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GEOHERMAL COMMERCIAL POWER PLANT STUDY

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Prepared by

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SUMMARY OF WORK ACCOMPLISHED

Efforts were concentrated on Task 10, Plant Operating Modes. The Heber plant, which was previously designed for constant brine temperature, was reviewed and changes necessary to accommodate declining brine temperature were determined.. Resultant required modifications to the computer code GEOTHM were made. The engineering, in terms of sketches and equipment lists, needed to support the capital cost estimate was determined. Attempts to use the computer program GEOTHM to develop the heat and mass balances for plants with declining geothermal fluid temperature disclosed that this code alone cannot be used for this purpose because it does not include turbine stage pressure-drop equations. It was determined that the most expedient method for obtaining the data needed for this study would be to develop a separate small computer program containing these turbine equations. With the assistance of a turbine consultant from Bechtel's San Francisco Power Division, the detailed methodology for the program was developed, and coding was started.

The new computer program, named GEOPRS, will be needed by anyone that performs reservoir temperature decline studies for flashed-steam power plants. Accordingly, GEOPRS should be incorporated into GEOTHM and GEOCOST by the originators of those computer programs.

The original plan for Task 10 was based on using GEOTHM to perform the heat and mass balances. The extra effort required for determining the need for the new program GEOPRS and for developing it, was not anticipated. However, additional manpower is being applied and the task schedules are being rearranged as described below under Future Plans, in order to assure that the overall project schedule is maintained.

DISCUSSION OF WORK ACCOMPLISHED

In reviewing the Heber plant, designed for constant brine temperature in Task 1, it was determined that the main equipment modification needed for the computer program GEOTHM in order to accommodate declining brine temperature was the addition of vacuum pumps in series with the condenser

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steam-jet ejectors. Vacuum pumps are necessary because, as the brine temperature declines, the steam pressure available to operate the steam-jet ejectors also declines and the ejectors become very inefficient. In consultations with a vacuum pump manufacturer, it was determined that a single-stage jet ejector and a vacuum pump in series would be the most efficient method for removing noncondensable gases from the condenser. Appropriate modifications were made to GEOTHM. Additional improvements made to GEOTHM included providing a heat and mass balance for the ejector after-condenser and increasing the accuracy of the predicted amount of blowdown from evaporative cooling towers.

The design team and the cost engineers jointly reviewed the changes to the 50 MWe Heber plant, previously designed in Task 1 for constant brine temperature, that would be necessary to incorporate similar 50 MWe units into 50, 100, and 200 MWe plants designed for declining brine temperature. Based on this review, the engineering necessary to support capital cost estimates for 50, 100, and 200 MWe plants designed for the constant power operating mode, and 50, 100, and 200 MWe plants designed for the constant brine flow rate operating mode, was delineated.

Endeavors to use GEOTHM to develop the heat and mass balance data needed for the input to the Chevron reservoir computer model as described in detail in the previous progress report, resulted in two major findings. One is that brine flow rate control should be used for both operating modes, the constant power output mode and the constant brine flow rate mode. The alternative is to control with the turbine throttle valves, but this introduces significant inefficiency. Another advantage in controlling brine flow is the possible elimination of the turbine throttle valves which are high cost items.

The second finding is that GEOTHM cannot be used by itself to develop the heat and mass balances. GEOTHM calculates the fraction of steam flashed from the brine in the first and second stage flash tanks based on input operating pressures for the two tanks. Each time new flash tank pressures are input, the program assumes a different turbine that will

fully utilize the resultant steam flow. However, the present study requires that plant performance be calculated for varying flash tank pressures with the same turbine. Since the second stage flash tank pressure is controlled by the pressure drop through the turbine which changes with varying conditions, it is necessary to calculate turbine stage pressure-drops. These equations are not in GEOTHM since they were not needed for its previous applications. It was determined that the most expedient method for obtaining the data needed for this study would be to write a separate small computer program that would contain the turbine stage pressure-drop equations. The calculation procedure for this new program, named GEOPRS, is described in the attachment to this report. Sufficient detail is given in the procedure to allow the originators of existing codes such as GEOTHM and GEOCOST to incorporate this capability. However, the task may be facilitated by supplying the FORTRAN listing after Bechtel has coded and debugged the program.

3 FUTURE PLANS

The project work plan will be rearranged to allow for the development of the computer program GEOPRS while maintaining the overall time schedule. This will be accomplished by undertaking parallel efforts on the computer program development and on Task 14, MSF/Binary Regeneration, during the next report period.

4 FINANCIAL STATUS

Total estimated contract cost		\$413,633
Previous expenditures	\$290,440	
Estimated expenditures this period	17,510	
Cumulative expenditures to date		307,950
Funds remaining		\$105,683

COMPUTER PROGRAM GEOPRS

CALCULATION PROCEDURE

1.0 OBJECTIVE OF COMPUTER PROGRAM GEOPRS

The steam turbine for a geothermal power plant using the flashed-steam energy conversion process is designed to admit steam at specified inlet pressures. As brine temperature declines over the life of the plant the flash pressures will adjust themselves so that the steam flow rate passed by the turbine equals the flow rate of steam flashed in the drums. Since flash pressures are part of the input to the computer program GEOTHM, it cannot be used by itself to calculate plant performance for reduced brine temperature with the same turbine. Program GEOPRS calculates the resulting flash pressures for a given turbine for two plant operating modes:

- 1) Constant plant net output power, which is maintained by controlling the brine flow rate.
- 2) Constant brine flow rate

Flash pressures calculated by GEOPRS are input to GEOTHM which calculates the plant performance.

2.0 ASSUMPTIONS

The following assumptions have been made:

- 1) The energy in the steam that flows to the steam jet ejector is negligible.
- 2) Perfect gas relationships hold.
- 3) Impulse-type turbines such as those manufactured by GE and Mitsubishi are used.
- 4) The turbine contains five stages with admission of low pressure steam between the second and third stages. The program can be readily extended to perform calculations for any number of stages.
- 5) A two-stage flashed steam energy conversion process is used.
- 6) The computations are being performed for low salinity geothermal brine resources whose thermodynamic properties can be closely approximated by those of pure water.

3.0 CALCULATIONS

3.1 CONSTANTS THAT ARE INPUT TO THE PROGRAM:

- Brine Temperature, T_B
- Turbine mechanical efficiency, η_m
- Generator electrical efficiency, η_e
- Gross power production, P_G , is input to the program for the "constant net power" plant operating mode
- Brine flow rate, $\dot{w}_B$, is input to the program for the "constant net power" plant operating mode

3.2 INITIAL VALUES THAT ARE INPUT TO THE PROGRAM

After the first iteration of the program, these parameters have the values obtained from the last simultaneous solution of equations 10 through 18 listed below.

- Turbine stage pressures p_1 through p_5
- Overall turbine expansion efficiency, η_t .

3.3 CALCULATION OF TURBINE CONSTANTS C_1 THROUGH C_5

3.3.1 Pressures p_1 and p_3 are selected to obtain maximum specific net energy for initial plant operation.

3.3.2 The GEOTHM program is run for the appropriate brine temperature and the desired net output.

3.3.3 h_{ex} is calculated from

$$h_{ex} = \frac{\dot{w}_H h_H' + \dot{w}_L h_L'}{\dot{w}_H + \dot{w}_L} \quad (1)$$

3.3.4 The initial value of the overall expansion efficiency is calculated from

$$\eta_t = \frac{h_{g1} - h_{ex}}{h_{g1} - h_s} \quad (2)$$

3.3.5 A semilog plot of turbine stage pressures is constructed by drawing a straight line through pressures p_1 and p_3 as shown in Figure A-1.

Stage Inlet Pressure Versus Stage Number

Figure A-1

- 3.3.6 Pressures p_2 , p_4 , and p_5 are read from the plot.
- 3.3.7 v_1 , the specific volume of the steam at the high pressure turbine inlet, is calculated.
- 3.3.8 h_{2s} is the enthalpy after an isentropic expansion of the high pressure steam from pressure p_1 to pressure p_2 . h_2 is the actual enthalpy upstream of the turbine's second stage (at pressure p_2) and is calculated from
- $$h_2 = h_{g1} - (h_{g1} - h_{2s}) \eta_t \quad (3)$$
- 3.3.9 v_2 is determined at the state point defined by pressure p_2 and enthalpy h_2 .
- 3.3.10 Specific volumes v_3 , v_4 , and v_5 are calculated by the same procedure used to calculate v_2 . For each case, expansion is taken from the saturated vapor state at pressure p_1 , using the expansion efficiency η_t .

3.3.11 Turbine constants C_1 through C_5 are calculated from:

$$C_1 = \frac{\dot{w}_H \sqrt{\frac{v_1}{p_1}}}{\left(\frac{p_2}{p_1}\right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_2}{p_1}\right)^{\frac{K-1}{K}}}} \quad (4)$$

$$C_2 = \frac{\dot{w}_H \sqrt{\frac{v_2}{p_2}}}{\left(\frac{p_3}{p_2}\right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_3}{p_2}\right)^{\frac{K-1}{K}}}} \quad (5)$$

$$C_3 = \frac{(\dot{w}_H + \dot{w}_2) \sqrt{\frac{v_3}{p_3}}}{\left(\frac{p_4}{p_3}\right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_4}{p_3}\right)^{\frac{K-1}{K}}}} \quad (6)$$

$$C_4 = \frac{(\dot{w}_H + \dot{w}_L) \sqrt{\frac{v_4}{p_4}}}{\left(\frac{p_5}{p_4}\right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_5}{p_3}\right)^{\frac{K-1}{K}}}} \quad (7)$$

$$C_5 = \frac{(\dot{w}_H + \dot{w}_L) \sqrt{\frac{v_5}{p_5}}}{\left(\frac{2}{K+1}\right)^{\frac{1}{K-1}} \sqrt{\frac{K-1}{K+1}}} \quad (8)$$

3.4 CALCULATION OF STATE POINT PROPERTIES

A subroutine containing the thermodynamic properties of steam (Ref. 1) is part of the main program. This feature enables the program to compute specific volumes and enthalpies.

3.4.1 Calculation of Specific Volumes

- v_1 , the specific volume of the steam at the high pressure turbine inlet, is computed from pressure p_1 at the saturated vapor state
- h_{2s} is the enthalpy after an isentropic expansion of the high pressure steam from its saturated vapor state at p_1 to pressure p_2 . h_2 is the actual enthalpy at pressure p_2 and is calculated from

$$h_2 = h_{g1} - (h_{g1} - h_{2s}) \eta_t \quad (9)$$

- v_2 is determined at the state point defined by pressure p_2 and enthalpy h_2 .
- Specific volumes v_3 , v_4 , and v_5 are calculated by the same procedure used to calculate v_2 . For each case, expansion is taken from the saturated vapor state at pressure p_1 , using the expansion efficiency η_t .

3.4.2 Calculation of Enthalpies

- Given pressures p_1 and p_3 , enthalpies h_{f1} , h_{g1} , h_{f3} , and h_{g3} are computed at their saturated states.

3.5 EQUATION SOLVING

The following nine equations are solved simultaneously for unknowns p_1 , p_2 , p_3 , p_4 , p_5 , h_{ex} , $\dot{w}_H$, $\dot{w}_L$, and $\dot{w}_B$. Equations 1 through 5 are derived from basic relationships of compressible fluid flow (Ref. 2). Equations 6 through 9 are energy balances.

$$\dot{w}_H = C_1 \sqrt{\frac{p_1}{v_1}} \left(\frac{p_2}{p_1} \right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_2}{p_1} \right)^{\frac{K-1}{K}}} \quad (10)$$

$$\dot{w}_H = C_2 \sqrt{\frac{p_2}{v_2}} \left(\frac{p_3}{p_2} \right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_3}{p_2} \right)^{\frac{K-1}{K}}} \quad (11)$$

$$\dot{w}_H + \dot{w}_L = C_3 \sqrt{\frac{p_3}{v_3}} \left(\frac{p_4}{p_3} \right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_4}{p_3} \right)^{\frac{K-1}{K}}} \quad (12)$$

$$\dot{w}_H + \dot{w}_L = C_4 \sqrt{\frac{p_4}{v_4}} \left(\frac{p_5}{p_4} \right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{p_5}{p_4} \right)^{\frac{K-1}{K}}} \quad (13)$$

$$\dot{w}_H + \dot{w}_L = C_5 \sqrt{\frac{p_5}{v_5}} \left(\frac{2}{K+1} \right)^{\frac{1}{K-1}} \sqrt{\frac{K-1}{K+1}} \quad (14)$$

$$\dot{w}_H h_{g1} + \dot{w}_L h_{g3} - (\dot{w}_H + \dot{w}_L) h_{ex} = \frac{3413.14 \times P_G}{\eta_m \times \eta_e} \quad (15)$$

$$\dot{w}_H = \dot{w}_B \left(\frac{h_B - h_{f1}}{h_{g1} - h_{f1}} \right) \quad (16)$$

$$\dot{w}_2 = \dot{w}_B \left(\frac{h_{f1} - h_{f3}}{h_{g3} - h_{f3}} \right) \left(1 - \frac{h_B - h_{f1}}{h_{g1} - h_{f1}} \right) \quad (17)$$

$$\begin{aligned} \dot{w}_B h_B = & \frac{3413.14 \times P_G}{\eta_m \times \eta_e} + (\dot{w}_H + \dot{w}_L) h_{ex} \\ & + (\dot{w}_B - \dot{w}_H - \dot{w}_L) h_{f3} \end{aligned} \quad (18)$$

A standard equation solving subroutine (Ref. 3) is included in the main program for the purpose of solving these equations simultaneously. The brine flow rate $\dot{w}_B$ is the ninth unknown variable for the "constant power" operating mode. The gross power production P_G becomes the ninth unknown variable for the "constant brine flow rate" operating mode and thereby replaces $\dot{w}_B$, which is constant.

3.6 CALCULATION OF OVERALL EXPANSION EFFICIENCY

Using the most recently calculated values of p_1 and h_{ex} , expansion efficiency η_t is calculated from:

$$\eta_t = \frac{h_{g1} - h_{ex}}{h_{g1} - h_s} \quad (19)$$

where h_s is the enthalpy after an isentropic expansion from p_1 to the condenser pressure (taken as 4 inches Hg absolute). $\eta_t (n)$, the value after the n 'th iteration, is compared to $\eta_t (n-1)$, the value after the $(n-1)$ th iteration, to satisfy the following convergence criterion:

$$\eta_t (n) - \eta_t (n-1) < 0.01 \quad (20)$$

Once satisfied, the calculation is completed, and the program outputs the final values of the nine unknown variables. If the convergence criterion is not satisfied, the latest computed values of pressures p_1 through p_5 and expansion efficiency η_t are used to calculate new state point properties. The equations are again solved simultaneously, and the aforementioned procedure is repeated until the convergence criterion is satisfied.

4.0 A CHECK OF PROGRAM RESULTS

4.1 CONSTANT POWER OPERATING MODE

Pressures p_1 and p_3 , obtained as part of the constant power solutions, are used as input to program GEOTHM to calculate the gross power production of the plant. This value for gross power production must match (within $\pm 2\%$) the value used as input for the equation solving program GEOPRS. Otherwise, GEOPRS must be resubmitted with a new gross power.

4.2 CONSTANT FLOW RATE OPERATING MODE

Pressures p_1 and p_3 , obtained from GEOPRS for the "constant brine flow rate" operating mode are used as input to program GEOTHM to calculate the required auxiliary power for a constant net output. The resulting brine flow rate $\dot{w}_B'$ is compared to the constant value $\dot{w}_B$ used as input to program GEOPRS and the auxiliary power is scaled accordingly:

$$P_a = P_a' \left(\frac{\dot{w}_B'}{\dot{w}_B} \right) \quad (21)$$

where P_a' and $\dot{w}_B'$ are the auxiliary power and brine flow rate, respectively, calculated by GEOTHM for a constant net output, and P_a and $\dot{w}_B$ are the actual auxiliary power and brine flow rate, respectively, for the "constant brine flow rate" operating mode under consideration. The net power for this case is determined by subtracting P_a from P_G .

Nomenclature

<u>Symbol</u>	<u>Description</u>
$\dot{w}_H$	High pressure steam flow rate (lb/hr)
$\dot{w}_L$	Low pressure steam flow rate (lb/hr)
$\dot{w}_B$	Brine flow rate (lb/hr)
$\dot{w}_B'$	Brine flow rate for any constant net output (lb/hr)
p_1	Pressure ahead of first turbine stage (psia)
p_2	Pressure ahead of second turbine stage (psia)
p_3	Pressure ahead of third turbine stage (psia)
p_4	Pressure ahead of fourth turbine stage (psia)
p_5	Pressure ahead of fifth turbine stage (psia)
T_B	Downhole temperature of brine ($^{\circ}\text{F}$)
C_1	First turbine stage flow rate proportionality constant
C_2	Second turbine stage flow rate proportionality constant
C_3	Third turbine stage flow rate proportionality constant
C_4	Fourth turbine stage flow rate proportionality constant
C_5	Fifth turbine stage flow rate proportionality constant
η_t	Overall turbine expansion efficiency

Nomenclature

<u>Symbol</u>	<u>Description</u>
η_m	Turbine mechanical efficiency
η_e	Generator electrical efficiency
$\eta_t(n)$	Turbine expansion efficiency from latest iteration
$\eta_t(n-1)$	Turbine expansion efficiency from previous iteration
v_1	Specific volume ahead of first turbine stage (ft ³ /lb)
v_2	Specific volume ahead of second turbine stage (ft ³ /lb)
v_3	Specific volume ahead of third turbine stage (ft ³ /lb)
v_4	Specific volume ahead of fourth turbine stage (ft ³ /lb)
v_5	Specific volume ahead of fifth turbine stage (ft ³ /lb)
h'_H	Turbine exhaust enthalpy of high pressure steam (Btu/lb)
h'_L	Turbine exhaust enthalpy of low pressure steam (Btu/lb)
h_2	Actual enthalpy of steam upstream of the turbine's second stage (Btu/lb)
h_{2s}	Enthalpy of steam upstream of the turbine's second stage assuming an isentropic expansion across the first stage (Btu/lb)
h_{f1}	Saturated liquid enthalpy at the high flash pressure (Btu/lb)
h_{g1}	Saturated vapor enthalpy at the high flash pressure (Btu/lb)
h_{f3}	Saturated liquid enthalpy at the low flash pressure (Btu/lb)
h_{g3}	Saturated vapor enthalpy at the low flash pressure (Btu/lb)

Nomenclature

<u>Symbol</u>	<u>Description</u>
h_{ex}	Mixed exhaust enthalpy of high and low pressure steam (Btu/lb)
h_s	Exhaust enthalpy of high pressure steam assuming an isentropic expansion (Btu/lb)
K	Ratio of specific heat c_p/c_v
P_G	Gross power production of the plant (MWe)
P_a	Plant auxiliary power (MWe)
P'_a	Plant auxiliary power for any constant net output (MWe)

5.0 REFERENCES

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