American Institute of Chemical Engineers

STUDENT CONTEST PROBLEM

1979

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Geothermal Secondary-Fluid Power Cycle Optimization

AGUA CALIENTE ENGINEERING, INC.

Interoffice Memorandum

TO: J. R. Word
DATE: January 9, 1980
FROM: D. N. Carter—Mgr. of Engineering Design

As we discussed in the staff meeting today, you have been assigned as the Design Engineer on the Geothermal contract that we have received from URDA. The following documents, consequently, are attached:

1. Cover letter from URDA
2. Scope Package

You are to perform the design work indicated in the second document.

You should be able to complete your report by this coming Monday.

UNCONVENTIONAL RESOURCE DEVELOPMENT AGENCY

January 2, 1980

Dr. D. N. Carter
Manager of Design Engineering
Agua Caliente Engineering, Inc.
Sunnycity, Sunshinestate 77777

RE: Geothermal—Secondary-Fluid Power Plant Optmization

Dear Doris,

As I mentioned on the telephone yesterday, I am enclosing the Scope Package for the project indicated above. URDA has decided to award the design contract for this module of ECEP to ACE. I think that you should put your new engineer, Julia Word, on this job.

The formal contract package with all standard terms, conditions, affidavits, attestations, and schedules will be expedited through our Office of URDA Procurement (OURDAP) and your Contract Administration Department (CAD). However, I am sending you this Scope Package unofficially so that we can get on with the work of the world through the "old girl" network.

See you at homecoming.

Betty

B. U. Cratte

Deputy Assistant Chief Administrator
Geothermal Resource Branch,
Terrestrial Energy Resources Division
Medium Range Time Frame Section
Unconventional Resource Development Agency

Geothermal—Secondary-Fluid Power Cycle Optimization Scope of Design

CONTENTS

I. INTRODUCTION

The proposed general geothermal-energy plant consists of five sections:

1. Brine Production and Collection
2. Fuel Plant
3. Hydraulic Power Plant
4. Thermal Power Plant
5. Brine Disposal

The purpose of this project is to optimize the design of the thermal-power-plant section, which will generate electricity from the thermal energy stored in the geothermal, geopressured brine reservoirs of the Texas Gulf Coast. The thermal power plant will be a secondary-fluid power plant.

In Section II the general geothermal-energy plant envisioned for the exploitation of this resource is described. The secondary-fluid power plant proposed for the thermal power plant is described in Section III. In Section IV the economic criteria to be used for this design project are presented, and the base technical criteria are in Section V. Sections VI and VII give the report format and the references, respectively.

This design project is but one module of the comprehensive, mutlimodular Energy Crisis Elimination Program (ECEP) sponsored by URDA.

II. GEOTHERMAL-ENERGY PLANT

The large reservoirs of hot geothermal waters that underlie most of the Texas Gulf Coast are deep, geopressured, moderately hot, and moderately saline. *Deep* means 3.0 to 4.5 kilometers. *Geopressured* means that the geothermal waters in question are under a greater pressure than simply the geostatic loading of the overlying formations. These formation pressures are in the range of 70 to 85 megapascals; the geostatic pressures, in the range of 40 to 55 megapascals. *Moderately hot* means that the geothermal waters in question are at 435 to 450 K. *Moderately saline* means about 10,000 parts per million (1 percent by weight) of total dissolved solids (inorganic salts or other compounds); whereas seawater has an average salinity of 35,000 parts per million (3.5 percent by weight). The geothermal waters in question are also believed to be saturated with methane.

Interest in the exploitation of this geothermal resource has been stimulated by increasing energy costs. Although no plants have yet been built, one scheme for exploiting this resource is described in reference 1. This scheme is illustrated by an overall block diagram (Figure 1).

The first block of Figure 1 represents the geothermal-brine production field and gathering network. No geopressured, geothermal fields have been developed to date; however, typical numbers in use for speculative designs such as this one are that a well can produce about 70 kg/s of hot brine for 20 years. The gathering network will bring the brine production from a number of wells to a central location for further processing. Typical well-head pressures for the above-mentioned production rate are in the range of 15 megapascals.

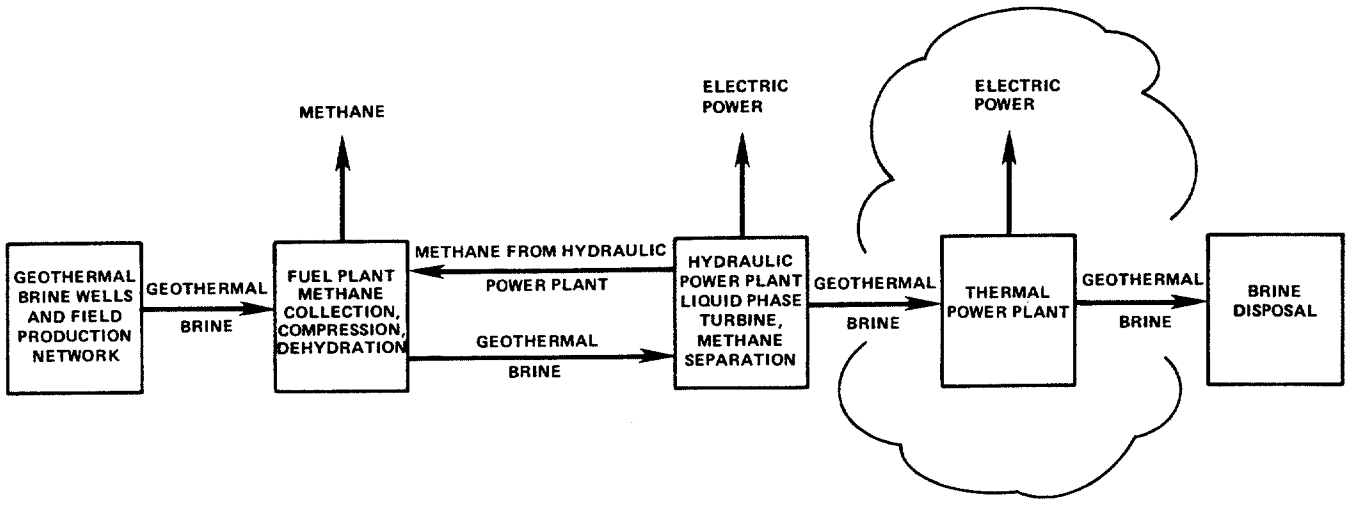

Fig. 1. Geothermal energy plant.

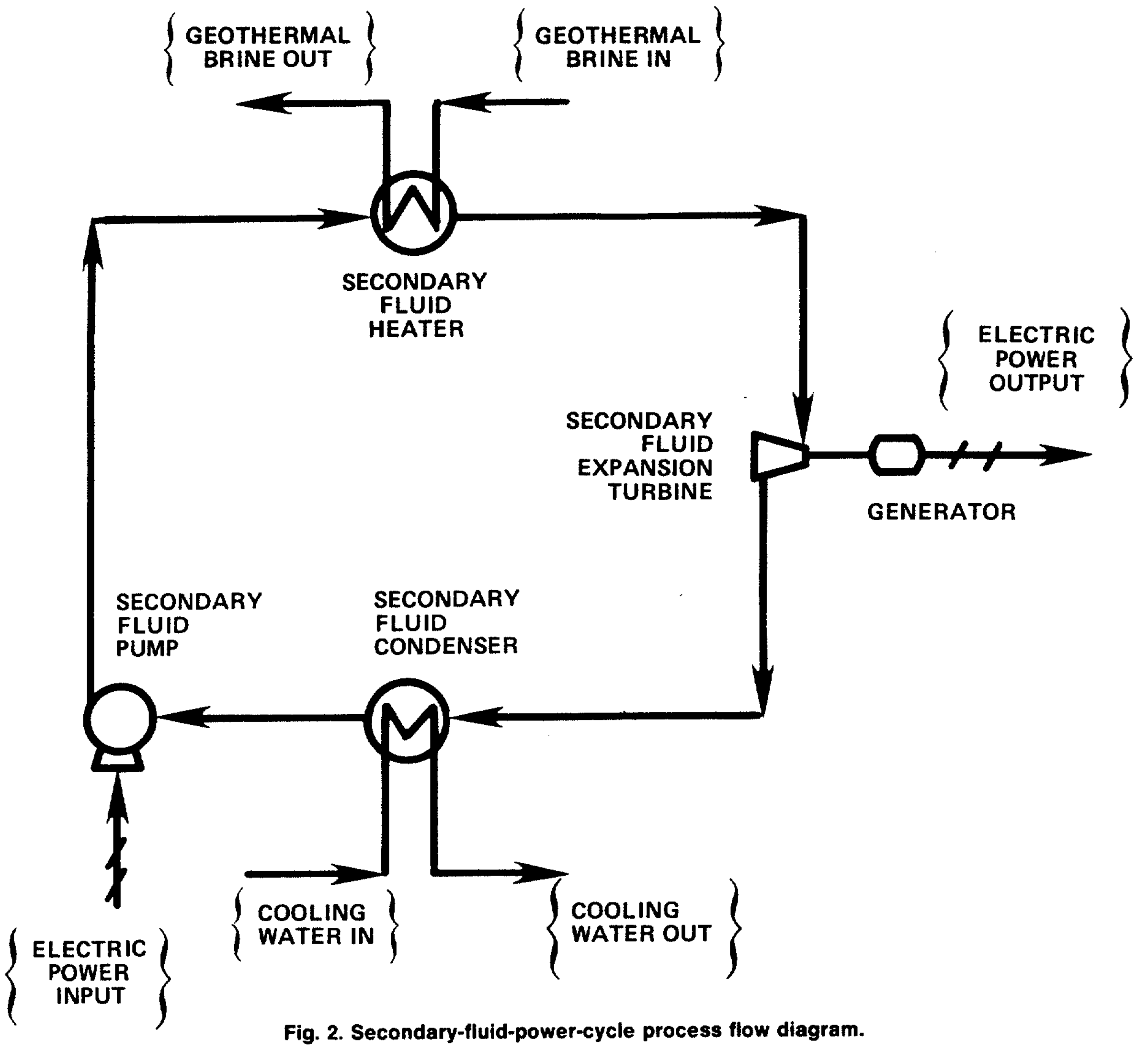

Fig. 2. Secondary-fluid-power-cycle process flow diagram.

The second block of Figure 1 represents the fuel plant. The geothermal brine passes through a methane separator operating in the neighborhood of 15 megapascals. The partially degassed brine passes on to the hydraulic power plant. The methane from the 15-megapascal separator is pressure-reduced to pipeline pressure. This pressure-reduced methane joins compressed methane which comes from lower pressure separators in the hydraulic power plant. The combined gas streams are dehydrated and prepared for pipeline.

The third block of Figure 1 represents the hydraulic power plant. The 15-megapascal brine passes through a hydraulic turbine for power recovery and electric-power generation. The turbine-outlet pressure and the number of stages of low-pressure methane separation can vary. These are design questions to be resolved in conjunction with the compression requirements for the fuel plant. Reference 1 gives a turbine-outlet pressure of 2 megapascals with two stages of methane separation at 2 megapascals and 1 megapascal. The separated methane, as previously mentioned, is returned to the fuel plant for compression and further treating. The geothermal brine leaves the hydraulic power plant at 1 megapascal and 435 K.

The fourth block of Figure 1 represents the thermal power plant. One approach for thermal energy recovery, a double-stage steam flash scheme, was studied in reference 1. In that study 10 to 20 percent of the brine was flashed to steam. The steam then passed through a steam turbine for electric-power generation. The remaining 80 to 90 percent of the brine was rejected to brine disposal at about 355 K. In the present study, however, we shall utilize a different approach for thermal energy recovery, namely, the secondary-fluid power cycle.

Finally, the fifth block of Figure 1 represents the disposal of the geothermal brine. This must be accomplished in an economically and environmentally sound manner. Reinjection into the production formation would be environmentally sound. It is thought, however, that this method would be uneconomical because of high formation pressure and, hence, high pumping costs. Reinjection into a shallower formation at lower pressure has been proposed as an economical method of disposal. The environmental effects would depend upon the specific location. For a facility near the sea, it may be feasible to discharge the brine into the sea since the geothermal brine has a salinity less than that of sea water. For this same reason, the brine would be a good feedstock for a desalination plant. Although all these schemes need more study, the currently most favored method of disposal is reinjection of the brine into another formation.

The thermal-power-plant block is clouded to emphasize that this design project treats only this portion of the geothermal-energy plant. At this point the brine has been thoroughly degassed. Pumping for disposal is included in the brine cost.

III. SECONDARY-FLUID POWER CYCLE

Here the secondary-fluid cycle is described in general terms, a process flow diagram being given in Figure 2. Thermodynamically, this is referred to as the *organic Rankine cycle*. An idealized cycle is illustrated on a pressure-enthalpy diagram for a hypothetical secondary fluid in Figure 3.

First, heat is transferred from the geothermal brine to the secondary fluid. This transfer is accomplished in the secondary fluid heater (Figure 2) and corresponds to segment A-B on the cycle diagram of Figure 3. This segment is shown ideally as a horizontal line. Actually, the line would slope downward to the right because of pressure drop through the exchanger and associated piping.

Next, the secondary fluid is expanded through the secondary-fluid expansion turbine. Here the thermal energy of the geothermal brine, which has been transferred to the secondary fluid, is converted to shaft work and thence to electric power by the generator (segment B-C on Figure 3). The segment is shown ideally as a line of constant entropy. Actually, the line would lie to the right of this isentropic line because of turbine inefficiencies.

Next, the secondary fluid is condensed in the secondary-fluid condenser. This step is illustrated by segment C-D in Figure 3. This idealized horizontal line would actually slope downward to the left because of pressure drop in the condenser and associated piping.

TABLE 1. RETURN ON INVESTMENT (ROI), CALCULATION STATEMENT

1) Capital employed
    Total capital investment ____________

2) Profit statement
    Sales revenue ____________
    Manufacturing costs (____________)
    Gross profit ____________
    Overhead expenses (____________)
    Taxable income ____________
    Income taxes (@ 48%) (____________)
    Net profit after taxes ____________

3) Cash flow statement
    Net profit after taxes ____________
    Depreciation ____________
    Cash flow ____________

4) ROI calculation

$$\text{ROI} = \frac{\text{Cash flow} \times 100}{\text{Total capital investment}}$$

ROI = ______________%

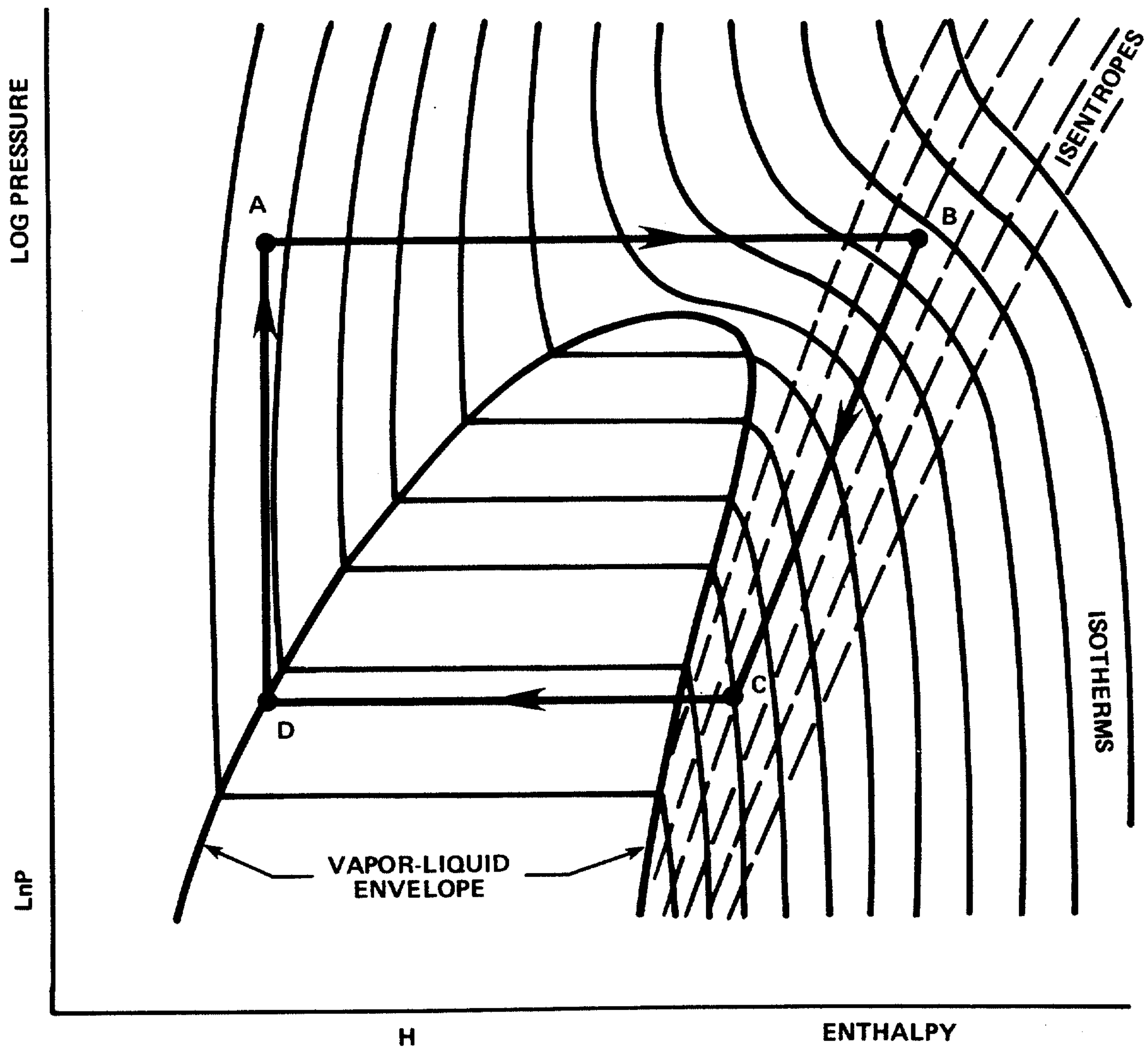

Fig. 3. Organic Rankine cycle.

Finally, the condensed secondary fluid is pumped to the higher cycle pressure by the secondary-fluid pump (segment D-A on Figure 3). This operation completes the secondary-fluid cycle.

IV. ECONOMIC CRITERIA

The purpose of this design project is to determine the optimal design of a secondary-fluid power plant subject to the technical and economic constraints presented here. This design will be preliminary because of the relative novelty of the process, which has necessitated the somewhat arbitrary selection of some of the economic and design-basis parameters. Because of the preliminary nature of this project, a simple profitability criterion is to be used. Here *optimal design* means that design which gives the best "instantaneous" ROI (Return on Investment). The definition of the ROI to be used on this project is given by Table 1.

The format for presentation of the economic calculations is given in Tables 1 through 4. Table 1 presents the format for calculation of the ROI. Tables 2 through 4 summarize various line items on Table 1.

Table 2 is the Capital-Investment-Summary format. The process unit cost is to be estimated from the costs of the major equipment items, which may be determined from reference 2. The offsites will include site preparation, buildings, storage facilities, utilities, auxiliary facilities, and offsite piping. That is, offsites will include all equipment required other than the major items shown on the flow diagram (Figure 2). Offsites are to be estimated at 40 percent of the process unit cost. Startup costs are to be estimated as 7 percent of the fixed assets. Working capital is to be estimated as 3 percent of the fixed assets.

Table 3 is the Manufacturing-Cost-Summary format. On the basis of previous studies, the raw material costs (the geothermal brine) are to be taken as 0.13 mil/kg. These include both brine supply and disposal costs. The bases for estimating operations, maintenance, and utilities costs are given in Table 5.

Table 4 is the Overhead-Expense-Summary format. The bases for estimating these costs are given in Table 6.

The gross generated electric-power output is to be sold at 90 mils/kw-h. The Federal Income Tax is 48 percent of the Taxable Income.

Equipment escalation factors are as follow:

Year	Equipment-cost escalation index
1970	100.0
1972	109.5
1974	131.4
1976	155.7
1978	171.6
1980	187.5

All economic calculations are to be based on 1980 dollars. All economic data given in this scope are based on 1980 dollars.

Some special precautions are needed in the estimation of the capital cost for the rotating equipment. First, the base-capital-costs curves for centrifugal pumps as given in reference 2 are *not* to be extrapolated. The use of pumps restricted by the referenced curves may result in a multiplicity of pumps (series or parallel) and may seem unrealistic but will give reasonable capital-cost estimates. Second, the capital cost of a turbine-generator set is to be estimated as being the same as the capital cost of a motor-driven centrifugal compressor set, each having the same Gas Power. No auxiliaries will be required for these "compressors."

TABLE 2. CAPITAL-INVESTMENT SUMMARY

Process unit	________	
Offsites	________	
Subtotal—Fixed assets		________
Startup costs	________	
Working capital	________	
Subtotal—Other assets		________
Total capital investment		________

TABLE 3. MANUFACTURING-COST SUMMARY

Raw materials costs		________
Operations costs		
Operating supplies	________	
Operating labor	________	
Operating supervision	________	
Operating payroll burdens	________	
Maintenance costs		________
Maintenance supplies	________	
Maintenance labor	________	
Maintenance supervision	________	
Maintenance payroll burdens	________	
Utilities costs		________
Electric power	________	
Cooling water	________	
Total manufacturing costs		________

TABLE 4. OVERHEAD-EXPENSE SUMMARY

General administration	________
Sales and marketing	________
Finance and accounting	________
Technical services	________
Capital interest	________
Insurance	________
Local taxes	________
Royalties	________
Other general expenses	________
Depreciation	________
Total overhead expenses	________

TABLE 5. MANUFACTURING-COST BASIS

Operations-Cost Basis	
Operating jobs	2 Operators/shift
Operating supervision	50% Direct operating labor
Direct labor rate	$24,000/man-year
Operating-payroll burden	30% Direct operating labor
Operating supplies	10% Direct operating labor
Maintenance-Cost Basis	
Maintenance labor	1.5% Capital investment
Maintenance supervision	1.0% Capital investment
Maintenance-payroll burden	30% Direct maintenance labor
Maintenance materials	1.0% Capital investment
Utilities-Cost Basis	
Electric power	90 mils/kw-h
Circulating cooling water	
Wet-bulb temperature	300 K
Dry-bulb temperature	308 K
Cooling-water temperature to condenser	305 K
Cooling-water temperature from condenser, K	Cooling-water cost, $/[(yr) (kg/s)]
313	288
316	295
319	306
322	319
325	332
328	347

TABLE 6. OVERHEAD-EXPENSE BASIS

General administration	0.8% Capital investment
Sales and marketing	0.2% Capital investment
Finance and accounting	0.5% Capital investment
Technical services	1.0% Capital investment
Capital interest	9.0% Capital investment
Insurance	1.0% Capital investment
Local taxes	0.5% Capital investment
Other general expenses	1.0% Capital investment
Royalties	12% Raw-material costs
Depreciation	10 yr., straight-line, zero salvage value

V. TECHNICAL CRITERIA

1. Geothermal Brine

The flow rate of the geothermal brine for this design is to be constant and fixed at 177 kg/s. Other parameters are

Inlet pressure	1.0 megapascal
Inlet temperature	435 K
Outlet temperature (min.)	345 K

Approximate Composition (weight percent)

Methane	(CH_4)	0.00
Silica	(SiO_2)	0.05
Salt	(NaCl)	0.95
Water	(H_2O)	99.00
Total		100.00

The minimum-outlet-temperature criterion is for the prevention of silica deposition.

2. Secondary Fluid

The secondary fluid to be considered is propane. Some data and references to other data are in reference 3.

3. Equipment Design

All equipment is to be designed in accordance with established engineering principles. The design methods of references 3, 4, and 5 are particularly recommended. Reference 6 should provide additional insight.

For purpose of design, construction, and operating flexibility and for economy, each major equipment item on the flow diagram (Figure 2) is to be composed of a number of identical standard-size units operating in parallel or in series, depending upon context.

Additional criteria for the major equipment items follow.

4. Secondary-Fluid Heaters

Each unit (if more than one is required) is to be a horizontal, one-pass, countercurrent shell-and-tube, fixed-tube-sheet heat exchanger. Other details are

TEMA size	60 × 480 (maximum)
TEMA type	BEM
Tubes	3/4-in. admiralty, 14 BWG 15/16-in. triangular pitch
Minimum baffle spacing	
Baffle cut	20 to 30 percent
Tubeside fluid	Geothermal brine
Tubeside velocity	1.5 m/s (minimum) 2.5 m/s (maximum)
Temperature approach	10 K
Total fouling factor	0.001735 ($m^2 \cdot s \cdot K$)/J

5. Secondary-Fluid Condensers (each unit)

All specifications for the Secondary-Fluid Heaters shall apply to these exchangers with the following differences:

Tubeside fluid	Cooling water
Tubeside inlet temperature	305 K
Tubeside outlet temperature	330 K (maximum)

6. Secondary-Fluid Pumps (each unit)

Maximum capacity	75 kg/s (specific gravity = 0.47)
Efficiency	75 percent
Electric motor included in each unit	
Maximum motor kw	185 kw
Motor voltage	4.16 kv, 3 phase, 60 Hz

7. Secondary-Fluid Expansion Turbines (each unit)

Gas power	7 450 kw
Efficiency	85 percent

8. Generators (each unit)

One per turbine	
Maximum input power	7 450 kw
Output voltage	13.2 kv, 3 phase, 60 Hz

9. Spare Equipment

No spare equipment items are to be furnished.

VI. REPORT FORMAT

1. Cover letter or transmittal document.
2. Introduction
   A concise statement of the problem, covering background and objectives.
3. Summary
   a. A brief description of the work involved in the evaluation

    b. The conclusions or recommendations.

4. Technical information

   A description of the proposed process, including a flow sheet detailing flow rates, concentrations, and equipment sizes.

   Calculation summaries of important operating and design parameters, detailing the equations used and the assumptions employed.

   Statements justifying the final conditions chosen for the process variables.

   Summaries of equipment specifications and costs, capital investment, cash flow tabulation, and overall plant profitability as a percentage return on the total investment.

5. Appendix

   Calculations, graphs, an explanation of all the assumptions made, and any details not included elsewhere.

VII. REFERENCES

1. Wilson, J. S., "A Geothermal Energy Plant," *CEP*, vol. 73, No. 11 (Nov.-1977), pp. 95-98.
2. Guthrie, K. M., *Process Plant Estimating, Evaluation and Control*, Craftsman Book Company of America, Solana Beach, CA (1974).
3. Perry, J. H., *Chemical Engineers' Handbook*, 5 ed., McGraw-Hill, New York (1973).
4. Peters, M. S., and K. D. Timmerhaus, *Plant Design and Economics for Chemical Engineers*, 2 ed., McGraw-Hill, New York (1968).
5. Rase, H. F., and M. H. Barrow, *Project Engineering of Process Plants*, Wiley, New York (1957).
6. Shepherd, D. G., "Pick up Energy from Low Heat Sources," *Hydrocarbon Processing* (Dec. 1977).