermal Test Facility. It contains a detailed description of 18 tasks. Each of these tasks discusses the objectives, justification and relation to future design, general test procedures, test conditions, required experimental measurements, and methods of calculation and expected results. Implementation of these tasks will provide the basic information necessary for the design, construction, and initial operation of a 50-MWe geothermal demonstration plant.

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Section 1

SUMMARY AND RECOMMENDATIONS

San Diego Gas and Electric Company issued Purchase Order GTF-00049 to Bechtel for the development of a detailed test program for the Niland Geothermal Test Facility (GTF). The test facility is intended to serve two purposes: to determine the technical and economic feasibility of using geothermal resources in a heat exchange train in order to provide basic information necessary for the design, construction, and initial operation of hydrothermal-geothermal power plants; and to gain information on the extent and characteristics of the geothermal reservoir at the site. Bechtel's activities cover the heat exchange train; namely, the four-stage flash/binary process.

This report contains a detailed description of 18 tasks. This Final Report incorporates the text of the Interim Report, which was submitted by Bechtel in August of 1976. These tasks, arranged in order of descending priority, will address the following problem areas:

1. Operational stability of the flash/binary process, plant response to transients and upsets
2. Overall heat and mass balance of the plant under baseline conditions
3. Clean-tube heat transfer coefficients with water as the binary fluid
4. Purity of vapor; scrubber performance

5. Scale prevention
6. Materials and component evaluation
7. Effect of noncondensable gases on the heat transfer coefficients
8. Continued monitoring of heat transfer coefficients and fouling resistance in multistage heat exchangers
9. Restoration of clean-tube transfer coefficients
10. Operational stability of the flash/binary process during isobutane runs
11. Overall heat and mass balance baseline for isobutane runs
12. Condenser performance with isobutane as the working fluid
13. Heat transfer and pressure drop performance in and around the critical region of isobutane
14. Performance of liquid isobutane heat exchangers E-1A, 1B, 1C, and E-5
15. Determination of nonequilibrium and boiling point elevation
16. Comparison of flashing devices and mist eliminators
17. Analysis of turndown capability of the flash process
18. Long-term run under baseline conditions

Prior to the preparation of the task definitions, it was necessary to perform analytical and computational work essential to establishing a baseline from which to develop the detailed task descriptions.

These were to:

- Prepare overall heat and mass balance for the case in which water is used as the working fluid instead of isobutane
- Establish a baseline operational mode for both the water and isobutane cases

- Analyze the heat exchangers and assume heat transfer coefficients to allow baseline calculations
- Determine the operational limits of the existing equipment

The results of the above analyses are incorporated in, and form an essential part of the individual task logic.

The program, as presented, is based on the assumption that it will be implemented by skilled personnel operating the test facility. Consequently, the assignment did not include the preparation of detailed safety procedures. It is understood, however, that before each task is performed, a safety analysis will be performed by the facility management.

The test program described in this report is based on the following information, obtained from San Diego Gas and Electric, which are used as a reference throughout the task descriptions:

Drawing KE-1, Rev. 7 P and ID
Drawing D-3201, Rev. 0 Process Flow Diagram
Mechanical Data Books I, II, III, and IV

It is recommended that the test program presented in this report be undertaken. Implementation of these tasks will provide the basic information essential to the design, construction, and initial operation of a 50-MWe geothermal demonstration power plant.

Bechtel Corporation

Engineers - Constructors

Fifty Beale Street
San Francisco, California 94119

September 24, 1976

San Diego Gas & Electric
Company
1101 Ash Street
P.O. Box 1831
San Diego, CA 92112

Attention: Dr. Harry K. Bishop

Subject: Schedule for the Niland Geothermal
Test Facility Test Program
Job 12012-00-001

Reference: Detailed Test Program for
the Niland Geothermal Test Facility,
dated September, 1976
P.O. GTF-00079, Job 12012

Gentlemen:

In accordance with your request on September 15, 1976, the schedule for task-level testing at the Niland Geothermal Test Facility program is forwarded herewith.

The schedule provides for a test program duration of about eighteen months on the basis of continuous operations. It has been developed to a level of detail consistent with the tasks described in the reference. Time has been allowed for establishment of operating conditions and for minor maintenance and adjustments. In cases where it appears that operations will permit, concurrent testing is indicated on the schedule bar chart. However, each of the eighteen tasks shown on the bar chart includes from one to twelve separate tests. These tests should be considered separately when detailed test operating procedures and schedules are developed by you for use of field operating personnel. It is suggested that, as part of that effort, a matrix be prepared showing operating conditions and the task and test number for which data should be recorded. This would help to prevent unnecessarily repetitive establishment of operating conditions and, also, should provide a useful check-off list for the collection and use of data.

San Diego Gas &
Electric Company
Attention: Dr. H.K. Bishop
September 24, 1976

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Bechtel would be pleased to assist in this further development of the test program and schedule if it is desired.

Please call if we can be of any further assistance.

Very truly yours,

cc:
T.E. Walsh
Power Technology Group Manager
Research and Engineering

TRF/ah

Attachment

TASK 1

TITLE

Operational stability of the flash/binary process; plant response to transients and upsets.

OBJECTIVES

To establish operational emergency procedures. To verify the structural adequacy of the plant during upsets. To determine the flashing brine behavior in flash drums, conditions of foaming, stratification, flooding, or blowthrough. To establish methods of controlling the flash process independently of the heat exchange process, and vice versa. To determine how to control the level of liquid in the main condenser. To determine the response of the plant to various postulated upset conditions while the system is charged with distilled water.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

Presently, no operational experience with geothermal flash/binary plants exists. Consequently, safe and effective operational procedures are not available.

Plant upsets can cause damage if proper actions are not taken by operators. This task is needed to establish emergency operating and shutdown procedures for the future geothermal demonstration power plant. It will identify the need for safety devices necessary to avoid plant damage due to emergency failures, and will verify the brine feeding and withdrawal system for the large geothermal power plants.

Stable operation of a production plant is an important criterion for design. The flash/binary geothermal process involves mass and energy transfer. This energy and mass transfer may cause cycling under certain conditions depending upon the plant response.

In order to test the flashing process, it is imperative that flash pressures be adjusted by methods of control that are compatible with stable plant operation. Similarly, it is desirable to adjust fluid temperatures when the heat exchangers are tested. Verification of proposed control methods can be obtained while the binary side of the system is charged with distilled water.

Control of liquid level in the main condensers will permit heat transfer data to be taken while all the condenser tubes are not flooded. These data are more important for the isobutane case. However, while the system is charged with water, various methods of controlling liquid level can be evaluated. The purpose of the test is to determine if it is necessary to spend funds for raising the elevation of the condensers before the isobutane tasks.

Upset conditions that result from lost brine flow, pump outages, or other possible unexpected occurrences may cause damage to equipment and piping in the facility. Leaks could be especially hazardous when the system is filled with isobutane; therefore, it would be advantageous to determine the system responses to possible upsets while the system is charged with water.

GENERAL TEST PROCEDURES

Task 1 is divided into the following three subtasks:

Subtask A - Control of flash process and heat exchanger
condensing temperatures

Subtask B - Control of flooding in the main condensers

Subtask C - Simulation of upset conditions

Subtask A - Control of Flash Process and Heat Exchanger Condensing Temperatures

Butterfly valves ahead of the heat exchangers will be adjusted to obtain desired operating flash pressures in all of the flash drums. Valves downstream of the heat exchangers (in the condensate lines) will be adjusted to control the level of condensate in the heat exchangers. Pressure of the vapor downstream of the butterfly valves will be measured and recorded. This subtask will first be performed for the base-line operating conditions and then will be repeated for a narrowing of the range of flashing temperatures, flashing over equal temperature differences, flashing over equal pressure differences, and elimination of level control.

Subtask B - Control of Flooding in the Main Condensers

Reduction of cooling water flow. Valves in the cooling water line will be used to reduce the flow of cooling water after stable operating conditions for the baseline mode have been attained. The change in level of the condensate in the condenser will be observed and recorded. (There is no existing means of measuring condensate level).

Reduction in cooling water spray. Valves in the cooling water line will be opened so that full flow of cooling water is restored. Additional valves will be used to bypass some of the spray nozzles and permit a portion of the cooling water to flow directly from the condensers to the spray pond without spraying. The change in condensate level in the condensers will be observed and recorded.

Bypass of one condenser shell. Use of all the spray nozzles will be restored with the full flow of circulating water. Valve will be closed on the tubeside of one of the two condensers so that all of the condensation will take place in the other condenser. The change in level in the active condenser will be observed and recorded.

Subtask C - Simulation of Upset Conditions

Brine flow of 400,000 lb/hr from two wells. The system will be operated in the baseline temperature-pressure conditions with 400,000 lb/hr of brine flow from two wells. Flow rates and temperatures at critical points in the system will be recorded.

Brine flow of 800,000 lb/hr from two wells. The system will be operated in the baseline temperature-pressure conditions with 800,000 lb/hr of brine flowing from two wells. Flow rates and temperatures at critical points in the system will be recorded.

Reduction in brine flow. The system will be operated in the baseline mode with two wells flowing. The valves at the production wells or in the brine production lines will be closed rapidly. The transient response of the pilot plant system to the perturbation will be detected by taking continuous temperature, pressure, and flow measurements at various preselected points throughout the system. These points will be connected to the data logger for displaying continuous changes in conditions.

Outage of brine reinjection pump. The system will be operated in the baseline mode with two wells flowing. Electrical power to the brine reinjection pump will be suddenly terminated. Continuous measurements of temperature, pressure, and flow will be taken at various preselected points throughout the system. Where manual operation of valves is required to prevent flooding of vessels, the plant operators will perform the required manual functions that are anticipated.

DESCRIPTION OF TEST PROCEDURE

Subtask A - Control of Flash Process and Heat Exchanger Condensing Temperatures

Subtask A consists of five tests in an attempt to demonstrate that stable plant operation can be maintained while controlling the pressures in

the flash drums to desired levels and maintaining constant heat exchanger condensing temperature. It is also important to determine if, while controlling pressure in the drums, the heat exchangers can be operated in an unflooded state.

- Test Number 1: Baseline Operating Conditions

- Test Conditions:

- (1a) Flow of brine will be from one well only* and will be approximately 400,000 lb/hr into either flash drum V-1 or flash drum V-4.

- (1b) The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

- (1c) Use 24-inch butterfly valve to control pressure upstream of valve PV 303 to 43 psia as indicated by PI 313.**

- (1d) The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

* Preliminary calculations indicate that if the condensers are operated at vacuum pressure, the heat input from 2 wells will result in steam velocities over 1,000 fps in the inlet piping. Such high velocities, if actually achieved, could damage the condensers.

** This should result in pressure downstream of valve being approximately 20 psia.

- (1e) Water flow rate, as measured by flow element FE 104, will be controlled by valve FV 104W to about 422,000 lb/hr.
- (1f) Cooling water flow rate, as measured in line 24"-WC1-L by water meter, will be controlled to 4,625,000 lb/hr by condenser outlet butterfly valves.

Pressures in the flash drums will be maintained at the prescribed levels by adjusting the butterfly valves on the vapor side of each heat exchanger. Initially, valves in the condensate line downstream of the heat exchangers are opened completely. After control of pressures in the flash drums is achieved, the downstream valves will be adjusted so that the heat exchangers will drain properly.

— Test Measurements:

The test duration will be 48 hours. The time interval for measurements will be 1 hour initially. The frequency of measurement will be adjusted as necessary to obtain good data during the course of the tests.

- (1a) Record pressure and temperature downstream of the butterfly valves that are just ahead of heat exchangers E-3, E-1A, E-1B, and E-1C every hour. No temperature or pressure indicator is there presently.
- (1b) Record inlet and outlet brine flow rates every hour as measured by flow elements FE 107, FE 108, FE 100, FE 109, and FE 105.
- (1c) Record brine temperatures at the inlet and outlet of the plant every hour as measured by temperature indicators TI 501 and TI 502, and temperature element TE 511.
- (1d) Record water and steam temperature every hour at outlet of E-3. No temperature indicator is there presently.

- Test Number 2: Reduce the Temperature Range Over Which Flashing Occurs

- Test Conditions:

- (2a) Flow of brine will be from one well only and will be approximately 400,000 lb/hr into either flash drum V-1 or flash drum V-4.
 - (2b) The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	120 psia
V-7	PI 316	90
V-14	PI 344	65
V-11	PI 333	45
V-13	PI 336	20

- (2c) Same as 1c
 - (2d) Same as 1d
 - (2e) Same as 1e
 - (2f) Same as 1f

- Test Measurements:

- (2a) Same as 1a
 - (2b) Same as 1b
 - (2c) Record temperatures in flash drums as measured by temperature indicators TI 501, TI 502, TI 508, TI 507 and temperature element TE 511.

- Test Number 3: Flashing over equal ΔT 's

- Test Conditions:

- (3a) Same as 1a
 - (3b) The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	136 psia
V-7	PI 316	72
V-14	PI 344	33.5
V-11	PI 333	13.3
V-13	PI 336	11.5

(3c) Same as 1c

(3d) Same as 1d

(3e) Same as 1e

(3f) Same as 1f

— Test Measurements:

(3a) Same as 1a

(3b) Same as 1b

(3c) Same as 2c

● Test Number 4. Flashing over equal Δp 's

— Test Conditions:

(4a) Same as 1a

(4b) The following flash pressure will be maintained.

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	114.5
V-14	PI 344	63.9
V-11	PI 333	13.3
V-13	PI 336	11.5

(4c) Same as 1c

(4d) Same as 1d

(4e) Same as 1e

(4f) Same as 1f

— Test Measurements:

(4a) Same as 1a

(4b) Same as 1b

(4c) Record pressures in flash drums as measured by pressure indicators PI 304, PI 310, PI 316, PI 344, PI 333, and PI 336.

- Test Number 5: Elimination of Level Control
 - Test Conditions:
 - (5a) Same as 1a
 - (5b) Same as 1b
 - (5c) Same as 1c
 - (5d) Level control on all flash drums will be disconnected so that level will be controlled by the fixed orifices only
 - (5e) Same as 1e
 - (5f) Same as 1f
 - Test Measurements:
 - (5a) Record levels in flash drums V-1, V-4, V-7, V-14, and V-11 every hour as measured by level gauges LG 701, LG 702, LG 713, LG 715, and LG 719, respectively.
 - (5b) Same as 1b
 - (5c) Same as 1c

Subtask B — Control of Condensate Level in Main Condensers

Subtask B consists of three tests in an attempt to find a method by which flooding of the condenser tubes can be controlled. The degree of sensitivity of condensate level to variations in cooling water flow rate and other variations is of particular interest in this subtask. The demonstration of unflooded operation by adjustment of existing plant controls could eliminate the need for raising the condensers.

- Test Number 1: Reduction in Cooling Water Flow Rate
 - Test Conditions:
 - (1a) Flow of brine will be from one well only and will be approximately 400,000 lb/hr into either flash drum V-1 or flash drum V-4.

- (1b) The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

- (1c) Use 24-inch butterfly valve to control pressure upstream of valve PV-303 to 43 psia as indicated by PI 313. (Also must add temperature indicator.)
- (1d) The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

- (1e) Water flow rate as measured by flow element FE 104 will be controlled by valve FV 104W to about 422,000 lb/hr
- (1f) Cooling water flow rate as measured in line 24"-WC1-L by the water meter will be controlled to 3,500,000 lb/hr (approximately 75 percent of full flow) by the condenser outlet butterfly valves.

— Test Measurements:

Test duration will be 24 hours. Record liquid level in the main condensers, E-4A and -4B, every hour. (No level indicator is present at this time.)

- Test Number 2: Reduction in Cooling Water Spray

- Test Conditions:

- (2a) Same as 1a
 - (2b) Same as 1b
 - (2c) Same as 1c
 - (2d) Same as 1d
 - (2e) Same as 1e
 - (2f) Cooling water flow rate as measured in line 24"-WC1-L by the water meter will be controlled to 4,625,000 lb/hr by the condenser outlet butterfly valves. Valves in the piping over the spray pond will be used to bypass no more than 50 percent of the water flow from the spray nozzles or no more than what is required to maintain a cooling water temperature into the condenser below 140°F.

- Test Measurements

Test duration will be 24 hours. Record liquid level in the main condensers E-4A and -4B every hour. (No level indicator at present).

- Test Number 3: Bypass of One Condenser Shell

- Test Conditions:

- (3a) Same as 1a
 - (3b) Same as 1b
 - (3c) Same as 1c
 - (3d) Same as 1d
 - (3e) Same as 1e
 - (3f) Cooling water flow rate as measured in line 24"-WC1-L by the water meter will be controlled to 4,625,000 lb/hr by condenser outlet butterfly valves. The full flow will pass through the spray nozzles. An existing butterfly valve on the tube-side outlet of one of the condensers will be closed.

- Test Measurements:

Test duration will be 24 hours. Record liquid level in the active condenser every hour. (No level indicator at present).

Subtask C – Simulation of Upset Conditions

Subtask C consists of four tests to obtain information on the responses of the plant to changes in brine flow rate and to other possible upset conditions. The data logger will be of particular value for this subtask because it will record the change in conditions at many positions in the system while the system adjusts to the imposed upsets.

- Test Number 1: Brine Flow of Approximately 400,000 lb/hr from 2 Wells

– Test Conditions:

(1a) Flow of brine will be from 2 wells and will be approximately 400,000 lb/hr total (about 200,000 lb/hr from each well) into both flash drums V-1 and V-4.

(1b) The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

(1c) Use 24-inch butterfly valve PV 303 to control temperature upstream of valve to 272°F. (Must add temperature indicator.)

(1d) The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

- (1e) Water flow rate as measured by flow element FE 104 will be controlled by valve FV 104W to about 422,000 lb/hr.
- (1f) Cooling water flow rate as measured in line 24"-WC1-L by the water meter will be controlled to 4,625,000 lb/hr by the condenser outlet butterfly valves.
- (1g) Test duration will be 48 hours.

- Test Measurements:

- (1a) Record pressure and temperature downstream of the butterfly valves that are just ahead of heat exchangers E-3, E-1A, E-1B, and E-1C every hour. (No pressure or temperature indicators are there presently.)
- (1b) Record inlet and outlet brine flow rates every hour as measured by flow elements FE 107, FE 108, FE 100, FE 109, and FE 105.
- (1c) Record brine temperatures at the inlet and outlet of the plant every hour as measured by temperature indicators TI 501 and TI 502 and temperature element TE 511.
- (1d) Record temperature of water and steam at the outlet of E-3 every hour. (No temperature indicator is there presently.)

- Test Number 2: Brine Flow of Approximately 800,000 lb/hr from 2 Wells

- Test Conditions:

- (2a) Flow of brine will be from 2 wells and will be approximately 800,000 lb/hr into both flash drums V-1 and V-4.
- (2b) Same as 1b
- (2c) Same as 1c
- (2d) Same as 1d
- (2e) Same as 1e
- (2f) Same as 1f
- (2g) Same as 1g

— Test Measurements:

- (2a) Same as 1a
- (2b) Same as 1b
- (2c) Same as 1c
- (2d) Same as 1d

Note

It is essential that this test be performed after the completion of Subtask B and Subtask C, Test No. 1, and after it has been analytically and experimentally confirmed that the condensers can operate above atmospheric pressure.

● Test Number 3: Reduction in Brine Flow

— Test Conditions:

Initial test conditions are exactly the same as those for Test Number 2. Then each of the following subtests will be performed:

- (3-1) The valve at the wellhead of one of the two production wells will be closed partially so that flow from this well will be reduced to about one-half its initial flow (i. e. , reduced to about 200,000 lb/hr). This will result in a total brine flow of about 600,000 lb/hr.
- (3-2) The system will be returned to full flow conditions (800,000 lb/hr) and stabilized. The wellhead valve will be closed completely so that brine flow to the pilot plant is from one well only (total flow will be about 400,000 lb/hr).
- (3-3) The system will again be returned to full flow conditions and stabilized. The wellhead valves on both production wells will be closed completely to simulate a total loss of flow to the pilot plant.

— Test Measurements:

(3-1) The plant response to the sudden loss of brine will be primarily determined from the output of the data logger. Pressure, temperature, and flow rate at the measurement points of the system will be recorded at intervals determined by maximum data recording speed. In addition, plant recorders will show continuous changes in conditions at various points in the system.

(3-2) Same as 3-1 above.

(3-3) Same as 3-1 above.

● Test Number 4: Outage of Brine Reinjection Pump

— Test Conditions:

Initial test conditions are exactly the same as those for Test Number 2. Then electrical power to the brine reinjection pump will be shut off.

— Test Measurements:

The plant response to the loss of reinjection flow will be primarily determined from the output of the data logger. Pressure, temperature, and flow rate at the measurement points of the system will be recorded at the smallest interval of data recording capability. In addition, plant recorders will show continuous changes in conditions at various points in the system.

RESULTS

Data on temperature, pressure, flow rates, and levels, taken during Subtasks A, B, and C of Task Number 1, will be plotted as a function of time. This Task attempts to demonstrate methods of control that will attain stable plant operation, and at the same time, enable acquisition of good data on heat transfer and on the flashing process. At the completion of Task 1 of the test program, startup and shutdown procedures for the pilot plant can be recommended. Additional recommendations on new plant controls and their use may be another possible result.

A list of emergency procedures (to be followed during operation of the pilot plant) may be written from information obtained during the course of Subtask C. Such a list will be especially useful for plant operation when isobutane is used as the binary fluid. In addition, more information will be available on the limitations of plant equipment during abrupt changes in well flow or during other upset conditions.

TASK 2

TITLE

Overall heat and mass balance of the plant under baseline operating conditions.

OBJECTIVE

To establish a uniform calculational procedure, with built-in cross checks, which will provide a basis for data reduction in all future pilot plant tests.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

It is necessary to corroborate the design conditions that had been assumed in arriving at the initial heat and mass balance. The accuracy of pilot plant test data must be confirmed by the results of several independent calculations of the important process variables (for example, heat duty as calculated by vapor condensation versus coolant flow and temperature rise). Any unexpected interactions in the plant cycle will be revealed by such baseline calculations.

GENERAL TEST PROCEDURE

Measurement of fluid flows, temperatures, pressures, and concentrations will be used to develop the overall mass balance followed by the overall heat balance.

TEST CONDITIONS

Flow of brine will be from one well only and will be approximately 400,000 lb/hr into either flash drum V-1 or flash drum V-4. The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

- Use 24-inch butterfly valve to control pressure upstream of valve PV-303 to 43 psia as indicated by PI 313.
- The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

- Water flow rate as measured by flow element FE 104 will be controlled by valve FV 104W to about 422,000 lb/hr.
- Cooling water flow rate as measured in line 24"-WC1-L by the water meter will be controlled to 4,625,000 lb/hr by condenser outlet butterfly valves.

EXPERIMENTAL MEASUREMENTS

Measurements on streams that flow into the plant are as follows:

	<u>Measurement Point</u>	<u>Fluid</u>	<u>Location</u>	<u>Indicator</u>	<u>Symbol</u>
1	Flow Rate	Steam + CO ₂	Downstream V-1	FE 100	w ₁
1	Temperature	Steam + CO ₂	Downstream V-1	TR 510	t ₁
1	Pressure	Steam + CO ₂	V-1	PI 304	p ₁
2	Flow Rate	Steam + CO ₂	Downstream V-4	FE 109	w ₂
2	Temperature	Steam + CO ₂	Downstream V-4	TR 510	t ₂
2	Pressure	Steam + CO ₂	V-4	PI 310	p ₂
3	Flow rate	Brine	Downstream V-1	FE 107	w ₃
3	Temperature	Brine	V-1	TI 501	t ₃
3	Concentration	Brine	V-1	Sample Pt.	x ₃
4	Flow rate	Brine	Downstream V-4	FE 108	w ₄
4	Temperature	Brine	V-4	TI 502	t ₄
4	Concentration	Brine	V-4	Sample Pt.	x ₄
5	Flow rate	Cooling water	From spray pond	Water meter 24"-WC1-L	w ₅
5	Temperature	Cooling water	From spray pond	TE 500-4	t ₅

Measurements on streams that flow from the plant are as follows:

	<u>Measurement Point</u>	<u>Fluid</u>	<u>Location</u>	<u>Indicator</u>	<u>Symbol</u>
6	Flow rate	Brine	Downstream P-2	FE 105	w ₆
6	Temperature	Brine	Downstream V-11	TE 511	t ₆
6	Concentration	Brine	Downstream P-2	Sample Pt.	x ₆

	<u>Measurement Point</u>	<u>Fluid</u>	<u>Location</u>	<u>Indicator</u>	<u>Symbol</u>
7	Flow rate	Condensate	Downstream P-9 and P-10	FE 119	w ₇
7	Temperature	Condensate	Downstream P-9 and P-10	TE must be added	t ₇
8	Flow rate	Condensate	Downstream E-5	FE 120	w ₈
8	Temperature	Condensate	Downstream E-5	TE 500-3	t ₈
9	Flow rate	Cooling water	Downstream E-4	FE must be added	w ₉
9	Temperature	Cooling water	Downstream E-4	TI 513 and TI 514	t ₉
10	Flow rate	Cooling water	Downstream VP-1 cooler	FE must be added	w ₁₀
10	Temperature	Cooling water	Downstream VP-1 cooler	TI must be added	t ₁₀
11	Flow rate	Steam + CO ₂	Downstream V-6	FE 103	w ₁₁
11	Temperature	Steam + CO ₂	Downstream V-6	TI 519	t ₁₁
11	Pressure	Steam + CO ₂	Downstream V-6	PI 308	P ₁₁
12	Flow rate	Steam + CO ₂	Downstream VP-1	FE must be added	w ₁₂
12	Temperature	Steam + CO ₂	Downstream VP-1	TE 500-15	t ₁₂

CALCULATIONS

Balance of Mass Flow Rates

If the pilot plant is defined as all equipment and piping other than the storage ponds, and the plant is operated under reasonably stable conditions so that liquid levels in the vessels are constant, the total mass flow rate into the plant should equal the total flow rate out of the plant (with allowances for small leakages) within an acceptable level of accuracy;

$$W_{in} = W_{out}$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = w_6 + w_7 + w_8 + w_9 + w_{10} + w_{11} + w_{12}$$

Heat Balance

When stable operation has been achieved and a satisfactory mass balance has been established, the heat flow into the plant must equal the heat flow out of the plant. The heat balance will include an allowance for unmeasured heat losses. It is possible, however, that the accuracy of the heat balance may be somewhat impaired by using the Office of Saline Water's enthalpy values based on sodium chloride solutions rather than actual geothermal brine, for which only meager data are available. Corresponding adjustments may be required in the heat balance calculations. The discrepancy between measured and predicted heat balances should not exceed 10 percent. The basic relationships are:

$$Q_{in} = Q_{out}$$

$$q_1 + q_2 + q_3 + q_4 + q_5 = q_6 + q_7 + q_8 + q_9 + q_{10} + q_{11} + q_{12}$$

Heat flow rates q_1 and q_2 are determined from temperature and pressure measurements at points 1 and 2, respectively. The steam tables are used to obtain h_1 and h_2 .

Then,

$$q_1 = h_1 w_1$$

$$q_2 = h_2 w_2$$

Heat flow rates q_3 , q_4 , and q_6 are determined from temperature and concentration measurements at points 3, 4, and 6, respectively.

Enthalpies are obtained from data for solutions of water and sodium chloride.

$$q_3 = h_3 w_3$$

$$q_4 = h_4 w_4$$

$$q_6 = h_6 w_6$$

Heat flow rate q_{11} is determined from temperature and pressure measurements at point 11. The measured temperature is the saturation temperature of the steam, and the corresponding saturation pressure is the partial pressure of the steam in the steam/ CO_2 mixture. The total pressure of the mixture is the measured pressure at point 11. Hence, the partial pressure of CO_2 is calculated by subtraction, and the state points of both the steam and the CO_2 are then determined. The enthalpy of the CO_2 is obtained from tables at its partial pressure and at the temperature of the mixture. The enthalpy of the steam is obtained similarly. The separate mass flow rates for the CO_2 and steam are calculated from the following two equations:

$$\frac{w_{\text{H}_2\text{O}}}{w_{\text{CO}_2}} = \left(\frac{p_{\text{H}_2\text{O}}}{p_{\text{CO}_2}} \right) \left(\frac{M_{\text{H}_2\text{O}}}{M_{\text{CO}_2}} \right) \quad (1)$$

$$w_{11} = w_{\text{H}_2\text{O}} + w_{\text{CO}_2} \quad (2)$$

where,

w_{H_2O} = mass flow rate of steam

w_{CO_2} = mass flow rate of CO_2

p_{H_2O} = partial pressure of steam

p_{CO_2} = partial pressure of CO_2

M_{H_2O} = molecular weight of steam

M_{CO_2} = molecular weight of CO_2

Heat flow rate q_{11} is calculated from:

$$q_{11} = h_{H_2O} w_{H_2O} + h_{CO_2} w_{CO_2}$$

Heat flow rate q_{12} is calculated in a similar manner from measurement of temperature at point 12. The pressure at point 12 is assumed to be atmospheric pressure. The remaining heat flow rates, q_5 , q_7 , q_8 , q_9 , and q_{10} are calculated from measurements of temperature only. Since all of these flows are water in the liquid phase, enthalpy is determined from temperature.

After enthalpies are calculated, the remaining heat flow rates are calculated from:

$$q_5 = h_5 w_5$$

$$q_7 = h_7 w_7$$

$$q_8 = h_8 w_8$$

$$q_9 = h_9 w_9$$

$$q_{10} = h_{10} w_{10}$$

RESULTS

The most important result of this test will be an overall heat and mass balance for the plant based on pilot plant measurements under base line operating conditions. A secondary but important result will be a check on the accuracy of using OSW thermodynamic data for solutions of sodium chloride in water in the place of specific thermodynamic data for various geothermal brines.

TASK 3

TITLE

Clean-tube heat transfer coefficients with water as the binary fluid.

OBJECTIVES

To determine the clean-tube coefficients of the first stage exchangers, E-2 and E-3, second stage exchanger, E-1A, third stage exchanger, E-1B, fourth stage exchanger, E-1C and condensate cooler E-5. Compare these results with the predictions of analytical methods.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The heat transfer surface area requirement represents a major portion of the capital cost in a geothermal power plant. The clean-tube coefficients are needed to confirm the suitability of available heat transfer correlations and to provide a baseline for the detection of fouling with continued operation. Since the heat transfer coefficients of the water side are predictable with a fair degree of reliability, operation with water as the binary fluid allows a good check of the heat transfer correlations for the brine side. This is imperative if meaningful information is to be obtained when the binary fluid is switched to isobutane.

The performance of condenser E-4A and E-4B cannot be tested under water operation since it will be flooded; however it will furnish heat balance data.

GENERAL TEST PROCEDURE

The overall heat transfer coefficients for the clean tubes will be determined from a heat and mass balance around the heat exchangers and measurements of operating conditions. Task 3 is divided into the following three subtasks:

- Subtask A related to Exchangers E-1A, E-1B, E-1C
- Subtask B related to Exchanger E-5
- Subtask C related to Exchangers E-2 and E-3

TEST CONDITIONS

During the initial tests, the following modes of operation are required:

- The E-2 exchanger will operate with forced circulation of water in the tubes and steam condensing in the presence of the noncondensable gases on the shellside. The valve on the shellside inlet of E-3 must be adjusted so that no boiling occurs on the tubeside of E-2.
- The E-3 exchanger will operate with water heating and partially vaporizing inside the tubes and steam condensing nearly isothermally on the shellside.
- The E-1A, E-1B and E-1C exchangers will operate with forced circulation water on the shellside and steam condensing inside the tubes. The valves must be adjusted such that flooding of the exchangers does not occur.
- The E-5 exchanger will operate with forced circulation condensate on the shellside and forced circulation water in the tubes.

- The E-4A and E-4B exchangers will operate partially flooded on the shellside at a pressure of about 20 psia at the inlet. This pressure will be maintained by the valve on the shellside inlet. Brackish water will be in the tubes.

EXPERIMENTAL MEASUREMENTS

The following measurement location numbers for each test refer to the Table of Measurement locations.

Subtask A – E-1A Test Measurements

1, 8, 9, 10, 11, 35, 38, 39, 44

E-1B Test Measurements

1, 6, 7, 8, 9, 36, 40, 41, 45

E-1C Test Measurements

1, 4, 5, 6, 7, 37, 42, 43, 46

Subtask B – E-5 Test Measurements

1, 2, 3, 4, 5, 27, 33, 34, 47

Subtask C – E-2 and E-3 Test Measurements

1, 2, 3, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19,
20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31,
32, 33, 34

Table of Measurement Locations

CIRCULATING WATER MEASUREMENTS

<u>No.</u>	<u>Location</u>	<u>Measurement</u>	<u>Indicator</u>
1	10"-PP3-B	Water flow to E-5	FT-104
2	10"-PP3-B	Temp to E-5	Must be added
3	10"-PP3-B	Press to E-5	Must be added
4	10"-PP5-B	E-5 Temp out	TE-500-14
5	10"-PP5-B	E-5 Press out	Must be added
6	10"-PP6-B	E-1C Temp out	TE-500-13

<u>No.</u>	<u>Location</u>	<u>Measurement</u>	<u>Indicator</u>
7	10"-PP6-B	E-1C Press out	Must be added
8	10"-PP7-B	E-1B Temp out	TE-500-12
9	10"-PP7-B	E-1B Press out	Must be added
10	12"-PP8-B	E-1A Temp out	TE-500-11
11	12"-PP8-B	E-1A Press out	Must be added
12	18"-PP9-B	E-2 Temp out	TI-504
13	18"-PP9-B	E-2 Press out	Must be added
14	18"-PP10-B	E-3 Temp out	Must be added
15	18"-PP10-B	E-3 Press out	Must be added
16	18"-PP11-A	E-4 Temp in	Must be added
17	18"-PP11-A	E-4 Press in	Must be added
18	16"-PP12-A	E-4A, B Temp out	TE-500-9
19	10"-PP12-A	E-4A, B Press out	Must be added

COOLING WATER MEASUREMENTS

<u>No.</u>	<u>Location</u>	<u>Measurement</u>	<u>Indicator</u>
20	24"-WC1-L	E-4A, B Cooling water flow	Must be added
21	24"-WC1-L	Cooling water supply temp	TE-500-4
22	24"-WC1-L	Cooling water supply press	Must be added
23	24"-WR3-L	Cooling water E-4A, B out temp (before mixing with condensate)	Must be added
24	24"-WR3-L	Cooling water E-4A, B out press	Must be added

BRINE/STEAM MEASUREMENTS

<u>No.</u>	<u>Location</u>	<u>Measurement</u>	<u>Indicator</u>
25	10"-SM1-AC	V-1 Steam out	FT-100
26	10"-SM2-AC	V-4 Steam out	FT-109
27	4"-SC7-AA	E-5 Cond out	FT-120
28	6"-SH7-AC	V-6 Vent gas out	FT-103
29	16" E-3 inlet	E-3 in Temp (dwn strm of valve)	Must be added
30	16" E-3 inlet	E-3 in press (dwn strm of valve)	Must be added
31	16" E-3 outlet	E-3 out temp	TI-505
32	16" E-3 outlet	E-3 out press	Must be added
33	6"-SM6-AC	E-2 out temp	TI-503
34	6"-SM6-AC	E-2 out press	Must be added
35	10"-SM9-AC	V-9 steam out flow	FT-113
36	10"-SM12-AC	V-10 steam out flow	FT-115
37	12"-SM15-AC	V-12 steam out flow	FT-117
38	8" E-1A inlet	E-1A temp in (dwn strm valve)	Must be added
39	8" E-1A inlet	E-1A press in (dwn strm valve)	Must be added
40	8" E-1B inlet	E-1B temp in (dwn strm valve)	Must be added
41	8" E-1B inlet	E-1B press in (dwn strm valve)	Must be added
42	8" E-1C inlet	E-1C temp in (dwn strm valve)	Must be added
43	8" E-1C inlet	E-1C press in (dwn strm valve)	Must be added
44	8" E-1A outlet	E-1A temp out	Must be added
45	8" E-1B outlet	E-1B temp out	Must be added
46	8" E-1C outlet	E-1C temp out	Must be added
47	8" E-5 outlet	E-5 temp out	TE-500-3

EVALUATION OF TEST DATA

Subtask A - Exchangers E-1A, E-1B, E-1C

A-1 Heat Balance

Steam side:

$$Q_s = W_s (h_1 - h_2)$$

Water side:

$$Q_w = W_w C_w (T_{out} - T_{in})$$

Exchanger duty:

$$Q_e = (Q_s + Q_w)/2$$

where:

Q_s = Heat load calculated from steam side, Btu/hr

Q_w = Heat load calculated from water side, Btu/hr

Q_e = Average of Q_s and Q_w , Btu/hr

W_s = Mass flow rate of steam, lb/hr

W_w = Mass flow rate of water, lb/hr

C_w = Specific heat of water, Btu/lb °F

h_1 = Enthalpy of steam entering exchanger, Btu/lb

h_2 = Enthalpy of condensate leaving exchanger, Btu/lb

T_{in} = Inlet water temperature to exchanger, °F

T_{out} = Outlet water temperature from exchanger, °F

A-2 Mean Temperature Difference, E-1A, B, C

$$\Delta T_m = \frac{(T_s - T_{out}) - (T_s - T_{in})}{\log_e \left(\frac{T_s - T_{out}}{T_s - T_{in}} \right)}$$

where:

T_s = Steam condensing temperature, °F

T_{in} & T_{out} are as defined in A-1 above

ΔT_m = mean temperature difference, °F

A-3 Overall Clean Tube HTC, E-1A, B, C

$$U_{ct} = \frac{Q_e}{A_e \Delta T_m} = \frac{Q_e}{5724 \Delta T_m}$$

where:

A_e = Effective surface area of exchanger, ft²

U_{ct} = Overall clean tube HTC, Btu/hr-ft²-°F

Subtask B - Exchanger E-5

B-1 Heat Balance

Water (tubeside):

$$Q_w = W_w C_w (T_{out} - T_{in})$$

Condensate (shellside):

$$Q_c = W_c C_c (T_{in} - T_{out})$$

Exchanger duty:

$$Q_e = (Q_w + Q_c)/2$$

where:

Q_w = Heat load calculated from water, Btu/hr

Q_c = Heat load calculated from condensate, Btu/hr

Q_e = Average of Q_w & Q_c , Btu/hr

W_c = Flow rate of condensate, lb/hr

W_w = Flow rate of water, lb/hr

C_c = Specific heat of condensate, $\frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{F}}$

C_w = Specific heat of water, $\frac{\text{Btu}}{\text{lb} \cdot ^\circ\text{F}}$

T_{in}, T_{out} = Inlet and outlet temperatures of the
respective sides, $^\circ\text{F}$

B-2, Mean Temperature Difference, E-5

$$\Delta T_m = F \times \text{LMTD}$$

where:

$$\text{LMTD} = \frac{(T_{s1} - T_{t2}) - (T_{s2} - T_{t1})}{\log_e \left(\frac{T_{s1} - T_{t2}}{T_{s2} - T_{t1}} \right)}$$

F is from Figure T-3.2A of Ref. 5
as a function of P & R with:

$$P = \frac{T_{t2} - T_{t1}}{T_{s1} - T_{t1}}$$

$$R = \frac{T_{s1} - T_{s2}}{T_{t2} - T_{t1}}$$

where:

T_{s1} = Shellside inlet temperature, $^{\circ}\text{F}$

T_{s2} = Shellside outlet temperature, $^{\circ}\text{F}$

T_{t1} = Tubeside inlet temperature, $^{\circ}\text{F}$

T_{t2} = Tubeside outlet temperature, $^{\circ}\text{F}$

B-3 Overall Clean Tube HTC, E-5

$$U_{ct} = \frac{Q_e}{A_e \Delta T_m} = \frac{Q_e}{1510 \Delta T_m}$$

where:

A_e = Effective surface area of exchanger, ft^2

U_{ct} = Overall clean tube HTC, $\text{Btu/hr-ft}^2\text{-}^{\circ}\text{F}$

Subtask C — Exchangers E-2 and E-3

C-1 Heat Balance

Total heat load for exchangers E-2 and E-3, Q_{23} :

Primary method

$$Q_{23} = W_{s3} h_{s3} - W_{s2} h_{s2} - W_{l2} h_{l2} + W_{NC} C_{NC} (T_3 - T_2)$$

Secondary method

$$Q_{23} = Q_4 - [Q_p + Q_5 + Q_{1A} + Q_{1B} + Q_{1C} + Q_{1C}]$$

Total heat load for exchangers E-2, Q_2 :

Primary method

$$Q_2 = W_{s23} h_{s23} + W_{l23} h_{l23} - W_{s2} h_{s2} - W_{l2} h_{l2} + W_{NC} C_{NC} (T_{23} - T_2)$$

Secondary method

$$Q_2 = W_w C_w (t_{23} - t_2)$$

Heat load for exchanger E-3, Q_3 :

Primary method

$$Q_3 = W_{s3} h_{s3} - W_{s23} h_{s23} - W_{l23} h_{l23} + W_{NC} C_{NC} (T_3 - T_{23})$$

Secondary method

$$Q_3 = Q_{23} - Q_2$$

It will be necessary to calculate the quantity of steam and CO_2 from measured pressures and temperatures. This must be obtained from steam partial pressures corresponding to the measured saturation temperatures at the inlet and outlet of E-2. Note that the temperature measured at the inlet to E-3 will not correspond to the steam saturation temperature as it is slightly superheated at this point due to throttling.

Nomenclature for Heat Balance

- Q_p = circulating water pump power, Btu/hr
- Q_{1A} = heat load for exchanger E-1A, Btu/hr
- Q_{1B} = heat load for exchanger E-1B, Btu/hr
- Q_{1C} = heat load for exchanger E-1C, Btu/hr
- Q_2 = heat load for exchanger E-2, Btu/hr
- Q_3 = heat load for exchanger E-3, Btu/hr
- Q_4 = heat load for exchanger E-4A & B, Btu/hr
- Q_5 = heat load for exchanger E-5, Btu/hr

Q_{23} = combined heat load = $Q_2 + Q_3$, Btu/hr
 h_s = enthalpy of steam at temp & partial press, Btu/lb
 h_l = enthalpy of condensate at temp & press, Btu/lb
 W_s = flow rate of steam, lb/hr
 W_l = flow rate of condensate, lb/hr
 W_{NC} = flow rate of noncondensable gas (CO_2), lb/hr
 W_W = flow rate of water, lb/hr
 C_{NC} = specific heat of noncondensable, Btu/lb- $^{\circ}F$
 C_W = specific heat of water, Btu/lb- $^{\circ}F$
 T = hot fluid temperature, $^{\circ}F$
 t = cold fluid temperature, $^{\circ}F$
 T_{SI} = steam saturation temp at inlet to E-3, $^{\circ}F$
 T_{SO} = steam saturation temp at outlet of E-2, $^{\circ}F$

SUBSCRIPTS (Refer to Figure 2-1)

2 refers to the cold terminal end

3 refers to the hot terminal end

23 refers to the intermediate point (between exchangers E-2 and E-3), $^{\circ}F$

Figure 2-1 EXCHANGER CONFIGURATION E-2 AND E-3

C-2 Mean Temperature Difference

Construct the heat release curves (temp vs heat load) for the combined exchangers E-2 and E-3. The heat curve is constructed by selecting intermediate temperatures for the steam/CO₂ side and calculating the heat load for the temperature interval. (Refer to Kern example, Ref. 2, page 347.)

The water side heat curve is also constructed on the same coordinates as shown in Figure 2-2. The boiling point (temp t_g on Figure 2-2) of the water is calculated by heat balance with the steam/CO₂ side.

For each temperature interval chosen, calculate the log mean temperature difference, LMTD. This is demonstrated on pages 350 and 351 of the Kern example. This should be done both for E-2 and for E-3. The weighted LMTD's then are:

$$WLMTD_2 = \frac{Q_2}{\sum(q/\Delta t_{lm})_2}$$

$$WLMTD_3 = \frac{Q_3}{\sum(q/\Delta t_{lm})_3}$$

where:

WLMTD = Weighted log mean temp diff., °F

Q = Total heat load, Btu/hr

q = Heat load for interval, Btu/hr

Δt_{lm} = LMTD for interval, °F

Subscripts 2 and 3 refer to E-2 and E-3 respectively

**Figure 2-2 HEAT LOAD VERSUS TEMPERATURE PROFILE
WATER AS BINARY FLUID**

Calculate the LMTD correction factor, F, for each shell. The F value is obtained from Figure T-3.2A of Ref. 5 as a function of P and R where:

$$P = \frac{t_o - t_i}{T_i - t_i}$$

and

$$R = \frac{T_i - T_o}{t_o - t_i}$$

where:

T designates the hot fluid temp

t designates the cold fluid temp

subscripts i and o designate the inlet and outlet

of the exchanger

Calculate the corrected mean temperature difference for each exchanger as:

$$\Delta T_{m2} = F_2 \times \text{WLMTD}_2 \quad , \text{ for E-2}$$

$$\Delta T_{m3} = F_3 \times \text{WLMTD}_3 \quad , \text{ for E-3}$$

C-3 Overall Heat Transfer Coefficient, U

The overall heat transfer coefficient may be calculated as:

For exchanger E-2:

$$U_2 = Q_2 / (\Delta T_{m2} \times A_2)$$

For exchanger E-3:

$$U_3 = Q_3 / (\Delta T_{m3} \times A_3)$$

where: $A_2 = A_3 = 4,156 \text{ ft}^2$

COMPARISON WITH ANALYTICAL PROCEDURE

Comparison with Analytical Procedure for Subtasks A and B

Calculate the individual heat transfer coefficients of the tubeside and shellside for each of the four exchangers (E-1A, E-1B, E-1C, and E-5).

The overall coefficient is then calculated as:

$$\frac{1}{U_{\text{calc}}} = \frac{1}{h_{\text{io}}} + \text{foul} + \text{wall} + \frac{1}{h_{\text{o}}}$$

where:

h_{io} and h_{o} are the tubeside and shellside coefficients, respectively, calculated from the equations in the following pages

foul = fouling resistance

$$\text{wall} = \frac{d_{\text{o}}}{24 \text{ km}} \log_e \left(\frac{d_{\text{o}}}{d_{\text{i}}} \right) = \text{tube wall resistance}$$

km = Tube metal thermal conductivity, Btu/hr-ft-°F

These values of overall heat transfer coefficients are for comparison with the measured values of the respective coefficients from parts A-3 and B-3.

Shellside Heat Transfer Coefficient, Liquid Heating

$$h_{\text{o}} = 0.29 a \left(\frac{12k}{dv} \right) R_e^{.6} P_r^{1/3}$$

where:

$$P_r = 2.42 C_p \mu / k = \text{Prandtl No.}$$

$$R_e = 124 G dv / \mu = \text{Reynolds No.}$$

$$G = W/25 A_f = \text{Mass velocity, lb/sec-ft}^2$$

a = Geometry factor for tube arrangement

d_v = Hydraulic diameter tube arrangement, inches

W = Fluid flowrate, lb/hr

A_f = Effective flow area, sq. in.

C_p = Fluid specific heat, Btu/lb-°F

μ = Fluid viscosity, cP

k = Fluid thermal conductivity, Btu/hr-ft-°F

h_o = Heat transfer coefficient, Btu/hr-ft²-°F

For exchangers E-1A, E-1B & E-1C:

$$a = .721$$

$$d_v = .725$$

$$A_f = 153 \text{ sq. in.}$$

In dimensional form for this specific geometry:

$$h_o = .49 \frac{k^{2/3} C_p^{1/3}}{\mu^{.267}} W^{.6} \quad \text{for E-1A, B, C}$$

For exchanger E-5

$$a = .578$$

$$d_v = .543$$

$$A_f = 97.3 \text{ sq. in.}$$

In dimensional form for this specific geometry:

$$h_o = .578 \frac{k^{2/3} C_p^{1/3}}{\mu^{.267}} W^{.6} \quad \text{for E-5}$$

Tubeside Heat Transfer Coefficient, Liquid Heating

For turbulent flow inside tubes, the Dittus-Boelter equation will be used.

$$h_{io} = .023 \frac{(12k)}{d_o} Re^{.8} Pr^{.4}$$

where:

$$R_e = 124 G d_i / \mu = \text{Reynolds No.}$$

$$P_r = 2.42 C_p \mu / k = \text{Prandtl No.}$$

$$G = W/25A_f = \text{Mass velocity, lb/sec-ft}^2$$

$$d_i, d_o = \text{Inside \& outside tube diameters, inches}$$

$$A_f = \text{Flow area, in}^2$$

$$C_p = \text{Fluid specific heat, Btu/lb - } ^\circ\text{F}$$

$$\mu = \text{Fluid viscosity, cP}$$

$$k = \text{Fluid thermal conductivity, Btu/hr-ft-} ^\circ\text{F}$$

$$h_{io} = \text{Tubeside heat transfer coefficient referred to outside surface area, Btu/hr-ft}^2\text{-} ^\circ\text{F}$$

For exchanger E-5:

$$d_i = .68$$

$$d_o = .75$$

$$A_f = 84.6 \text{ sq. in.}$$

In dimensional form for this specific geometry:

$$h_{io} = .0397 k \cdot 6 \left(\frac{C_p}{\mu} \right)^{.4} W^{.8} \quad \text{for E-5}$$

Steam Condensation Inside Tubes

For steam condensation inside tubes the Boyko & Kruzhilin, Ref. 4, will be used. For total condensation inside tubes the equation is:

$$h_{co} = h_{io} \left[\frac{1 + \sqrt{\rho_l / \rho_v}}{2} \right]$$

where:

ρ_l, ρ_v = Liquid and vapor density, lb/ft³

h_{io} = Heat transfer coefficient calculated from the Dittus-Boelter equation using the liquid flow and properties, Btu/hr-ft²-°F

h_{co} = Condensing coefficient referred to outside surface area, Btu/hr-ft²-°F

For the specific geometry of E-1A, B, C this becomes:

$$h_{co} = .0118 k \cdot 6 \left(\frac{C_p}{\mu} \right)^{.4} W^{.8} \left[\frac{1 + \sqrt{\rho_l / \rho_v}}{2} \right]$$

Comparison with Analytical Procedure for Subtask C

Calculation of the heat exchanger performance for E-2 and E-3 requires a repetitive stepwise calculation of the heat transfer coefficients and temperature profiles throughout each exchanger. While the most sophisticated analytical methods currently available are those of HTRI, they

are proprietary to HTRI members. However, the methods outlined here and in Appendix C are expected to give very reasonable results.

- Shellside - Steam and CO₂

For local heat transfer coefficients on the shellside the procedure of Colburn and Hougen will be used. This procedure is well documented with an example calculation in Reference 1. Kern, Reference 2, also covers the procedure in detail with an example calculation, however, some errors are noted in his presentation.

- Tubeside - Water: Heating/Vaporizing

Heat transfer coefficients in the liquid heating sections of the exchangers will be predicted with the well-known Dittus-Boelter equation. Modification of this equation for the existing geometry results in:

$$h_{io} = .0178 k_f^6 \left(\frac{Cp_l}{\mu_l} \right)^4 (W_w)^{.8}$$

For the vaporizing section, convective rather than nucleate boiling will be assumed to be the dominant mechanism and the correlation of Fair, Reference 3, will be used. Since, in this portion of the exchanger, the water is nearly isothermal the heat transfer coefficient will vary only as a function of the amount of water vaporized.

$$h_{io} = .0546 K^{.6} \left(\frac{Cw}{\mu w} \right)^{.4} \left(\frac{\rho_l}{\rho_v} \right)^{.25} \left(W_w \right)^{.8} \left(\frac{1-X}{X^{.45}} \right)^{1.25}$$

This equation applies strictly to the existing geometry and is derived from the general equations in the Appendix C.

The quality, X, at any point in the vaporizing section may be calculated as:

$$X = \frac{Q - W_w C_w (t_s - t_2)}{W_w h_{fg}}$$

where:

t_s is the saturation temperature of the water, °F

Q is the total head load at the point in consideration,
Btu/hr

Other variables are as defined in the heat balance
nomenclature section.

The procedure for calculation is outlined in
Appendix C, with reference to the Kern example.

TASK 4

TITLE

Purity of vapor; scrubber performance.

OBJECTIVES

To evaluate the performance of the scrubbers by measuring the purity of the outlet vapor as a function of its purity at the inlet, the vapor velocity, and the flow of condensate wash. To measure pressure drop as a function of the above three parameters.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

High purity vapor is essential to the long-term, trouble-free operation of a geothermal power plant. Minimization of pressure losses is also important because geothermal power plants operate with relatively low-pressure steam. The effectiveness of the scrubbers in removing impurities can be determined while the binary fluid is water. Data taken from measurements of vapor purity and pressure drop as functions of the critical parameters in scrubber design will aid in the selection of scrubbers for a future 50-MWe power plant.

GENERAL TEST PROCEDURE

The pilot plant will be started up and operated at the baseline operating conditions using the control techniques that are established in Task 1

(still using water as the binary fluid). Brine flow rate will be varied to control the volume of flashed vapor, and hence, the vapor velocity in the scrubber, by making the necessary adjustments to the appropriate valves. Then, while holding the brine flow rate constant, pressure changes between flash stages will be adjusted to control the level of carryover in the vapor. Measurements will be taken for four different flow rates, and for each of these cases, three sets of flash pressures will be run. Furthermore, for each of these 12 test runs, the condensate wash flow rate will be varied 4-fold. As a result, vapor purity and pressure drop can be plotted for 48 different data points.

DESCRIPTION OF THE TEST PROCEDURE

It is the intention of these tests to measure vapor purity at the outlet of the scrubber as a function of vapor velocity, vapor purity at the inlet, and condensate wash flow. The degree of purity at the inlet can be varied by changing the Δp between flash stages. Larger pressure differences cause greater atomization in the flashing process and thus contribute to carryover of solids in the vapor. Three values of Δp are recommended in this test. Vapor velocity is controlled in each test case by the flow rate of brine from the wells.

Summary of Tests for Task 4

<u>Test</u>	<u>Brine Flow (10^3 lb/hr)</u>	<u>ΔP (psi)</u>
1	300	50
2	300	30
3	300	15

<u>Test</u>	<u>Brine (Flow 10³ lb/hr)</u>	<u>ΔP (psi)</u>
4	400	50
5	400	30
6	400	15
7	600	50
8	600	30
9	600	15
10	800	50
11	800	30
12	800	15

- Test Number 1: Brine flow rate will be 300,000 lb/hr. Δp of flash will be approximately 50 psi.

— Test Conditions:

- (1a) Flow of brine will be from one well and will be approximately 300,000 lb/hr into either flash drum V-1 or flash drum V-4.
- (1b) The following flash drum pressures will be maintained.

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	114.5
V-14	PI 344	63.9
V-11	PI 333	13.3
V-13	PI 336	11.5

- (1c) Use 24-inch butterfly valve to control pressure upstream of valve PV-303 to 43 psia as indicated by PI 313.

- (1d) The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

- (1e) Water flow rate as measured by flow element FE 104 will be controlled by valve FV 104W to about 422,000 lb/hr.
- (1f) Cooling water flow rate, as measured in line 24"-WC1-L by water meter, will be controlled to 4,625,000 lb/hr by condenser outlet butterfly valves.

— Test Measurements:

Sufficient time will be allowed for the plant to reach stable operating conditions at the above settings. Pressure control valve PC 339A will be set to control the flow rates of condensate into the scrubber vessels as measured by flow indicator FI 125, FI 112, FI 124, and FI 116. The following set of measurements will be taken for flow rates of 4 gpm, 2 gpm, 1 gpm, and 0 gpm, respectively. The test duration in each case will be 24 hours.

- (1a) Record the temperature of the vapor flowing from scrubber vessels V-8, V-9, V-10, and V-12 as measured by temperature indicators TI 529, TI 528, TI 524, and TI 506, respectively
- (1b) Record the pressure of the vapor flowing into each scrubber vessel as measured by pressure indicators PI 307, PI 346, PI 348, and PI 335.

- (1c) Record the pressure of the vapor flowing from each scrubber vessel as measured by pressure indicators PI 306, PI 345, PI 347, and PI 334.
 - (1d) Record the flow rates of steam flowing from scrubber vessels V-9, V-10, and V-12 as measured by flow elements FE 113, FE 115, and FE 117, respectively. Record the sum of the flow rates measured by flow elements FE 100 and FE 109 as an estimate of the flow rate of steam flowing from scrubber vessel V-8.
 - (1e) Record the level of total dissolved solids in ppm from samples of condensed vapor taken from the following steam lines (flows to scrubber vessels): 10"-SM1-AC, 10"-SM2-AC, 10"-SM8-AC, 10"-SM11-AC, and 12"-SM14-AC.
 - (1f) Record the level of total dissolved solids in ppm from samples of condensed vapor taken from the following steam lines (flows from scrubber vessels): 12"-SM3-AC, 10"-SM9-AC, 10"-SM12-AC, and 12"-SM15-AC.
- Test Number 2: Brine flow rate will be 300,000 lb/hr.
 Δp of flash will be approximately 30 psi.
 - Test Conditions:
 - (2a) Same as 1a
 - (2b) The following flash drum pressures will be maintained.

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	120 psia
V-7	PI 316	90
V-14	PI 344	60
V-11	PI 333	30
V-13	PI 336	11.5

(2c) Same as 1c

(2d) Same as 1d

(2e) Same as 1e

(2f) Same as 1f

— Test Measurements:

Same measurements as in Test Number 1.

- Test Number 3: Brine flow rate will be 300,000 lb/hr. Δp of flash will be approximately 15 psi.

— Test Conditions:

(3a) Same as 1a

(3b) The following flash drum pressure will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	90 psia
V-7	PI 316	75
V-14	PI 344	60
V-11	PI 333	45
V-13	PI 336	11.5

(3c) Same as 1c

(3d) Same as 1d

(3e) Same as 1e

(3f) Same as 1f

— Test Measurements:

Same measurements as in Test Number 1.

- Test Number 4: Brine flow rate will be 400,000 lb/hr. Δp of flash will be approximately 50 psi.

— Test Conditions:

(4a) Flow of brine will be from one well and will be approximately 400,000 lb/hr into either flash drum V-1 or flash drum V-4.

(4b) Same as 1b

(4c) Same as 1c

(4d) Same as 1d

(4e) Same as 1e

(4f) Same as 1f

— Test Measurements:

Same measurements as in Test Number 1.

- Test Number 5: Brine flow rate will be 400,000 lb/hr.
 Δp of flash will be approximately 30 psi.

— Test Conditions:

(5a) Same as 4a

(5b) Same as 2b

(5c) Same as 1c

(5d) Same as 1d

(5e) Same as 1e

(5f) Same as 1f

— Test Measurements:

Same measurements as in Test Number 1.

- Test Number 6: Brine flow rate will be 400,000 lb/hr.
 Δp of flash will be approximately 15 psi.

— Test Conditions:

(6a) Same as 4a

(6b) Same as 3b

(6c) Same as 1c

(6d) Same as 1d

(6e) Same as 1e

(6f) Same as 1f

— Test Measurements:

Same measurements as in Test Number 1.

- Test Number 7: Brine flow rate will be 600,000 lb/hr.
 Δp of flash will be approximately 50 psi.

- Test Conditions:

- (7a) Flow of brine will be from two wells and will be approximately 600,000 lb/hr into flash drums V-1 and V-4

- (7b) Same as 1b

- (7c) Same as 1c

- (7d) Same as 1d

- (7e) Same as 1e

- (7f) Same as 1f

- Test Measurements:

- Same measurements as in Test Number 1.

- Test Number 8: Brine flow rate will be 600,000 lb/hr.
 Δp of flash will be approximately 30 psi.

- Test Conditions:

- (8a) Same as 7a

- (8b) Same as 2b

- (8c) Same as 1c

- (8d) Same as 1d

- (8e) Same as 1e

- (8f) Same as 1f

- Test Measurements:

- Same measurements as in Test Number 1.

- Test Number 9: Brine flow rate will be 600,000 lb/hr.
 Δp of flash will be approximately 15 psi.

- Test Conditions:

- (9a) Same as 7a

- (9b) Same as 3b

- (9c) Same as 1c

- (9d) Same as 1d
- (9e) Same as 1e
- (9f) Same as 1f
- Test Measurements:
Same measurement as in Test Number 1.
- Test Number 10: Brine flow rate will be 800,000 lb/hr.
 Δp of flash will be approximately 50 psi.
 - Test Conditions:
 - (10a) Flow of brine will be from two wells and will be approximately 800,000 lb/hr into flash drums V-1 and V-4.
 - (10b) Same as 1b
 - (10c) Same as 1c
 - (10d) Same as 1d
 - (10e) Same as 1e
 - (10f) Same as 1f
 - Test Measurements:
Same measurements as in Test Number 1.
- Test Number 11: Brine flow rate will be 800,000 lb/hr.
 Δp of flash will be approximately 30 psi.
 - Test Conditions:
 - (11a) Same as 10a
 - (11b) Same as 2b
 - (11c) Same as 1c
 - (11d) Same as 1d
 - (11e) Same as 1e
 - (11f) Same as 1f
 - Test Measurements:
Same measurements as in Test Number 1.

- Test Number 12: Brine flow rate will be 800,000 lb/hr.
 Δp of flash will be approximately 15 psi.

- Test Conditions:

- (12a) Same as 10a

- (12b) Same as 3b

- (12c) Same as 1c

- (12d) Same as 1d

- (12e) Same as 1e

- (12f) Same as 1f

- Test Measurements:

- Same measurements as in Test Number 1.

CALCULATIONS

Pressure drop in the scrubber vessel for each test case can be determined by subtracting the measured pressure in the outlet vapor stream from the pressure in the inlet stream.

Measured pressure and temperature in the outlet vapor stream, together with its known CO_2 content, can be used to obtain the density of vapor from the steam tables. The cross-sectional area of the scrubber column, together with the measured vapor flow rate and density, can be used to calculate the vapor velocity for each test case.

The efficiency of the scrubber can be calculated for each test case by subtracting the concentration of dissolved solids (ppm) in the outlet vapor stream from the concentration in the inlet stream, and dividing the difference by the concentration in the inlet stream.

RESULTS

The purity of scrubbed vapor, as measured by concentration of dissolved solids or by the scrubber efficiency, can be plotted as a function of the purity of the unscrubbed vapor, the vapor velocity in the scrubber column, and the condensate wash flow. In addition, pressure drop can be plotted against these same three variables. The scrubber will be judged to perform best when it attains the best efficiency with the least pressure drop. If the scrubbers perform equally well without condensate wash (the test case with 0 gpm flow), it may be concluded that a knockout drum or demister pads may be less costly alternatives to the use of scrubbers.

Future tests may include the chemical treatment of condensate wash to absorb noncondensable gases such as CO_2 and H_2S . Additional future tests may be set up to measure the performance of either a knockout drum or demister pads, and their respective performances may be compared to that of the scrubbers.

TASK 5

TITLE

Scale prevention

OBJECTIVES

To characterize scales formed from the geothermal brine and to define methods of scale control. To characterize the brine and effluent. To identify suspended solids. To develop treatments for the effluent geothermal brine.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The characterization of brine and any potential scale-forming reactions is mandatory for the successful operation of a commercial geothermal power plant. In addition, the long-term operation of the reinjection wells requires methods of effluent treatment to prevent plugging of the formation.

GENERAL TEST PROCEDURE

The detailed scale prevention program is included in Report No. UCID-17209 of Lawrence Livermore Laboratory, in accordance with the agreement between San Diego Gas and Electric Company and ERDA. See Appendix F.

TASK 6

TITLE

Materials and component evaluation.

OBJECTIVES

To extend the corrosion test results of the Geothermal Loop Experimental Facility at Niland to the flash/binary process. To test materials for corrosion rate under conditions of exposure to geothermal brine and to evaluate test results. To evaluate substitute materials for any components undergoing excessive corrosion in the plant.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

Suitable materials of construction must be selected prior to the design of a commercial geothermal power plant.

GENERAL TEST PROCEDURE

The materials and component evaluation program is included in Report No. UCID-17209 of Lawrence Livermore Laboratory, in accordance with the Agreement between San Diego Gas and Electric Company and ERDA. See Appendix F.

TASK 7

TITLE

Effect of noncondensable gases on the heat transfer coefficient.

OBJECTIVE

To determine the effect of the concentration of noncondensable gases on the heat transfer performance of exchangers E-2 and E-3. To compare and correlate the effect with theoretical predictions.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

To optimize plant performance with respect to capital cost, it is essential to be able to predict the effect of noncondensibles on heat exchanger cost. This will provide a basis for selecting the most economical heat recovery scheme with respect to the amount of steam condensed from the first-stage flash drum.

GENERAL TEST PROCEDURE

In the presence of noncondensable gases, the heat transfer coefficient is a function of the amount of heat transferred as well as flows and physical properties. The outlet temperature from exchanger E-2 will be varied by adjusting the temperature controller on V-6. This

will result in changing the flow from V-1, thus changing the heat load and the concentration of noncondensibles in exchangers E-2 and E-3. Three temperature settings on V-1, of approximately 230, 250, and 270°F, will provide a range of noncondensible concentrations for analysis. The actual settings may have to vary somewhat from the above values after the results of Task 1 and Task 3 are reviewed.

TEST CONDITIONS

Refer to Task 3, E-2 and E-3 test section, for description of required test conditions.

EXPERIMENTAL MEASUREMENTS

Refer to Task 3, E-2 and E-3 test section, for description of required measurements and locations.

EVALUATION OF TEST DATA

Refer to the entire section in Task 3 relating to E-2 and E-3 data evaluation.

COMPARISON AND CORRELATION OF THEORETICAL AND EXPERIMENTAL RESULTS

Comparison of the experimental results with the theoretical predictions of the effect of noncondensibles on heat transfer (as described in Task 3) will provide a means of evaluating the suitability of the theoretical approach for future application as a design method. In the event that a significant difference is observed between measured and predicted results, empirical adjustments to the theoretical model may be required.

TASK 8

TITLE

Continued monitoring of heat transfer coefficients and fouling resistance in multistage heat exchangers.

OBJECTIVE

To determine the extent of deterioration of heat exchanger performance with time as fouling occurs. To determine if the change in fouling resistance is asymptotic with time and to measure the fouling resistance by comparison with the clean tube coefficients determined in Task 3.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

An excessive allowance for fouling in heat exchanger design can result in extremely high capital cost of equipment. Realistic allowances must be made so that operation can continue over a reasonable period of time between shutdowns for cleaning. Knowledge of the fouling resistance, and its variation with time for specific services, allows the exchangers to be designed to operate for acceptable periods of time and at the minimum capital cost.

GENERAL TEST PROCEDURE

The test procedure involved is to repeat the tests specified in Task 3 at intervals during the period of plant operation and testing. For each test, the water side should be adjusted as nearly as possible to the same conditions of temperature, pressure, and flow as in the Task 3 tests. This will result in increasingly higher vapor inlet pressures for E-2, E-3, and E-1A, B, C as the surface area fouls and performance deteriorates. Steam flows and overall heat transfer coefficients will be calculated from test measurements and plotted against onstream time.

TEST CONDITIONS

Refer to Task 3, Test Conditions.

EXPERIMENTAL MEASUREMENTS

Refer to Task 3 section on measurements for description and location of required measurement.

CALCULATION

The measured overall heat transfer coefficients will be calculated in the manner described in Task 3. Since the desired test conditions are at nearly the same flows and heat loads, the variations in individual film and metal heat transfer coefficients may be neglected and the fouling resistance calculated as:

$$\text{foul} = \frac{1}{U_m} - \frac{1}{U_{CT}} \quad (\text{eqn. 1})$$

where: foul = fouling resistance, $\text{hr-ft}^2\text{-}^\circ\text{F/Btu}$
 U_{CT} = clean tube coefficient, $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$
 measured in Task 3
 U_m = measured coefficient, $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$

In the event that similar heat loads cannot be achieved under fouled conditions and the flows are substantially different from Task 3, it will be necessary to calculate the individual heat transfer coefficients and determine the fouling resistance as follows:

$$foul = \frac{1}{U_m} - \left(\frac{1}{h_{io}} + Wall + \frac{1}{h_o} \right) \quad (eqn. 2)$$

where: h_{io} is the tubeside coefficient calculated by Task 3 methods.

h_o is the shellside coefficient calculated by Task 3 methods.

Wall is the tube metal resistance calculated by Task 3 methods.

In the case of E-2 and E-3, since the heat transfer coefficients and temperature differences are calculated over successive intervals of the exchanger, it would be necessary to calculate the overall clean heat transfer coefficient as outlined in Task 3 and use eqn. 1 to calculate the fouling resistance.

However, it is preferable that the constant heat load approach be used.

RESULTS

For each exchanger, the fouling resistance should be plotted as a function of time. If an asymptotic level of fouling is observed, this task may be discontinued at that time.

If fouling resistance continues to increase or to cycle, monitoring throughout the remainder of the plant operating period should be continued.

TASK 9

TITLE

Restoration of clean-tube heat transfer coefficients.

OBJECTIVES

To obtain clean heat transfer surfaces after water runs, before isobutane runs can be established at its baseline operation. To demonstrate the effectiveness of various cleaning procedures for cleaning heat transfer surfaces.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The Niland Test Facility anticipates fouling of the heat transfer surfaces. Methods of periodically restoring high values of HTC are required for economical performance of a commercial binary geothermal power plant. The Niland Test Facility provides an ideally sized plant to demonstrate cleaning techniques and evaluate them from a practical rather than a theoretical viewpoint.

GENERAL TEST PROCEDURES

Various methods are available for cleaning inside and outside tube surfaces. These procedures include mechanical methods like hydro-blasting, chemical cleaning by circulation of inhibited acid, base, or chelating solutions, and vapor-phase onstream cleaning by injecting gases such as CO_2 , SO_2 , or NH_3 while operating.

DETAILED TEST PROCEDURES

A test on water at the baseline test conditions will be accomplished prior to and after cleaning. Thus, the degree of fouling compared to the initial clean tests of Task 3, the restoration as compared to this task, and the effectiveness of various cleaning procedures will be determined.

The severest fouling is expected on the geothermal vapor side of the exchangers with the potential of scaling deposits being present. The waterside fouling should involve mostly corrosion products which should be easily removed. Figure 2-3 shows the probable cleaning techniques.

Cleaning of the tubeside of E-1C will be accomplished by the introduction of suitable gases, as described in Subtask 9E. This will be done after significant scale is observed and prior to the chemical cleaning.

Subtask 9A

Samples of scale from the geothermal vapor flow path will be obtained and analyzed to determine the most appropriate cleaning procedure. This will be done prior to the initiation of the tube cleaning and in time to obtain the required chemicals. Subtasks 9B, C, and D may be modified to incorporate any improved techniques developed.

C — CAUSTIC (TASK 9D)
 H — HYDROBLASTING (TASK 9B)
 A — INHIBITED ACID (TASK 9C)

Figure 2-3. CLEANING PROCEDURES

Subtask 9B

Hydroblasting of the tubeside of exchangers for removal of scale from the inside surface is commercially practiced and vendors can be contacted who will do this.

Subtask 9C

Tubes will be cleaned by filling the exchangers with an inhibited acid solution suitable for removal of metal oxide fouling or scaling from the geothermal vapor.

Subtask 9D

Tubes will be cleaned by filling the exchangers with a caustic solution for removal of silica scale. Caution will be exercised to prevent damage to the carbon steel vessels. This technique is discussed in "Test and Evaluation of a Geothermal Heat Exchanger" for EPRI, which was prepared by San Diego Gas and Electric Company.

Subtask 9E

Vapor-phase cleaning of the inside tube surfaces will be performed by injecting gases such as carbon dioxide, sulfur dioxide, and ammonia while operating. These gases will be injected into the vapor inlet of E-1C. Use of a sulfur dioxide at a concentration of 0.1 to 1 percent has been reported by L. Bromley, et. al., to clean the surface of tubes during operation (AIChE Journal, March, 1968). Carbon dioxide and ammonia will also be tested. It is possible that the carbon dioxide concentration in the condenser vent stream will be sufficient for cleaning.

In all of the above described procedures, the heat transfer coefficient will be measured before and after the cleaning procedure (and during cleaning if applicable) by the procedure described in Task 3. This task is a continuing one, closely allied with Task 8, the charting of long-term trends of the heat transfer coefficient.

TEST CONDITIONS

The complete heat and material balance data will be taken at the same standard conditions as outlined in Tasks 3 and 8. Procedures for the actual cleaning will be developed as a definite schedule is set for the various subtasks.

EXPERIMENTAL MEASUREMENTS

Experimental measurements will be the same as in Task 3. In addition, certain analytical tests will be required during the actual cleaning procedure to monitor the depletion of cleaning agent, the pickup of fouling intended to be removed, and the progress of possible corrosion reactions. Detailed procedures will be developed as schedules are set.

RESULTS

The degree of restoration of the heat transfer coefficient will be determined by comparison with the results of Tasks 3 and 8.

For purposes of evaluation, exchanger E-5 will not be cleaned. By evaluating the degree of improvement between exchangers E-1A, E-1B, and E-1 C, the effectiveness of the three different techniques can be determined. Comparison of the results

of E-2 and E-3 will show the difference between using caustic and inhibited acid for shellside cleaning.

The results will be used to recommend a procedure for future cleaning of the plant.

TASK 10

TITLE

Operational stability of the flash/binary process during isobutane runs.

OBJECTIVES

To establish methods of controlling the flash process independently of the heat exchange process, and vice-versa, while the system is charged with isobutane. To evaluate the stability of plant operation when operating in the baseline mode with isobutane as the working fluid. To develop plant startup and shutdown procedures for the isobutane case.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

To test the flashing process, it is imperative that flash pressures be adjusted by methods of control that are compatible with stable plant operation. Similarly, it is desirable to adjust fluid temperature when the heat exchangers are tested. Verification of proposed control methods should be obtained as soon as the system is charged with isobutane and before any of the other isobutane tests are run.

GENERAL TEST PROCEDURES

The same methods of control that were established in Task 1 for controlling the flash process will be used for the isobutane baseline test run. Flow of brine into the pilot plant will be from two wells and will

be approximately 800,000 lb/hr. Pressure upstream of the main bypass valve will be controlled to about 500 psia, which is slightly below the critical point. Then three more cases will be run, with pressure controlled to 550 psia (supercritical case), 525 psia (critical case), and 450 psia (subcritical case), respectively. Finally, an additional subcritical case will be run with brine and isobutane flow rates reduced to about 60 percent of the baseline flow rates. For all five test runs, measurements of pressure and temperature will be taken at key points in the isobutane system at hourly intervals.

DESCRIPTION OF TEST PROCEDURES

This test attempts to establish methods of plant control that can be used to obtain stable plant operation during the isobutane test runs.

- Test Number 1: Baseline Operating Conditions

- Test Conditions:

- (1a) Flow of brine will be from two wells and will be approximately 800,000 lb/hr into flash drums V-1 and V-4.

- (1b) The following flash drum pressure will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 and V-4	PI 304 and PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

(1c) Use valve PV-303 to control pressure upstream of valve to 500 psia as indicated by PI-313.

(1d) The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

(1e) Isobutane flow rate, as measured by flow element FE-104, will be controlled by valve FV-104W to about 3,827 gpm.

(1f) Cooling water flow rate as measured in line 24" - WC1-L by water meter will be controlled to 9,250,000 lb/hr by condenser outlet butterfly valves.

— Test Measurements:

The test duration will be 24 hours. The time interval for measurements will be one hour initially. The frequency of measurement will be adjusted, as necessary, to obtain good data during the course of the tests.

(1a) Record pressure upstream of the main bypass valve as measured by PI-313.

(1b) Record the temperature of the isobutane vapor at the outlet of E-3. No temperature indicator is there presently.

- (1c) Record pressure in vessel V-2 as measured by pressure indicator PI-319.
- (1d) Record temperature of isobutane condensate on recorder TR-500-9 as measured by temperature element TE-500-9.
- (1e) Record pressure at the discharge of the main circulation pump as measured by pressure indicator PI-321.
- (1f) Record temperature of isobutane between heat exchangers E-2 and E-3 as measured by temperature indicator TI-504.
- Test Number 2: Supercritical Throttle Conditions
 - Test Conditions:
 - (2a) Same as 1a
 - (2b) Same as 1b
 - (2c) Use valve PV-303 to control pressure upstream of valve to 550 psia as indicated by PI-313
 - (2d) Same as 1d
 - (2e) Same as 1e
 - (2f) Same as 1f
 - Test Measurements:
 - (2a) Same as 1a
 - (2b) Same as 1b
 - (2c) Same as 1c
 - (2d) Same as 1d
 - (2e) Same as 1e
 - (2f) Same as 1f
- Test Number 3: Critical Throttle Conditions
 - Test Conditions:
 - (3a) Same as 1a
 - (3b) Same as 1b
 - (3c) Use valve PV-303 to control pressure upstream of valve to 525 psia as indicated by PI-313
 - (3d) Same as 1d
 - (3e) Same as 1e
 - (3f) Same as 1f

- Test Measurements:
 - (3a) Same as 1a
 - (3b) Same as 1b
 - (3c) Same as 1c
 - (3d) Same as 1d
 - (3e) Same as 1e
 - (3f) Same as 1f
- Test Number 4: Subcritical Throttle Conditions
 - Test Conditions:
 - (4a) Same as 1a
 - (4b) Same as 1b
 - (4c) Use valve PV-303 to control pressure upstream of valve to 450 psia as indicated by PI-313.
 - (4d) Same as 1d
 - (4e) Same as 1e
 - (4f) Same as 1f
 - Test Measurements:
 - (4a) Same as 1a
 - (4b) Same as 1b
 - (4c) Same as 1c
 - (4d) Same as 1d
 - (4e) Same as 1e
 - (4f) Same as 1f
- Test Number 5: Subcritical Throttle Conditions with Reduced Brine and Isobutane Flow Rates
 - Test Conditions:
 - (5a) Flow of brine will be from two wells and will be approximately 480,000 lb/hr into flash drums V-1 and V-4 (240,000 lb/hr into each flash drum).

(5b) Same as 1b

(5c) Same as 4c

(5d) Same as 1d

(5e) Isobutane flow rate, as measured by flow element FE-104, will be controlled by valve FV-104W to about 2,296 gpm.

(5f) Same as 1f

— Test Measurements:

(5a) Same as 1a

(5b) Same as 1b

(5c) Same as 1c

(5d) Same as 1d

(5e) Same as 1e

(5f) Same as 1f

RESULTS

Temperature and pressure data taken during the five tests will be plotted as a function of time so that the stability of plant operation can be evaluated. At the completion of this task, startup and shutdown procedures for the remaining isobutane test runs can be recommended.

TASK 11

TITLE

Overall heat and mass balance baseline for isobutane runs.

OBJECTIVES

To establish the overall heat and mass balance of the plant from pilot plant measurements while operating the pilot plant in the baseline mode with isobutane as the working fluid.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The baseline mode for stable plant operation is predicted analytically by calculations of the plant's heat and mass balance. These calculations must be confirmed by measurements of actual conditions during operation of the plant with isobutane as the working fluid.

TEST CONDITIONS

- Flow of brine will be from two wells and will be approximately 800,000 lb/hr into flash drums V-1 and V-4. The following flash drum pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 and V-4	PI 304 and PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

- Use valve PV 303 to control pressure upstream of valve to 500 psia as indicated by PI 313.
- The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

- Isobutane flow rate, as measured by flow element FE 104, will be controlled by valve FV 104W to about 3,827 gpm.
- Cooling water flow rate as measured in line 24"-WC1-L by water meter will be controlled to 9,250,000 lb/hr by condenser outlet butterfly valves.

EXPERIMENTAL MEASURES

Measurements on streams that flow into and from the plant will be identical to those of Task 2. In addition to measurements on incoming and outgoing streams, the design brake horsepower for each of the following pumps will be included in the heat balance.

<u>Pump</u>	<u>Designation</u>	<u>Design Brake Horsepower</u>	<u>Symbol for Power Input</u>
P-1	Isobutane Circulation	1,465	p1
P-2	Brine Reinjection	626	p2
P-8	Isobutane Booster	36	p3
P-9	Condensate Pump	10	p4
P-10	Fourth-stage Condensate Pump	10	p5
P-7	Instrument Purge Water Pump	21	p6

CALCULATIONS

Balance of Mass Flow Rates

The total mass flow rate into the plant should equal the total flow rate out of the plant (with allowances for small leakages) within an acceptable level of accuracy;

$$W_{in} = W_{out}$$

$$W_1 + W_2 + W_3 + W_4 + W_5 = W_6 + W_7 + W_8 + W_9 + W_{10} + W_{11} + W_{12}$$

HEAT BALANCE

The heat flow into the plant, plus the mechanical power provided by all the pumps, must equal the heat flow out of the plant. Pump power, which is small when water is used as the binary fluid, was neglected in Task 2. However, pump power is included here because considerably more power is required to circulate isobutane. The heat balance will

include an allowance for unmeasured heat losses. However, the discrepancy between measured and predicted heat balances should not exceed 10 percent. The basic relationship is:

$$Q_{in} + P_{in} = Q_{out}$$

or in expanded form,

$$q_1 + q_2 + q_3 + q_4 + q_5 + p_1 + p_2 + p_3 + p_4 + p_5 + p_6 = q_6 + q_7 + q_8 + q_9 + q_{10} \\ + q_{11} + q_{12}$$

All heat flow rates are calculated by the methods described in Task 2. Pump power inputs in brake horsepower are converted to units of Btu/hr before they are used in the heat balance operation.

RESULTS

The importance result of this task will be an overall heat and mass balance for the plant based on pilot plant measurements during iso-butane baseline operation.

TASK 12

TITLE

Condenser performance with isobutane as the binary fluid.

OBJECTIVES

To determine the overall heat transfer coefficient and the isobutane condensing coefficient on exchangers E-4A and 4B. To measure the shellside and tubeside pressure drop. To compare the measured heat transfer and pressure drop results with the theoretical predictions.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The isobutane condenser represents a large capital investment. To minimize capital cost and assure adequate performance, reliable methods for prediction of heat transfer and pressure drop must be available. This task provides the basis for comparing the predictive methods with experimental results.

GENERAL TEST PROCEDURE

The overall heat transfer coefficient for clean-tube conditions will be determined from a heat and mass balance around the condenser and measurement of operating conditions. Pressure differentials across

the condenser will be measured and recorded. This task will consist of four tests: two isobutane flows, each with two levels of superheat.

DESCRIPTION OF TEST PROCEDURES

- Test Number 1: Baseline Operating Conditions
 - Test Conditions:

Flow of brine will be from two wells and will be approximately 1,000,000 lb/hr. Approximately 110°F of superheat will be present at the inlet of the condenser. Cooling water flows and the turbine bypass valve will be adjusted so that no flooding of the condenser occurs.
- Test Number 2: Reduced Brine Input at Baseline Isobutane Flow
 - Test Conditions:

Flow of brine will be reduced to approximately 600,000 lb/hr to reduce the amount of superheat at the condenser inlet to about 20-40°F. The flow of isobutane will be held at approximately 1,000,000 lb/hr. Cooling water flows and the turbine bypass valves will be adjusted to eliminate condenser flooding.
- Test Number 3: Reduced Isobutane Flow and Brine Input
 - Test Conditions:

Flow of isobutane will be at approximately 667,000 lb/hr and the brine input will be approximately 534,000 lb/hr. The level of superheat at the condenser inlet will be about 110°F. Cooling water flows and turbine bypass valves will be adjusted to eliminate condenser flooding.

- Test Number 4: Reduced Brine Input at 667,000 lb/hr Isobutane Flow

— Test Conditions:

Flow of isobutane will be at approximately 667,000 lb/hr and the brine input will be approximately 400,000 lb/hr. The level of superheat at the condenser inlet will be about 20-40°F. Cooling water flows and turbine bypass valves will be adjusted to eliminate condenser flooding.

EXPERIMENTAL MEASUREMENTS

For each of the above tests, the following measurements will be taken. The numbers refer to the Table of Measurement Locations in Task 3 under Experimental Measurements.

1, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24

EVALUATION OF TEST DATA

The following procedure will be used to evaluate the data from each of the four tests:

Heat Balance

Water side:

$$Q_w = W_w C_w (T_{out} - T_{in})$$

Isobutane side:

$$Q_i = W_i (h_1 - h_2)$$

Exchanger duty:

$$Q_e = (Q_w + Q_i)/2$$

where:

- Q_w = Heat load calculated from water side, Btu/hr
- Q_i = Heat load calculated from isobutane side, Btu/hr
- Q_e = Average of Q_w and Q_i , Btu/hr
- W_w = Cooling water flow rate, lb/hr
- W_i = Isobutane flow rate, lb/hr
- C_w = Cooling water specific heat, Btu/lb - °F
- h_1 = Enthalpy of isobutane at condenser inlet, Btu/lb
- h_2 = Enthalpy of isobutane at condenser outlet, Btu/lb

Mean Temperature Difference

Calculation of the mean temperature difference for the condensation of a superheated vapor is a subject requiring considerable analysis. A general discussion of this problem is included in Appendix E. Based upon the conclusions presented in Appendix E, the following procedure will be used for the evaluation of test data.

The mean temperature difference will be defined as:

$$\Delta T_m = \frac{(T_{s1} - t_2) - (T_{s2} - t_1)}{\log_e \left(\frac{T_{s1} - t_2}{T_{s2} - t_1} \right)}$$

where:

- T_{s1} = Isobutane saturation temperature at the condenser inlet pressure, °F
- T_{s2} = Isobutane saturation temperature at the condenser outlet pressure, °F
- t_1 = Cooling water inlet temp, °F
- t_2 = Cooling water outlet temp, °F

This definition will be used for evaluation of data from all four tests regardless of the level of superheat.

Overall Clean Tube HTC

For each of the four tests, the overall heat transfer coefficient will be calculated as:

$$U_{ct} = \frac{Q_e}{A_e \Delta T_m} = \frac{Q_e}{47,036 \Delta T_m}$$

where:

$$\begin{aligned} A_e &= \text{Effective surface area of condensers, ft}^2 \\ U_{ct} &= \text{Overall clean tube heat transfer coefficient,} \\ &\quad \text{Btu/hr-ft}^2 \text{ - } ^\circ\text{F} \\ \Delta T_m &= \text{Mean Temp difference, } ^\circ\text{F} \\ Q_e &= \text{Exchanger heat load, Btu/hr} \end{aligned}$$

It is expected that the overall HTC as calculated for tests 1 and 3 will be greater than those for 2 and 4. This is due to the effect of the large amount of superheat (refer to Appendix E discussion). If this is the case, the condensation coefficient of the isobutane side may not be calculated directly and would involve analysis of the tube wall temperatures to determine the point at which condensation occurs.

For tests 2 and 4, the isobutane condensation coefficient may be calculated as:

$$\frac{1}{h_o} = \frac{1}{U_{ct}} - \left(\frac{1}{h_{io}} + \text{wall} + \text{foul} \right)$$

where:

h_o = Isobutane condensation coefficient, $\frac{\text{Btu}}{\text{hr ft}^2 \text{-}^\circ\text{F}}$

h_{io} = Cooling water heat transfer coefficient, $\frac{\text{Btu}}{\text{hr ft}^2 \text{-}^\circ\text{F}}$

wall = Tube wall metal resistance, $\frac{\text{hr ft}^2 \text{-}^\circ\text{F}}{\text{Btu}}$

(1) f_{foul} = Fouling resistance, $\frac{\text{hr ft}^2 \text{-}^\circ\text{F}}{\text{Btu}}$

COMPARISON WITH ANALYTICAL PROCEDURE

The measured heat transfer coefficients and pressure drop as determined from the four tests will be compared with the calculated results using the methods of Gloyer (Reference 6).

(1) Fouling resistance is intended to be zero for the clean tube case. However, it is possible that complete restoration of clean tube performance is not achievable.

TASK 13

TITLE

Heat transfer and pressure drop performance of isobutane in and around the critical region.

OBJECTIVES

To obtain heat transfer coefficients, pressure drop data, and behavioral information of isobutane in the critical and near-critical region in exchangers E-2 and E-3. To measure shellside and tube-side pressure drops. To compare and correlate experimental results with predictive models.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

To minimize the capital cost of the first-stage flash heat exchangers and to also achieve adequate performance, a reliable method of heat transfer and pressure drop prediction must be available. From the standpoint of available data and reliable design procedures, this is the most critical heat exchanger service in the multistage flash train. Virtually no reliable information on heat transfer or physical properties are available at or near the critical point.

GENERAL TEST PROCEDURE

The overall heat transfer coefficient for clean-tube conditions will be determined from a heat and mass balance around the exchangers E-2 and E-3 and measurement of operating conditions. The procedure will be as outlined in Task 3.

Pressure differentials across the shellside and tubeside of each exchanger will be measured and recorded.

This task will consist of eight basic tests: two isobutane flows, each flow at four different pressure levels.

DESCRIPTION OF TEST PROCEDURES

In each of the tests, it will be attempted to limit exchanger E-2 to subcritical conditions.

- Test Number 1: High Isobutane Flow at Supercritical Pressure

- Test Conditions:

Isobutane flow will be set at 1,000,000 lb/hr with a pressure of approximately 550 psia upstream of PV 303. Brine flow will be adjusted to approximately 800,000 lb/hr. The butterfly valve at the inlet to E-3 will be adjusted to obtain at least the following two operating points: the maximum E-3 isobutane outlet temperature while maintaining the E-2 isobutane outlet temperature below 275°F; and an E-3 isobutane outlet temperature of approximately 280°F. Measurements will be taken and recorded for each operating point.

- Test Number 2: High Isobutane Flow at Near Critical Pressure
 - Test Conditions:

Isobutane flow and brine will be set at the values in Test 1 above. The pressure upstream of PV 303 will be adjusted to approximately 525psia. The butterfly valve at the inlet to E-3 will be adjusted to obtain two operating points as described in Test 1. Measurements will be taken and recorded for each point.
- Test Number 3: High Isobutane Flow at Baseline Pressure
 - Test Conditions:

Isobutane flow and brine flow will be set at the values in Test 1. The pressure upstream of PV 303 will be adjusted to approximately 500 psia. The butterfly valve at the inlet to E-3 will be adjusted to obtain two operating points as described in Test 1. Measurements will be taken and recorded for each point.
- Test Number 4: High Isobutane Flow at Subcritical Pressure
 - Test Conditions:

Isobutane flow and brine will be set at the values in Test 1. The pressure upstream of PV 303 will be adjusted to approximately 450 psia. The butterfly valve at the inlet to E-3 will be adjusted to obtain two operating points as described in Test 1. Measurements will be taken and recorded for each point.

- Test Number 5: Reduced Isobutane Flow at Supercritical Pressure
 - Test Conditions:

The flows of isobutane will be reduced to about 60 percent of the flows for Test 1. All other test conditions are the same as for Test 1.
- Test Number 6: Reduced Isobutane Flow at Near Critical Pressure
 - Test Conditions:

The flows of isobutane and brine will be the same as for Test 5. All other test conditions will be the same as for Test 2.
- Test Number 7: Reduced Isobutane Flow at Baseline Pressure
 - Test Conditions:

The flows of isobutane and brine will be the same as in Test 5. All other conditions will be the same as for Test 3.
- Test Number 8: Reduced Isobutane Flow at Subcritical Pressure
 - Test Conditions:

The flows of isobutane and brine will be the same as in Test 5. All other conditions will be the same as for Test 4.

EXPERIMENTAL MEASUREMENTS

For test measurements refer to Task 3, Experimental Measurements, Subtask C. Note that the circulating water measurements now refer to isobutane.

EVALUATION OF TEST DATA

Heat Balance

The heat balance on the steam side is determined as shown in Task 3, Evaluation of Data, Subtask C. The heat balance for the isobutane side is given by:

Total heat load for exchangers E-2 and E-3, Q_{23} :

$$Q_{23} = W_i (h_{i3} - h_{i2})$$

Heat load for exchanger E-2, Q_2 :

$$Q_2 = W_i (h_{i23} - h_{i2})$$

Heat load for exchanger E-3, Q_3 :

$$Q_3 = W_i (h_{i3} - h_{i23})$$

where:

W_i = isobutane flow rate, lb/hr

h_i = isobutane enthalpy, Btu/lb

All other variables are as defined in Task 3, Evaluation of Data, Subtask C.

Mean Temperature Difference

The mean temperature difference for each test will be calculated as described in Task 3, Evaluation of Data, Subtask C, except that the isobutane heat release curve must be calculated in place of the water side.

Overall Heat Transfer Coefficient, HTC

The overall heat transfer coefficient will be calculated as described in Task 3, Evaluation of Data, Subtask C.

COMPARISON WITH ANALYTICAL PROCEDURE

The calculational procedure for heat transfer performance for the steam/CO₂ side will be the same as described in Task 3, Subtask C. For the isobutane side, the local heat transfer coefficient for critical and supercritical region will be calculated by the Swenson correlation (Reference 7.)

$$h_{io} = .00459 \left(\frac{12k_w}{d_o} \right) \left(\frac{124Gd_i}{\mu_w} \right)^{.923} \left[2.42 \left(\frac{h_{iw} - h_{ib}}{T_w - T_b} \right) \frac{\mu_w}{k_w} \right]^{.613} \left(\frac{\rho_w}{\rho_b} \right)^{.231}$$

where:

G = mass velocity, lb/sec. ft²

d_i, d_o = inside and outside tube diameters, in.

μ = fluid viscosity, cP

k = fluid thermal conductivity, Btu/hr-ft. - °F

h_{io} = heat transfer coefficient, Btu/hr-ft² - °F

h_i = fluid enthalpy, Btu/lb

ρ = fluid density, lb/ft³

T = fluid temperature, °F

Subscripts b and w refer to bulk and wall temperatures respectively.

For the subcritical region, the equations in Task 3, Subtask C, for heating and vaporizing will be used.

The measured isobutane pressure drops will be compared to the predicted values from the equations in Appendix D and the following definitions. For subcritical pressures in the two-phase boiling region, use:

$$\rho = \frac{1}{\frac{X}{\rho_v} + \frac{1-X}{\rho_l}}$$

where:

μ = liquid viscosity, cP

X = vapor quality

ρ_v, ρ_l = vapor and liquid densities, lb/ft³

For all other conditions, the equations and definitions as presented will be used.

The measured pressure drops for the steam/CO₂ side will be compared to the values calculated from the equations in Appendix D with the following definitions:

$$\rho = \frac{1}{\frac{X}{\rho_v} + \frac{1-X}{\rho_l}}$$

where

μ = liquid viscosity, cP

X = vapor quality

ρ_v, ρ_l = vapor and liquid densities, lb/ft³

TASK 14

TITLE

Performance of liquid isobutane exchangers, E-1A, B, C, and E-5.

OBJECTIVES

To determine the overall heat transfer coefficients and the isobutane liquid heat transfer coefficients. To measure the shellside and tubeside pressure drops. To compare the measured heat transfer and pressure drop results with theoretical predictions.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

To minimize the capital cost of the heat exchanger train while ensuring adequate performance, reliable methods of heat exchanger design must be available. For most heat transfer mechanisms, the heat transfer coefficient is a function of the allowable pressure drop. Good pressure drop and heat transfer correlations are required to optimize a heat exchanger with respect to capital versus operating cost. This task provides the basis for comparing predictive methods for heat transfer and pressure drop with experimental results.

GENERAL TEST PROCEDURES

The overall heat transfer coefficients for clean-tube conditions will be determined from a heat and mass balance around the exchangers

and measurements of operating conditions. Pressure differentials across the shellside and tubeside of each exchanger will be measured and recorded.

TEST CONDITIONS

Exchangers E-1A, E-1B, and E-1C will operate with forced circulation isobutane on the shellside and steam condensing in the tubes. The valves must be adjusted in such a manner that flooding of the exchangers does not occur.

Exchanger E-5 will operate with forced circulation isobutane in the tubes and forced circulation condensate in the shell.

EXPERIMENTAL MEASUREMENTS

The measurements and locations are the same as those defined in Task 3 under Experimental Measurements for Subtasks A and B. (Note that in the table of measurement locations in Task 3, the circulating water measurements now refer to isobutane.)

EVALUATION OF TEST DATA

The overall clean-tube heat transfer coefficients, U_{ct} , will be calculated using the procedure defined in Task 3 under Evaluation of Test Data for Subtasks A and B. (Note that all references to water now refer to isobutane.)

The heat transfer coefficients for the isobutane side will be calculated as:

$$\frac{1}{h_o} = \frac{1}{U_{ct}} - \left(\frac{1}{h_{io}} + \text{wall} + \text{foul} \right), \text{ for E-1A, 1B, 1C}$$
$$\frac{1}{h_{io}} = \frac{1}{U_{ct}} - \left(\frac{1}{h_o} + \text{wall} + \text{foul} \right), \text{ for E-5}$$

where the variables are defined in Task 3 under Comparison With Analytical Procedure for Subtasks A and B.

COMPARISON WITH ANALYTICAL PROCEDURE

The isobutane heat transfer coefficients calculated from the preceding paragraphs will be compared with values as calculated with the equations in Task 3 under Comparison with Analytical Procedure for Subtasks A and B.

The measured pressure drops will be compared to the values calculated from the appropriate equations in Appendix D.

TASK 15

TITLE

Determination of nonequilibrium and boiling point elevation.

OBJECTIVE

To measure the nonequilibrium allowance (the approach to equilibrium) and boiling point elevation.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The submergence loss, as it is generally called, and boiling point elevation are irreversible losses in the flashing brine and decrease the mean temperature difference for heat transfer. These losses should be known at various process conditions of throughputs, flashdown, level, and temperature to derate the LMTD and accordingly provide extra heat transfer area in a flash or flash binary process.

There are various correlations available for nonequilibrium, but each involves a factor for the flash geometry and may not be applicable to the design of the prototype plant.

GENERAL TEST PROCEDURE

The plant will be stabilized at the test conditions and the stage brine and vapor temperature in the flash drum and stage condenser will be scanned.

DESCRIPTION OF TEST PROCEDURE

- Test Number 1:

- Test Conditions:

Brine flow will be about 800,000 lb/hr. Liquid levels and pressures in the flash drums will be set at the following values:

<u>Vessel</u>	<u>Level</u> <u>(from bottom of vessel)</u>	<u>Pressure</u>
V-1	42 inches	165 psia
V-4	24	165
V-7	35	60
V-14	24	28.3
V-11	45	13.3

- Test Measurements:

For each of the above vessels the following measurements are required:

Vapor flow

Vapor temperature and pressure

Brine temperature

Stage flashdown

Condensate temperature (as applicable)

- Test Number 2

- Test Conditions:

The flash drum pressures will be adjusted to the following values:

<u>Vessel</u>	<u>Pressure</u>
V-1	120 psia
V-4	120
V-7	90
V-14	65
V-11	45

All other conditions are the same as Test 1.

- Test Measurements:

Same as Test 1.

• Test Number 3:

- Test Conditions:

The flash drum liquid levels will be adjusted as follows:

<u>Vessel</u>	<u>Liquid Level (from bottom of vessel)</u>
V-1	30 inches
V-4	12
V-7	23
V-14	12
V-11	33

All other conditions will be the same as Test 1.

- Test Measurements:

Same as Test 1.

• Test Number 4:

- Test Conditions:

Brine flow will be about 800,000 lb/hr. Liquid levels will be set at values of Test 3. The flash drum pressures will be set at values of Test 2.

- Test Measurements:

Same as Test 1.

• Test Numbers 5 through 8: Repeat Tests 1 through 4 with a brine flow of 400,000 lb/hr.

• Test Number 9:

- Test Measurements:

The BPE will be measured in flash drum V-11 with a Cottrell Apparatus or other atmospheric device. The BPE for other temperatures will be extrapolated based on a comparison with the OSW curve in Appendix B.

Calculations Procedure

The nonequilibrium allowance Δ_b^1 is defined as $\Delta_b^1 = T_b - (T_S + \text{BPE})$ where T_b is the bulk brine temperature leaving the stage ($^{\circ}\text{F}$), T_S is the saturated water vapor temperature at the stage pressure ($^{\circ}\text{F}$), BPE is the boiling point elevation ($^{\circ}\text{F}$) due to TDS in the brine, (vapor superheat).

For vessels V-7, V-14, and V-11, T_S must be determined from the measured vapor pressure. The nonequilibrium allowance, Δ_b^1 , may then be calculated for each of the test conditions from the measured data. Vessels V-1 and V-4 will only be analyzed on the basis of overall measured temperature differences.

RESULTS

The effect of flow variation, flashdown, and liquid level on nonequilibrium for the various test conditions may be observed by comparison of the calculated Δ_b^1 values. The BPE as function of brine temperature and concentration and the overall temperature loss will be established.

TASK 16

TITLE

Comparison of flashing devices and mist eliminators.

OBJECTIVES

To determine the alternatives to the presently installed flashing impingement baffles for reducing entrainment of brine in the vapor and for increasing operational stability. To determine if mesh separators or hook-and-vane separators can eliminate the need for scrubbers. To verify the pressure drop and efficiency of separators.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

The flashing devices now installed in the pilot plant inherently produce a high level of brine atomization and increased entrainment in vapor. The potential problem of two-phase flow in inlet brine piping can be a source of instability of the flash process.

The use of a mist eliminator refluxed with condensate can provide an alternative means for vapor purification in a flash or binary geothermal power plant.

GENERAL TEST PROCEDURES

This task will involve three basic steps of vessel modification. These are:

- Install an orifice in the end of the existing pipe discharging into the vessel.
- Redirect the discharge end of the pipe with the orifice to discharge toward the liquid and at a level near the vapor liquid interface.
- Size and install mesh separator pads in the flash drums. (Hook and vane separators will not be considered at this time.)

TEST CONDITIONS

The tests to be performed and the test conditions for each of the above modifications will be the same as the tests in Task 4. Emphasis, however, will be on the vapor purity at the outlet of the flash drums and the relative stability of the multistage flash with the installed orifices.

TEST MEASUREMENTS

Test measurements will be the same as those described in Task 4 with the addition of a measurement of TDS from a sample of condensed vapor from the vessel downstream of the mesh separator.

RESULTS

Comparison of the vapor purity measured in this task with the results of Task 4 will show the relative effectiveness of the various flashing devices and mesh separators. Recommendations as to the future need for scrubbers may be made at this time.

Additionally, the effect of the flashing devices on stability of the multi-stage flash process by reducing two-phase flow in the lines may be evaluated.

TASK 17

TITLE

Analysis of turndown capability of the flash process.

OBJECTIVE

Determine minimum stable plant operating rate, and pinpoint the specific plant hardware design items that are responsible for these limitations.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

Turndown, or minimum stable plant operating rate, are of importance in the design of geothermal power plants. The variation in power demand of a utility system may require adjusting plant rates downward during low-demand periods. It is usually more desirable to operate at low throughputs than to shut down the plant and restart operation later. The maximum turndown capability of a geothermal power plant will probably be limited by instabilities in the flashing process and not be the inability of the turbine to operate at low flow rates. Discussions held with turbine manufacturers indicate that there is no limitation on turbine operation and control for inlet flow reductions down to 10 percent or less. Wide fluctuations in fluid temperature at the inlet to the turbine may or may not be a problem for the turbine, depending upon the extent of metal expansion and upon the designed internal clearances.

GENERAL TEST PROCEDURES

Taken together, the nine test cases will simulate a turndown schedule for a commercial power plant. The flow rate of brine into the plant will be reduced by steps of 20 percent. After each 20-percent reduction, measurements of temperature and pressure will be taken at key points in the isobutane and steam systems. Before making the next reduction in brine flow rate, a corresponding 20-percent reduction in isobutane flow rate will be made to avoid the occurrence of two-phase flow ahead of the main bypass valve. A new set of measurements will then be taken. For the 80-percent test case, an attempt will be made to obtain the flash drum pressures specified for the baseline case by throttling with the butterfly valves in the steam lines ahead of the heat exchangers. For each test case, measurements will be taken at hourly intervals for the duration of a 24-hour period.

DESCRIPTION OF TEST PROCEDURE

- Test Number 1: 80 percent of baseline brine flow rate and 100 percent of baseline isobutane flow rate
 - Test Conditions:
 - (1a) Flow of brine will be from two wells and will be approximately 640,000 lb/hr into flash drums V-1 and V-4 (320,000 lb/hr into each flash drum).
 - (1b) The butterfly valves in the steam lines ahead of the heat exchangers will be set in the wide-open position.
 - (1c) Use valve PV-303 to control pressure upstream of valve to 500 psia as indicated by PI 313.

- (1d) The level controls on the vessels will be set as follows:

<u>Vessel</u>	<u>Setting (from bottom of vessel)</u>
V-1	42 inches
V-4	24
V-7	35
V-14	24
V-11	45
V-12	40
V-13	24

- (1e) Isobutane flow rate, as measured by flow element FE 104, will be controlled by valve FV-104W to about 3,827 gpm.
- (1f) Cooling water flow rate, as measured in line 24"-WC1-L by the water meter, will be controlled to 4,625,000 lb/hr by the condenser outlet butterfly valves.

— Test Measurements:

The test duration will be 24 hours and the time interval for measurement will be adjusted, as necessary, for the taking of good data during the course of the tests.

- (1a) Record the temperature of the isobutane vapor at the outlet of E-3. No temperature indicator is there presently.
- (1b) Record pressure in vessel V-2 as measured by pressure indicator PI 319.
- (1c) Record temperature of isobutane condensate on recorder TR-500-9 as measured by temperature element TE-500-9.
- (1d) Record pressure at the discharge of the main recirculation pump as measured by pressure indicator PI 321.

(1e) Record the pressure in flash drums V-1, V-4, V-7, V-14, V-11, and V-13 as measured by pressure indicators PI 304, PI 310, PI 316, PI 344, PI 333, and PI 336, respectively.

- Test Number 2: 80 percent of baseline brine flow rate and 80 percent of baseline isobutane flow rate

- Test Conditions:

(2a) Same as 1a

(2b) Same as 1b

(2c) Same as 1c

(2d) Same as 1d

(2e) Isobutane flow rate, as measured by flow element FE 104, will be controlled by valve FV-104W to about 3,062 gpm

(2f) Same as 1f

- Test Measurements:

(2a) Same as 1a

(2b) Same as 1b

(2c) Same as 1c

(2d) Same as 1d

(2e) Same as 1e

- Test Number 3: Control of flash pressures

- Test Conditions:

For 80 percent of the baseline brine flow rate and 80 percent of the baseline isobutane flow rate, attempt to restore the baseline flow pressures by adjusting the butterfly valves ahead of the heat exchangers as demonstrated in Task 1. All test conditions for Test Number 2 except condition 2b will apply for this test, and, in addition, the following flash pressures will be maintained:

<u>Flash Drum</u>	<u>Pressure Indicator</u>	<u>Pressure</u>
V-1 or V-4	PI 304 or PI 310	165 psia
V-7	PI 316	60
V-14	PI 344	28.3
V-11	PI 333	13.3
V-13	PI 336	11.5

— Test Measurements:

- (3a) Same as 1a
- (3b) Same as 1b
- (3c) Same as 1c
- (3d) Same as 1d
- (3e) Same as 1e

- Test Number 4: 60 percent of baseline brine flow rate and 80 percent of baseline isobutane flow rate

— Test Conditions:

- (4a) Flow of brine will be from two wells and will be approximately 480,000 lb/hr into flash drums V-1 and V-4 (240,000 lb/hr into each flash drum).
- (4b) Same as 1b
- (4c) Same as 1c
- (4d) Same as 1d
- (4e) Same as 1e
- (4f) Same as 1f

— Test Measurements:

- (4a) Same as 1a
- (4b) Same as 1b
- (4c) Same as 1c
- (4d) Same as 1d
- (4e) Same as 1e

- Test Number 5: 60 percent of baseline brine flow rate and 60 percent of baseline isobutane flow rate

- Test Conditions:

- (5a) Same as 4a
 - (5b) Same as 1b
 - (5c) Same as 1c
 - (5d) Same as 1d
 - (5e) Isobutane flow rate, as measured by flow element FE 104, will be controlled by valve FV-104W to about 2,296 gpm.

- Test Measurements:

- (5a) Same as 1a
 - (5b) Same as 1b
 - (5c) Same as 1c
 - (5d) Same as 1d
 - (5e) Same as 1e

- Test Number 6: 40 percent of baseline brine flow rate and 60 percent of baseline isobutane flow rate

- Test Conditions:

- (6a) Flow of brine will be from one well and will be approximately 320,000 lb/hr into either flash drum V-1 or V-4.
 - (6b) Same as 1b
 - (6c) Same as 1c
 - (6d) Same as 1d
 - (6e) Same as 5e
 - (6f) Same as 1f

- Test Measurements:

- (6a) Same as 1a
 - (6b) Same as 1b

- (6c) Same as 1c
 - (6d) Same as 1d
 - (6e) Same as 1e
- Test Number 7: 40 percent of baseline brine flow rate and 40 percent of baseline isobutane flow rate
 - Test Conditions:
 - (7a) Same as 6a
 - (7b) Same as 1b
 - (7c) Same as 1c
 - (7d) Same as 1d
 - (7e) Isobutane flow rate, as measured by flow element FE 104, will be controlled by valve FV-104W to about 1,531 gpm.
 - (7f) Same as 1f
 - Test Measurements:
 - (7a) Same as 1a
 - (7b) Same as 1b
 - (7c) Same as 1c
 - (7d) Same as 1d
 - (7e) Same as 1e
- Test Number 8: 20 percent of baseline brine flow rate and 40 percent of baseline isobutane flow rate
 - Test Conditions:
 - (8a) Flow of brine will be from one well and will be approximately 160,000 lb/hr into either flash drum V-1 or V-4.
 - (8b) Same as 1b
 - (8c) Same as 1c
 - (8d) Same as 1d
 - (8e) Same as 7e
 - (8f) Same as 1f

- Test Measurements:
 - (8a) Same as 1a
 - (8b) Same as 1b
 - (8c) Same as 1c
 - (8d) Same as 1d
 - (8e) Same as 1e
- Test Number 9: 20 percent of baseline brine flow rate and 20 percent of baseline isobutane flow rate
 - Test Conditions:
 - (9a) Same as 8a
 - (9b) Same as 1b
 - (9c) Same as 1c
 - (9d) Same as 1d
 - (9e) Isobutane flow rate, as measured by flow element FE-104, will be controlled by valve FV-104W to about 765 gpm.
 - (9f) Same as 1f
 - Test Measurements:
 - (9a) Same as 8a
 - (9b) Same as 1b
 - (9c) Same as 1c
 - (9d) Same as 1d
 - (9e) Same as 1e

RESULTS

Data on temperature and pressure will be plotted as a function of time for each test case. The resulting pressures in the flash drums will be of particular interest as the flow rate of brine is reduced and no attempt is made to control these pressures. Furthermore, the results of Test

Number 3 will reveal whether restoration of the baseline flash pressure is in fact achievable, although whether the control methods used in the test can also be used in a commercial power plant, must be investigated.

It is expected that at some point during the course of the turndown operation flash drum pressures will fluctuate greatly and it will be difficult to determine a single value for pressure. This will occur at the point of maximum turndown capability of the plant.

Isobutane temperatures and pressures will also be plotted so that data will be available on the time change of fluid properties at key points in the binary loop during a turndown operation. This data will serve as the basis for estimating the nature and extent of temperature and pressure changes at the inlet to a turbine.

TASK 18

TITLE

Long-term run under baseline conditions.

OBJECTIVE

To determine the ability of the Niland Geothermal Test Plant to operate with isobutane over a long period of time at established optimum conditions.

JUSTIFICATION AND RELATION TO FUTURE DESIGN

A long-term run under baseline conditions is essential to demonstrate the stability and reliability of the pilot plant. During the long-term run, operation and maintenance procedures will be established and the need for equipment modifications brought to light.

TEST CONDITIONS

The pilot plant will be restored to its original clean condition. The operating conditions for the long-term run will be the optimum set of conditions as established by all the preceding test runs. The optimum test conditions will be those that result in stable operation, good performance, a minimum of required maintenance, and a minimum of unscheduled downtime.

TEST MEASUREMENTS

All of the measurements taken in Tasks 1 through 17 will be repeated.

CALCULATIONS

Calculations will be performed as specified in Tasks 4, 7, 8, 11, 12, 13, 14, and 15.

RESULTS

Data evaluation specified for all of the preceding tasks will also be performed during the long-term run. Data on temperature, pressure, flow rates, and levels will be plotted as a function of time so that the stability of plant operation can be evaluated. New heat transfer coefficients will be calculated. Scrubber efficiencies and pressure drops will be plotted as a function of the controlling parameters.

Following each unscheduled shutdown, the number of hours of continuous operation will be recorded as well as a description of the failure mode. Records will be kept of all equipment outages and required maintenance. Then the long-term run will be continued until a total of 1,200 hours of operation have been completed.

Any necessary revisions of the plant startup, shutdown, and emergency procedures can be made at the completion of the long-term run. Furthermore, new plant equipment and controls may be recommended.

APPENDIX A

Appendix A

SUMMARY OF HEAT EXCHANGER INFORMATION

Heat Exchanger	E-1A	E-1B	E-1C	E-2, 3	E-4A, 4B	E-5
TEMA Type	AET	AET	AET	BEU	CHN	BEU
Number of Tubes	1,146	1,146	1,146	1,270	4,069	466
Total Surface Area (ft ²)	5,724	5,724	5,724	8,312	47,036	1,510
Number of Passes	2	2	2	2	2	2
Tube Diameter (inches)	1.000	1.000	1.000	.750	.750	.750
Tube Wall Thickness (inches or BWG)	.060	.060	.060	20	14	20
Tube Length (inches)	240	240	240	192	360	192
Tube Layout (degrees)	30	30	30	60	60	60
Tube Pitch (inches)	1.25	1.25	1.25	.938	.938	.938
Shell Diameter (inches)	54	54	54	41	67	26
Tube Material	Ti	Ti	Ti	Ti	C. S.	Ti

APPENDIX B

Appendix B

PROPERTIES OF SODIUM CHLORIDE SOLUTIONS

To establish a consistent basis for calculations, correlations are appended for the properties of sodium chloride solutions. The curves are excerpted from the Engineering Data Book published by the Office of Saline Water (now the Office of Water Research and Technology). Experimental work is required to confirm that the data for sodium chloride solutions are applicable to the Niland geothermal brines.

AQUEOUS SODIUM CHLORIDE SOLUTIONS
...
HEAT CAPACITY

**AQUEOUS
SODIUM
CHLORIDE
SOLUTIONS
... ..
HEAT CAPACITY**

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1172(4-29-71)

THIS SHEET PREPARED BY
THE M.W. KELLOGG CO.
FOR THE OFFICE OF SALINE WATER
U.S. DEPT. OF THE INTERIOR
UNDER CONTRACT NO. 14-30-2639

TECHNICAL DATA BOOK
OFFICE OF SALINE WATER
SHEET 11 OSW 12.20
REVISED S.B.A. DATE 4-71

**AQUEOUS
SODIUM CHLORIDE
SOLUTIONS
LATENT HEAT OF VAPORIZATION**

LATENT HEAT, BTU/LB OF WATER EVAPORATED

REFERENCE:

Unterberg, W., Report No. 64-21:
*Thermophysical Properties of
Aqueous Sodium Chloride
Solutions*, p. 27, Univ. Calif.
Dept. of Engg., Los Angeles,
Calif. (May 1964).

NOTE:

THIS CHART IS BASED ON
PURE WATER - APPLIES
UP TO SATURATION WITHIN
± 1%.

AQUEOUS SODIUM CHLORIDE SOLUTIONS

ENTHALPY

THIS CHART PREPARED BY
THE M. W. KELLOGG CO.
FOR THE OFFICE OF SALINE WATER
U. S. DEPT. OF THE INTERIOR
UNDER CONTRACT NO. 14-01-001-211

... AQUEOUS SODIUM CHLORIDE SOLUTIONS ... BOILING-POINT RISE

REFERENCE:

*Aqueous Sodium Chloride Solutions-Vapor
Pressure, Curve No. OSW12.50 (10-60).*

AQUEOUS SODIUM CHLORIDE SOLUTIONS ... DENSITY

NOTE:

LINES WITH TEMPERATURES ABOVE 212°F AND WITH NaCl COMPOSITIONS ABOVE 12 WEIGHT PERCENT ARE EXTRAPOLATED BY REFERENCE 4.

FOR REFERENCES
SEE PAGE ONE.

TECHNICAL DATA BOOK
OFFICE OF SALINE WATER
CURV 12.60
DATE 1-66

APPENDIX C

Appendix C

HEAT TRANSFER CORRELATION FOR TASK 3

Convective Boiling Inside Tubes

$$h_{io} = 3.5 \left(\frac{1}{X_{tt}} \right)^{.5} h_l$$

where:

$$h_l = .023 \left(\frac{12k_l}{d_i} \right) \left(\frac{d_i}{d_o} \right) \left(\frac{124G_l d_i}{\mu_l} \right)^{.8} \left(\frac{2.42C_{p_l} \mu_l}{k_l} \right)^{.4}$$

$$G_l = \frac{W_w(1-X)}{25 A_f}, \text{ lb/sec} - \text{ft}^2$$

d_i, d_o = inside and outside tube diameter, inches

A_f = cross sectional flow area, in^2

G_l = mass velocity if liquid only were flowing
in tubes, $\text{lb/sec} - \text{ft}^2$

C_{p_l} = liquid specific heat, $\text{Btu/lb-}^\circ\text{F}$

μ_l = liquid viscosity, cP

k_l = liquid thermal conductivity, $\frac{\text{Btu}}{\text{hr} - \text{ft} - ^\circ\text{F}}$

$$\frac{1}{X_{tt}} \cong 0.77 \left(\frac{1-X}{X} \right)^{.9} \left(\frac{\rho_l}{\rho_v} \right)^{.5}$$

ρ_l, ρ_v = liquid and vapor density, lb/ft^3

W_w = total flow (liquid + vapor), lb/hr

X = quality of vapor

For the existing geometry of E-2 and E-3:

$$A_f = \frac{1270}{2} \times .3632 = 230.6 \text{ in}^2$$

$$d_i = .68 \quad , \quad d_o = .75$$

Combining equations for this geometry gives:

$$h_{io} = .0546 \left[k^{.6} \left(\frac{C_{pl}}{\mu_l} \right)^{.4} \left(\frac{\rho_l}{\rho_v} \right)^{.25} \right] (W_w)^{.8} \frac{(1-X)^{1.25}}{X^{.45}}$$

Liquid Heating Inside Tubes

The Dittus-Boelter Equation;

$$h_{io} = .023 (12k_l) \left(\frac{d_i}{d_o} \right) \left(\frac{124G_l d_i}{\mu_l} \right)^{.8} \left(\frac{2.42C_{pl} \mu_l}{k_l} \right)^{.4}$$

When modified for the specific geometry as above gives:

$$h_{io} = .0178 k_l^{.6} \left(\frac{C_{pl}}{\mu_l} \right)^{.4} (W_w)^{.8} , \text{ for E-2 and E-3}$$

Steam Condensing in the Presence of CO₂

A background discussion and detailed example of the calculational procedure is included in pages 340-351 of Ref. 2. Some specific comments on this reference are as follows.

In eqn. 13.32(b) replace h_{io} with U_o where:

$$1/U_o = 1/h_{io} + r_{wall} + r_{foul} + r_{cond}$$

$$\begin{aligned} r_{wall} &= \text{tube wall resistance} \\ &= .035/(12 \times 25) \\ &= .0012 \text{ for 20 bwg titanium} \end{aligned}$$

r_{foul} = fouling/scaling resistance
 = 0 for clean condition
 r_{cond} = condensate film resistance
 $\approx .0005$ for steam
 h_{io} = tubeside heat transfer coefficient
 (calculated for either water heating
 or vaporizing as presented earlier
 in this appendix.)

On page 346, step 2 of the calculation procedure, an average value of h_{io} is not acceptable for evaluation of E-2 and E-3. h_{io} must be calculated in each interval since it will vary significantly throughout the exchangers.

On page 347, the table of heat load vs temperature must also be constructed for the water as well as the steam and CO_2 side.

On page 348, replace the calculation of h_{io} with the appropriate equations included in this appendix. Also, for the specific geometry of E-2 and E-3, the following simplified equation for h_{o} is recommended.

$$h_{\text{o}} = 0.375 \frac{k^{2/3} C^{1/3}}{\mu^{.267}} W^{.6}$$

where:

C = specific heat of steam and CO_2 , Btu/lb - $^{\circ}\text{F}$
 k = thermal conductivity of steam and CO_2 , Btu/hr-ft- $^{\circ}\text{F}$
 μ = viscosity of steam and CO_2 , cP
 W = flowrate of steam and CO_2 , lb/hr

$$h_o = \text{heat transfer coefficient of steam and CO}_2, \\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Note: Steam and CO₂ above refers to the uncondensed steam plus the CO₂ gas mixture.

The calculated required surface area for each exchanger, E-2 and E-3, is calculated as the sum of the required areas for each interval divided by the LMTD correction factor, F.

$$A_{REQ} = \left[\sum \left(\frac{q}{U \Delta t_{lm}} \right) \right] / F$$

Note that in Kern's example he assumes that F=1, i.e., countercurrent flow. While the use of an F correction for nonlinear heat release is not strictly correct, it does attempt to correct for non-countercurrent flow effects. It is recommended that this correction be applied.

The calculated overall heat transfer coefficient is then calculated for each exchanger as:

$$(U_{CALC})_2 = \frac{Q_2}{(A_{REQ})_2 \Delta T_{M2}}, \text{ for E-2}$$

and

$$(U_{CALC})_3 = \frac{Q_3}{(A_{REQ})_3 \Delta T_{M3}}, \text{ for E-3}$$

These values will then be compared to the experimental values obtained.

APPENDIX D

Appendix D

PRESSURE DROP CORRELATIONS

Tubeside Pressure Drop (no phase change)

$$\Delta P_t = \frac{N_{tp} G_t^2 L}{154 \rho d_i} \left(f + \frac{.0416 d_i}{L} \right)$$

where:

f = friction factor

$$= .048 / R_e^2, R_e > \sim 3,000$$

R_e = Reynolds number

$$= 124 G_t d_i / \mu$$

G_t = tubeside mass velocity, lb/sec - ft²

$$= w / 25 A_f$$

d_i = inside tube diameter, in.

A_f = cross sectional flow area, in.²

μ = fluid viscosity, cP

ρ = fluid density, lb/ft³

N_{tp} = number of passes

L = tube length, ft

ΔP_t = tubeside pressure drop (includes two velocity heads for entrance, exit, and turnaround losses), psi

Shellside Pressure Drop (no phase change)

$$\Delta P_s = \Delta P_x + \Delta P_w$$

where:

$$\Delta P_x = 4.32(10^{-4})G_x^2 f N_r (N_b + 1) / \rho$$

$$\Delta P_w = 1.08(10^{-4})K_w G_w^2 N_b / \rho$$

$$\begin{aligned} G_x &= \text{crossflow mass velocity, lb/sec -ft}^2 \\ &= W F_l / 25 A_x \end{aligned}$$

$$\begin{aligned} G_w &= \text{window mass velocity, lb/sec -ft}^2 \\ &= W / 25 A_w \end{aligned}$$

$$A_x = \text{crossflow area, in.}^2$$

$$A_w = \text{net window area, in.}^2$$

$$F_l = \text{bundle leakage factor}$$

$$\begin{aligned} f &= \text{friction factor} \\ &= 0.48 B_n / R_e^{.145}, \text{ Re} > \sim 200 \end{aligned}$$

$$B_n = \text{geometry factor}$$

$$R_e = \text{Reynolds number}$$

$$= 124 G_x d_v / \mu$$

$$d_v = \text{hydraulic diameter, in.}$$

$$\mu = \text{fluid viscosity, cP}$$

$$N_r = \text{number of tube rows crossed}$$

$$N_b = \text{number of baffles}$$

$$K_w = \text{baffle window coefficient}$$

$$\rho = \text{fluid density, lb/ft}^3$$

APPENDIX E

Appendix E

BACKGROUND FOR TASK 12 MEAN TEMPERATURE DIFFERENCE

CALCULATIONS

Figure E-1 represents the temperature profiles for a superheated vapor being cooled by a fluid that is below the saturation temperature of the vapor at every point in the exchanger.

For simplification, the following assumptions apply:

- The surface is clean and the tube wall resistance is negligible, i. e., $t_{wo} = t_{wi}$
- The flow orientation is counter-current
- The condensate film resistance is negligible in the desuperheating region

The heat flow per unit area at any point in the exchanger may be calculated as:

$$\frac{Q}{A} = hc (T_w - T_c)$$

where:

hc = film coefficient of the coolant

Some general conclusions may be obtained from the following considerations:

Figure E-1. TEMPERATURE PROFILES

- Dry Wall Region

In the vapor inlet region, if the tube wall temperature is above the saturation temperature of the vapor, no condensation will occur. If this is the case, then:

$$T_w > T_{sat}$$

and

$$hc (T_w - T_c) > hc (T_{sat} - T_c)$$

The rate of heat transfer is higher than if condensation were assumed to exist.

- Wet Wall Region

At some point in the exchanger before the bulk vapor temperature reaches the saturation temperature, the tube wall temperature will drop to the saturation temperature of the vapor. Neglecting the condensate film resistance, the heat flux at this point or any point further down the length is given as:

$$\frac{Q}{A} = h_c (T_{sat} - T_c)$$

since

$$T_w = T_{sat}$$

Note that if a dry wall condition were assumed in this region, the calculated wall temperature would be less than saturation temperature of the vapor and the heat flux would be given as:

$$\frac{Q}{A} = h_c (T_w - T_c)$$

where:

$$T_w < T_{sat}$$

From the preceding considerations, it is observed that the selection of the proper mechanism for the region gives the highest rate of heat transfer and, conversely, assumption of an incorrect mechanism underpredicts the actual rate of heat transfer.

GENERALIZATION

When a superheated vapor is introduced into a heat exchanger in which the coolant temperature is everywhere below the saturation temperature of the vapor, the correct surface area may be determined as follows:

- Calculate the surface area for the desuperheating section assuming that condensation occurs throughout the exchanger
- Calculate the surface area for the desuperheating section assuming that no condensation occurs in this section
- The correct surface area is then the smaller of the two areas calculated. It should be noted that only two possibilities exist. Either the tube wall is wet throughout the desuperheating section or the tube wall is initially dry, becoming wet at some point within the desuperheating section. The tube wall is never dry throughout the desuperheating section if the coolant temperature is everywhere below the vapor saturation temperature. In the event that both dry and wet wall conditions occur, the correct surface area will be less than the surface areas calculated by either a or b since they both involve a partially incorrect assumption. For this case, if a conservative answer is not acceptable, the point at which the tube wall becomes wet must be determined and the surface areas for dry wall and wet wall conditions determined separately.

It may also be concluded that if either dry wall or wet wall conditions are assumed to exist, regardless of the actual situation, the calculated surface area will either be correct or too large. It will never be on the low side.

APPENDIX F

Lawrence Livermore Laboratory

THE LLL GEOTHERMAL INDUSTRIAL SUPPORT PROGRAM IN
CHEMISTRY AND MATERIALS FOR FY76T AND FY77

ROLAND QUONG

JULY 29, 1976

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

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FOREWORD

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THE LLL GEOTHERMAL INDUSTRIAL SUPPORT
PROGRAM IN CHEMISTRY AND MATERIALS
FOR FY76T AND FY77

INTRODUCTION

In response to ERDA/DGE*, LLL has initiated an Industrial Support Program (ISP) to provide technical assistance to joint ERDA/industry projects. The basic purpose is to:

- Carry out relevant research investigations in potential problem areas in order to broaden opportunities for solutions, and to provide alternate approaches where needed.
- Provide ad hoc technical assistance to help solve critical problems that may arise during the operations of joint ERDA/industry projects.

Much of the ongoing work at LLL to develop the Total Flow concept will find application, and the ISP will provide a mechanism for effective, timely use of the diverse talents at LLL and transfer of its geothermal expertise. This support program was established by ERDA/DGE in January, 1976, and currently is directed only toward the jointly funded project carried out by San Diego Gas and Electric (SDG&E) to construct and operate the Geothermal Loop Experimental Facility (GLEF) at Niland, California. It is expected that the ISP will eventually include assistance to other joint projects as they are developed.

Based on our experience in working with SDG&E on the GLEF since January, 1976, we have outlined a program plan in Chemistry and Materials for FY76T and FY77. This plan encompasses technical support in existing problem areas as well as suspected problem areas which have been identified during the initial operating phase of the GLEF.

* U.S. Energy Research and Development Administration, Division of Geothermal Energy

It should be recognized that the size of the ISP and, more specifically, the number of tasks and the level of activity in each task, will depend solely on the progress of the joint ERDA/industry projects and the level of funding. Clearly, if the GLEF encounters severe technical difficulties, or if more projects are added, the planned level of funding, already extremely constraining, will be inadequate to support a coherent program. The important point, however, is that the ISP will provide insurance in terms of a contingency plan for action against unforeseen problems. In this sense, the development of the Total Flow process is itself an alternate approach and is, in effect, a contingency plan. Hence, the ISP will be another important bridge to transfer the advanced technology developments from LLL to industry.

I. SCALE CONTROL AND BRINE HANDLING

1. Scale Characterization and Control

a. Field Tests: Surveillance of Scaling Rates in the SDG&E, GLEF.

Objective: To measure, in-situ, the rate of scale buildup in critical components and piping in the SDG&E test facility during operation.

Scope: Radiographs of critical components of the GLEF will be made during operation as a means of surveillance for scale deposition and growth. The temperature of the brine in the formation is approximately 500°F. It is flashed in the well-casing to approximately 350°F and continues to undergo temperature and pressure drops through the GLEF process, before being reinjected at approximately 200°F. The large temperature and pressure drops which these HT/HS brines undergo are near optimum conditions for promoting solids precipitation, a precursor to scale deposition and growth. This could lead to reduced operation if not total curtailment. Because of the uncertainty in the rate at which scale forms, surveillance of scale buildup

during facility operation becomes important, not only from an operational necessity, but from the standpoint of a need to understand how scaling rates vary with time during the period of operation. The ability to monitor scale buildup and to relate this to plant operation is important in enhancing the operator's ability to assess and, if necessary, safely curtail operation.

Radiographic surveillance will be made at frequent intervals during GLEF operation. As the operation progresses into a steady-state condition, radiographs every two weeks to a month will be taken at critical sites. Approximately 20 critical sites have already been radiographed. This was done before operation to obtain baseline information, and also during the initial operational phase of the GLEF at 50% flow capacity. With this field experience on the GLEF, we have developed an operating procedure and field capability to provide essentially on-the-spot radiographs showing scale deposition on the walls of pipes up to 12 in. diameter, pipe fittings, and valves. Change in scale thickness of 1 mm can be resolved by this method. Radiography is a completely external means of scale surveillance. Internal methods such as probes, depth gauges, etc. would, in themselves, promote local scaling and not give a true scaling rate on GLEF components.

b. Field tests: Effect of brine modification on scaling rates.

Objective: Determine through field tests whether chemical modification of the brine is an effective method for scale control.

Scope: Analyses of scales produced by HT/HS brines found in the Imperial Valley show principal constituents to be heavy metal sulfides and silica. The solubility of both phases is, of course, temperature dependent, but in addition, also strongly pH dependent. Furthermore, there is evidence

that the rate of silical deposition as a scale constituent is dependent on the degree of polymerization of the precipitated monomer, and that the rate of polymerization is also pH dependent. Field experiments will be conducted on the flowing brine to test these theories. Oxidation experiments will also be conducted to attempt to convert sulfide ions to relatively innocuous free sulfur. The temperature dependence of these chemical modification tests must also be known in order to determine the effectiveness of this technique when applied to the successively lower temperature steps in the GLEF process. We will conduct scaling rate experiments using nozzle expansion tubes where the temperature drops in the nozzle expander from wellhead temperatures of $\sim 230^{\circ}\text{C}$ to 100°C at the nozzle exit. Our experiences with these nozzles have shown that controlled scaling rate experiments at variable, but known temperatures, are executable in the field and that they provide valuable scaling data. Acidification of the brine will be accomplished by injecting inorganic acids such as HCl and HNO_3 . Modification of brine E_h will be accomplished by injecting FeCl_3 , Cl_2 and O_2 . Both the amount and rate of chemical addition will be carefully controlled to determine the optimum quantities required to reduce scaling rates.

c. Scale Characterization

Objective: Determine the mineralogical and chemical composition of scale deposits as they are formed in the various stages and components in the GLEF and relate their composition to the changes in the chemical and thermodynamic properties of the brine at the same locations in the GLEF.

Scope: During periods of suspended operation when inspection and maintenance take place in the GLEF, and at other opportune times, scale samples will be collected at various locations in the GLEF. Thickness, coloration,

texture, hardness, layering, and other physical characteristics will be recorded. Mineralogical and chemical analyses of these samples will be made. The type and number of different analyses to be made on a particular sample will depend on the nature and location in the GLEF of the scale sample. The samples are expected to be highly variable in composition because of the wide range of operating conditions in the GLEF. Analytical methods which will be used for scale inspection and analysis include: optical microscopy, transmission electron microscopy, electron microprobe spectrometry, scanning electron microscopy, instrumental and neutron activation, x-ray diffraction, x-ray fluorescence, emission spectroscopy, and atomic absorption spectroscopy. In addition, specific surface area analysis and particle size characterization will be made on selected samples.

The results of these scale analyses will be correlated with the chemical and thermodynamic properties of the brine and with the operating conditions in the GLEF in order to understand scaling parameters and what effect scaling will have on GLEF operation.

2. Brine and Effluent Characterization

a. Analysis of samples taken during GLEF operation.

Objective: Sample and analyze the various multiphasic process streams in the GLEF in order to understand the change in chemical and thermodynamic properties of the brine in the GLEF process.

Scope: Samples of brine, steam, suspended solids, and non-condensable gases will be taken from about 40 locations during GLEF operation. Initially, the brine, steam and suspended solids will each be analyzed semi-quantitatively for about 75 elements. They will be analyzed quantitatively

for approximately 30 constituents (cation, anions, and gases) of special interest. In addition, density, pH, E_h (oxidation potential), and total dissolved solids will be determined in brine and steam samples. Noncondensable gases will be given a multicomponent analysis by mass spectrometry and microwave spectrometry. They will be analyzed quantitatively for H_2S . The concentration, particle size distribution, mineralogical composition and surface area of suspended solids will also be determined. (Described in task 3a).

The frequency of sampling at any given location and the exact analysis to be made will depend on the rate of change in composition and the nature of the sample. GLEF operating conditions will also affect the sampling requirements. The 40 or so sampling points include points along the production and reinjection lines, and also the input and output streams of each stage for evaluation of stage efficiency. These samples are also required to properly interpret scaling phenomena, solids formation, and the relationship of brine chemistry to corrosion. By analyzing the brine for changes in silica, sulfides, and salt content we will be able to maintain a reasonable inventory of solids accumulation along points in the GLEF. In instances when the quantity and distribution of unreacted sulfides are required, special nonreactive sample bottles will be used. Where stratified and multiphasic flow prevails, a specially designed pitot-like sampling probe which traverses the full diameter of the pipe will be used to sample different points within the stream. The noncondensable gas stream entering the stack is a critical point in the GLEF for sampling. This stream is the source of ejected material into the environment and also the point where noncondensable gases leave the GLEF process. We will have analytical capability for analyzing this stream.

3. Suspended Solids Characterization and Control

a. Sampling and Characterization of Suspended Solids

Objective: Sample and characterize the suspended solids formed in the various brine streams during GLEF operation.

Scope: Part of this task involves the development of apparatus and techniques for sampling so that the properties of the solids can be preserved for subsequent characterization. It will be necessary to separate the solids from the brine in-situ in high temperature stages of the process because solids will separate continuously as the brine cools. For this work, a filtration apparatus was designed to operate at temperatures up to 300°C and pressures up to 600 psi.

If the particles are of a colloidal size and too small to collect on filters, in-situ analysis may have to be considered for the high temperature stages. It may be possible to obtain information on concentration and particle size distribution with a light-scattering spectrometer modified to operate at high temperatures and pressures. However, the technology for in-situ chemical and mineralogical analysis at high temperatures and pressures does not exist, and the time and effort for development of this technology may be prohibitively long and expensive.

The concentration of the solids in the brine will be obtained by weighing the solids collected on filters from a measured volume of brine. In addition, chemical composition by x-ray fluorescence or atomic absorption, mineralogical composition by x-ray diffraction or electron microprobe and surface area will be determined. A more accurate particle size distribution could be obtained with an electron microscope. Characterization of the solids which form at GLEF conditions is, of course, fundamental to the understanding of

scale formation and control. But of equal importance is the role of suspended solids in causing erosion and hold up problems in the GLEF, and potential plugging in the reinjection well.

b. Solids Mass Balance for the GLEF

Objective: To provide stage by stage and overall mass inventory of the GLEF process in order to fully evaluate stage efficiency, solids deposition, solids accumulation, and the distribution of the chemical components of the brine as a function of position and time.

Scope: Based on chemical analyses of brine, steam and non-condensable gas samples taken periodically at approximately 40 points in the GLEF during operation and from the recorded mass flow rates of the process streams, a mass balance will be made across each stage, and across the entire process. The amount of solids accumulation, scale formation, and suspended solids will be compared with data and analysis from sampling to provide a means of understanding the interaction of brine chemistry and process variables on solids production and scale formation.

The rate of produced solids will be small by comparison with the brine mass flow rates, and may be difficult to resolve over short times within the precision of the sample analysis. The severity of this problem will be variable, depending on the chemical species being followed. In addition, solids may deposit in one location and then migrate downstream over time, again to an extent depending on the particular species involved. This movement of material after deposition introduces a variable which adds another dimension to the inventory problem.

There are no viable alternative approaches to doing a material balance on the process except through period sampling and analysis. Therefore, this subtask will be dependent on results of other subtasks such as 1c, 2a and 3a.

There will be a small number of on-stream analyses, but these will be limited to the noncondensable gas streams.

c. Thermochemical Analysis of Solids Production and Control

Objective: The objective of this task is to develop the means of applying thermochemical principles and existing data to the solutions of severe solids management problems.

Scope: Scale and sludge formation in the GLEF are the result of chemical precipitation reactions. These can in principle be described in terms of kinetics and equilibrium solubilities. Preventive measures can be taken if the conditions under which precipitation will take place are known. However, the chemical complexity of natural brines, the extreme conditions and short time scale of processing make such interpretations difficult.

Our approach to obtaining a quantitative description of the process chemistry in a plant is to estimate activity products of scale forming species in the brine, and compare them with computed solubility products of scale solids. This is possible because data are available from the chemical literature which takes into account the effects of pH, temperature, and degree of chloride complexing on activity coefficients. Many individual chemical reactions can be evaluated in this way, although the method does not permit a complete description of the system, and requires some discretion and interaction with the investigator.

In the GLEF process each of the multiple stages of steam separation can be considered as a quasi-equilibrium situation. At these points, the residence time and reduced stream velocity are expected to allow solids to form and accumulate. The removal of noncondensable gases along with the steam also

affects the brine chemistry, and makes it important to be able to estimate their distribution.

Because of the considerable variability in operating parameters and the number of chemical reactions that must be considered, an essential feature of this task is in the development of a computer code which treats specified precipitation equilibria for any set of physical conditions existing in the GLEF. Input to the code includes the original chemical composition of the fluid, pressure and steam quality as function of temperature, solubility and dissociation of hydrogen sulfide, and effective activity coefficients for ionic species.

This code was first used to study the precipitation behavior of PbS. This is a material that preliminary experimental studies showed to be a pervasive solid even at the relatively high temperatures in the brine at the wellhead. The computed solubilities agree with this observation and indicate that PbS results primarily from a pH increase caused by the loss of CO₂ from the liquid phase.

Since pH change appears to be an important factor controlling precipitation, the effect of CO₂ evolution on pH will be introduced. The effects of imposed pH reduction (chemical modification) will be added as an option.

Additional chemical data will be obtained and added to the code to permit computations for other sulfides and for classes of compounds other than sulfides, such as oxides, hydroxides, sulfates and carbonates. Solids removal by pre-precipitation from hot brine before the fluid enters a plant, and post-treatment of spent brine before reinjection may eventually become necessary. A study will be made of the effects of potential additives for these purposes. Such processes would involve reactions at higher pH and oxidation states than are normally encountered. A mechanism will be added to

the code for specifying the oxidation state of the system. Extrapolations of activity coefficient data will be necessary to allow computations in alkaline solutions.

d. Assessment of Solids Control Methods

Objective: Define chemical methods for reducing solids production and the physical techniques for solids handling and/or removal in the GLEF process.

Scope: At the temperatures and pressures at which the GLEF operates, and examination of the thermodynamic equilibria of constituents such as silica and heavy metal sulfides, indicates that the quantity of scale that can be cemented on equipment surfaces is but a small fraction of the total solids which exceed equilibrium solubility. Those solids which are not immobilized as scale could potentially 1) cause plugging at points in the piping network, 2) separate and settle in the process vessels reducing their effective volume, brine residence time and hence stage efficiency, and 3) pass through the plant and into the reinjection wells causing a serious flow problem by reducing formation permeability. Potential solids production rate can be computed based on equilibrium solubility and brine composition as described in subtask 3c.

The actual production rate within the GLEF will be affected by kinetic factors, the dynamics of the flowing brine, partition of CO_2 and H_2S in the gas and liquid phases, and the chemistry of the hypersaline brine.

Selection of promising chemical and physical methods for solids control will be dependent on results of the brine and solids sampling and characterization phases of the field program. Whatever method is selected, it must be compatible with the total process including reinjection of the spent brine.

In conjunction with chemical modification techniques, the use of conventional solids processing methods in the GLEF process will be assessed as a means of controlling the flow of excess solids through the facility and the amount which is ultimately reinjected.

4. Effluent Conditioning for Reinjection

a. Assessment of Effluent Conditioning Procedures

Objective: Assess the chemical and engineering procedures involved in processing the spent brine stream containing suspended solids in the GLEF in order to prevent potential plugging of the formation during reinjection.

Scope: The assessment of procedures for solids handling depends on results of the other subtasks on solids characterization and control. A major distinction is made in that whatever procedure is selected, concern over energy degradation is no longer a primary factor in the spent brine stream. The main consideration is the prevention of solids from plugging the formation.

We will survey existing technology for separating solids from liquid streams. Promising methods will be evaluated along with an assessment of chemical and equipment design problems for GLEF application. We will make process design calculations for the selected separation process using input conditions and properties anticipated in the operation of the GLEF.

The main problem areas in processing the effluent stream for suspended solids are 1) exposure to oxygen which would increase the corrosive potential of the reinjected brine and 2) submicron particles sizes and low density solids constituents, making settling times long and separation difficult, and 3) continuing precipitation of solids in the brine even after separation.

Several techniques which may prove fruitful include 1) ponding the brine, settling and separation, followed by oxygen treatment, 2) filtration, and 3) inertial separation techniques. In addition, chemical seeding will be evaluated to co/pre-precipitate species that may come out of solution when reinjected.

b. Field Tests: Effluent Condition and Handling Methods

Objective: Conduct field tests of methods defined in subtask 4a for conditioning and handling of spent brine effluent for reinjection.

Scope: Based on the field program plan defined in subtask 4a, small scale field tests will be conducted on the most promising methods for conditioning and handling spent brine effluent. Equipment will be ordered and field installed.

Most of the tests will be designed toward use of commercially available process equipment in anticipation of the potential need for available, larger versions of equipment should an acceptable process be found. Atmospheric settling ponds may be a near-term practical solution. Following chemical treatment and settling, chemical or mechanical flocculation may be required to agglomerate the remaining fine grained particles. High efficiency, inertial type separators could then be used as the next stage to remove the relatively low density solids from the heavily salted spent brine. Because of the relatively low solids concentration in the spent brine and small density difference between the solid agglomerates and the brine it may be necessary to use equipment capable of producing very high centrifugal forces in which case equipment power consumption would be considerably increased. The effectiveness of the effluent conditioning and handling methods will be tested by passing samples of the treated effluent through core samples of the reinjection formation and observing the change in permeability at simulated in-situ conditions.

II. MATERIALS

1. Corrosion Surveillance and GLEF Support

a. Nondestructive Surveillance

Objective: To measure the rate of corrosion of piping and components during GLEF operation. Correlate the data with operating parameters and brine properties.

Scope: Approximately 30 sites on the GLEF have been selected for periodic measurement of wall thinning by ultrasonic techniques. The extent of corrosion will be evaluated with respect to the variation of process conditions, such as temperature, pressure, fluid velocity, pH, and the specific location of the corrosion site.

The technique utilizes a transducer coupled externally to the pipe or component wall for transmitting and receival of an ultrasonic signal. The signal is displayed and interpreted to give a measure of wall thickness. We expect to resolve changes of 10 mils. thickness in typical pipe walls.

Difficulties may arise in transducer compatability with the hot surfaces encountered in the upstream portions of the facility. Good surface contact is required between the transducer and the surface of the specimen. It may be necessary to use thermal standoffs which will degrade signal transmission to some extent, but not enough to negate the usefulness of the technique. If there is appreciable and rapid corrosion, then ultrasonics should detect this without great expense or without interruption of the process.

The radiographs at various sites on the GLEF for monitoring scale buildup will also provide information on wall thinning and localized corrosion. An interpretation of these radiographs will be made for corrosion and the data will be assembled and evaluated with other corrosion studies described elsewhere

in the LLL program. Radiographs of critical sites other than those for detailing scale buildup will also be made, especially elbows and regions downstream of control valves where large temperature and pressure drops occur.

b. Analysis of Materials Related Failures

Objective: Provide SDG&E with metallographic analytical support during operation of the GLEF. Inspect and analyze materials related failures of facility piping, fittings, and components. Recommend replacement materials, parts, and/or process modifications.

Scope: Because LLL has the facility and trained personnel for comprehensive and detailed metallographic analysis, LLL will provide support to SDG&E during operation of the GLEF. Inspection and analysis of materials related failures will be made, followed by recommendations for substitute materials and/or parts. We plan to do this on a timely basis, in order to impact on ongoing GLEF activities. Generally the parts will be sent to the laboratory for full analyses, although some capability will be available in the field, e.g., radiography and dye penetrant application. Materials related failures have already occurred in the operation of the GLEF in critical components. Elbows, the first stage control valve, and the tubing in the production and reinjection wells to monitor downhole pressure have already failed through a combination of erosion and corrosion. LLL is, at the present time, inspecting and analyzing these parts and have made recommendations for both provisional and long-term solutions. We anticipate that similar problems will occur in the ensuing operating phases of the GLEF. Should they occur, we will be prepared to provide support. Other parts of our industrial support program in materials addresses the problem of prevention of corrosion related failures.

2. Materials Test and Evaluation

a. Corrosion Tests of Substitute Plant Materials

Objective: The purpose of this task is to expose, to the raw brine, materials which can be substituted for currently used plant materials that may undergo excessive corrosion. Three categories of materials will be tested: 1) steels that are readily available as large diameter pipes and fittings, 2) materials that may be expected to exhibit better corrosion resistance than these pipe steels but are presently available only in other shapes, and 3) compositions which will provide important information as a data base for the long-range development of low-cost, corrosion-resistant alloys.

Scope: During the short period of operation of the SDG&E Test Facility, unacceptable corrosion rates of some plant components have become evident. Replacement materials will have to be selected. To assure that the proper substitute materials are specified, a knowledge of the relative corrosion behavior of readily available structural materials in the corresponding brines will be required.

Pipe materials will be exposed in the form of corrosion spools directly in the production line of the GLEF. Spools containing corrosion coupons will also be exposed in bypass lines. The structural materials at the test facility are mainly plain carbon steels, typically ASTM A-53, Grade B. The corrosion spools will be made out of readily available steel pipe such as S00-90, L-80, and others used in the petroleum industry. They will measure 0.61 M (2 ft) in length by 0.27 M (10-3/4 in.) in diameter. To obtain a measure of susceptibility to crevice corrosion, a crevice specimen of the material used for the spool will be inserted through and welded on to the wall of the spool. These samples will also contain a weld bead. Coupons of a large number of other materials will be exposed in the spools placed in bypass lines to expand our

data base on corrosion of materials in geothermal brines. This will provide information for potential long-range substitute materials and for the development of new alloys. In addition, this information will be useful for considering the substitution of materials for components which cannot tolerate excessive corrosion such as in valves and pumps. With respect to developing a data base for understanding the role of composition, we will include (1) low carbon steels with varying amounts of Cr and Mo and possibly Ni and Si, (2) austenitic stainless steels with varying amounts of Ni, Cr, and Mo, and (3) ferritic stainless steels with varying amounts of Cr and Mo and possibly Ni.

The corrosion spools will be examined radiographically and, at appropriate intervals, will be removed so that they can be checked metallographically. Corrosion coupons will be designed so that information on general corrosion, crevice corrosion, and pitting corrosion will be obtained. Duplicate samples will contain weld beads to simulate weldments. Weight and thickness measurements and metallographic analysis will be made. An analysis of initial and replacement costs will be made for these materials.

b. Electrochemical Corrosion Tests

Objective: This work will involve experiments using several electrochemical testing techniques in the field for the purpose of screening alloys for their corrosion resistance in high-temperature, high-salinity geothermal brines.

Scope: Three basic types of measurements will be carried out: (a) "instantaneous" corrosion-rate (also known as linear-polarization resistance, LPR) measurements; (b) open-circuit corrosion potential measurements; and (c) polarization curve measurements. The LPR measurements can, in theory, be conducted entirely with commercially available equipment. Measurements (b) and

(c) require a stable reference-electrode assembly suitable for use at $\sim 220^{\circ}\text{C}$ and 200 psi. Initially, measurements will be made with the hot, high-pressure unmodified, flowing brine and various prospective alloy materials will be tested. These materials include low carbon steels with varying amounts of Cr and Mo such as A36, S00-90, A387; stainless steels such as MP35N, 410, and Ti alloys such as Ti-6Al-4V, and Ti-38A Code 12. If chemical modification of the brine proves successful in abating scale formation, corrosion rate tests will also be conducted in the modified brines.

In addition to the field testing, a chemical laboratory facility will be maintained at LLL for concomitant, laboratory electrochemical measurements, and for checkout of the field equipment. This laboratory will be devoted primarily to short-term applied research or semi-routine tests.

Provided a reliable reference-electrode assembly can be developed, the principal problem area in the electrochemical measurements is the effect of scaling. All measurements will be carried out as a function of time, and this should yield some information on its influence. The inhibition of corrosion by scaling does not necessarily preclude obtaining meaningful electrochemical corrosion-rate measurements on the various materials.

Eventually, if LPR measurements prove to be valuable sensors of corrosion activity, permanent installations of this type will be considered at various locations in the GLEF. By sensing corrosion activity at several locations, the direct effect of changes in brine chemistry on corrosion activity can be determined.

c. Corrosion Tests in Modified Brines

Objective: Test corrosive effects of chemically modified brines on substitute plant materials.

Scope: This task will be closely coupled with subtask 1b under scale control and brine handling, where the brine will be modified chemically in attempts to control scale formation. These tests will be conducted using expansion tubes (nozzles). For corrosion tests, these tubes will be fabricated out of low and medium carbon steels, low and medium alloy steels, and stainless steels. These tests will enable us to determine the corrosive nature of these chemically modified brines. Two methods of brine modification anticipated in subtask 1b (scale control and brine handling) will be acidification and oxidation. Following each test, the expansion tubes will be sectioned and will undergo metallographic analysis. Corrosion rates on various materials in geothermal brines as a function of pH, E_H , and temperature will add significantly to our understanding of corrosion.

d. Test and Evaluation of Polymeric Materials

Objective: Test and evaluate polymeric liners, coatings, and platings on metallic surfaces as a means of preventing scaling and corrosion in low velocity components.

Scope: Samples of polymeric coating bonded to metal substrates will be exposed in bypass spools to low velocity brine flow. The amount of scaling and wear of the coating will be examined by several means - usually by weight, dimensional, and hardness changes and also by microscopic examination. Temperature, type and amount of suspended solids in the brine, and velocity are the primary parameters affecting the resistance of polymer coatings and liners. Methods of polymer application to metal substrates will also be evaluated. Some screening of materials and methods will be made in the laboratory prior to the field tests to assure that only prime candidate materials are tested in the field. Polymeric coatings may prove to be effective in preventing scale and corrosion in components where erosion is minimal.

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MONTHS FROM START

NOTES

1. = TASK NUMBER
2. = ACTIVITY OF UNDETERMINED DURATION
3. = TESTING ON "OPPORTUNITY" BASIS; NOT ON CRITICAL PATH
4. TESTING IS ON A CONTINUOUS BASIS,
I.E. 21 SHIFTS PER WEEK
5. SCHEDULE IS BASED ON FINAL REPORT
TITLED "DETAILED TEST PROGRAM FOR
THE NILAND GEOTHERMAL TEST
FACILITY", SEPT. 1976 (BECHTEL
JOB 12012-00-001).

7/24/79

2008-10-10

No.	DATE	REVISIONS	BY	CHECKED	DESIGN SUPV	ENGR	PROJ. ENGR	APPR
SCALE	NONE	REDIGNED	DRAWN	LOB		CHIEF ENGR		

BECHEL

SAN FRANCISCO

SAN DIEGO GAS & ELECTRIC CO.,
 NIIAND GEOTHERMAL TEST FACILITY

TASK-LEVEL TEST SCHEDULE

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