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OPTIMISATION OF COOLING SYSTEM DESIGN PARAMETERS FOR A GEOTHERMAL POWER PLANT

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ABSTRACT

The selection of cooling system design parameters for a geothermal power plant directly affects the annual energy generation, steam consumption and capital cost. The selected design parameters, which consist of condenser pressure, wet bulb temperature and cooling tower approach temperature, are used to size the cooling system.

The final aelection of the design parameters is dependent upon an optimisation study which is essentially an economic compromise between capital and operating expenditures and revenues f r a the energy generated. The objective of the optimisation study is the aelection of design parameters which minimise the overall unit cost of the energy generated for the life of the plant.

This paper summarises the assumptions and procedures for optimising the selection of design parameters for a geothermal power plant using an atmospheric cooling system.

The relevant equations presented have been used to facilitate selection of optimum design parameters for a geothermal power plant in Indonesia. The results of this optinisation are given, together with a sensitivity analysis, to demonstrate the procedures for the selection of the optimum design parameters.

INTRODUCTION

Selection of a low design condenser pressure, small design approach and high design ambient wet bulb temperature will result in an efficient plant, the output from which is little affected by actual ambient temperatures, but which has a very high capital cost. Alternatively a low capital cost plant can be designed which is less efficient and for which the power output varies depending on the ambient temperature.

Thus the final selection of the design parameters to give the lowest overall cost is dependent upon an optimisation study which is essentially an economic compromise between capital cost and operating costs and the revenues from the energy generated. The objective of this paper is to describe and demonstrate the procedures for optimising the selection of the design parameters for a geothermal power plant using an atmospheric cooling system.

OPTIMISATION PROCEDURE

1 Cooling System Description

The optimisation procedures discussed in this paper are applicable to any type of geothermal atmospheric cooling system. However, for the purposes of this paper a cooling system comprising of the following principal plant items will be considered:

Direct contact condenser
Cooling water can pumps
Steam ejector gas extractors
Mechanical draught crossflow cooling tower

A typical plant layout incorporating these items is shown in Figure 1.

2 Optinisation 'Variables

2.1 Optinisation Parameters

The opthisation programme finds the optimum design value for the following three parameters :

- P - condenser pressure
- T_{WB} - ambient wet bulb temperature
- A - cooling tower approach temperature

These three design parameters fully define the cooling system and from then all other cooling system design parameters can be calculated a8 follows :

(i) The steam partial pressure in the condenser (P_{SAT}) is calculated from P using Dalton's law of partial pressures.

(ii) The condenser temperature (T_{SAT}) is the steam saturation temperature at P_{SAT}.

(iii) The on-tower temperature, $T_{ON} = T_{SAT} - TTD$ (TTD is the terminal temperature differ* — and is assumed to be a constant).

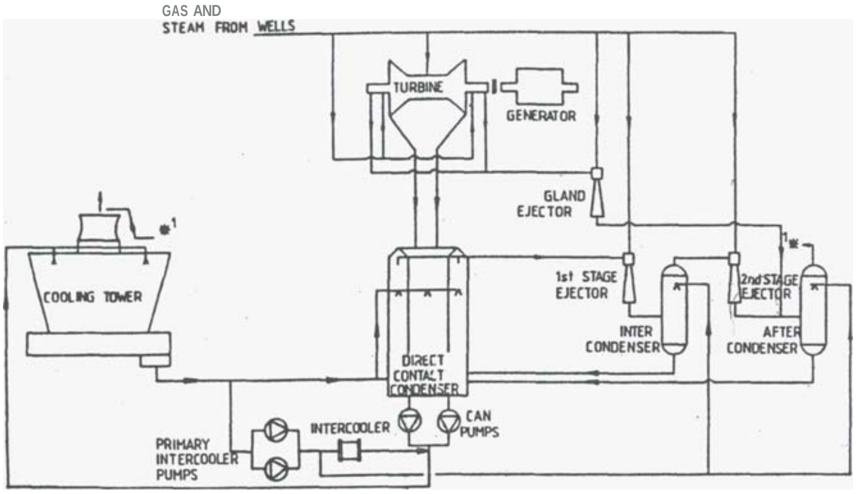

FIGURE 1: TYPICAL GEOTHERMAL POWER PLANT COOLING SYSTEM

(iv) The off tower temperature, $T_{OFF} = T_{WB} + A$
(v) The range, $R = T_{ON} - T_{OFF}$
(vi) The steam flaw (M) is calculated from P_{SAT} using the turbine isentropic efficiency.
(vii) The cooling water flow (Q) is calculated from M and R using the main condenser heat balance.

Note : Each parameter has a design value (the nominal value used to design the plant) and operating values (those which occur during actual plant operation and are continuously varying as the ambient temperature varies).

2.2 Effect of Variations in Design Condenser Pressure

If the design condenser pressure is increased, more steam must be supplied to the turbine in order for the turbine to produce the rated output (i.e. the efficiency of the plant has reduced).

2.3 Effect of Variations in Design Approach

The size and cost of the cooling tower is very sensitive to design approach, and increases as design approach is reduced.

2.4 Effect of Variations in Design Ambient Wet Bulb Temperature

Figure 2 illustrates the power station output as a function of the design wet bulb temperature. In Figure 2(a) the ambient wet bulb temperature never exceeds the selected design wet bulb temperature and, consequently the gross turbine output is always available. In addition to this, when ever the ambient wet bulb temperature is less than the design wet bulb teaperature it is possible to reduce the speed and power of the cooling tower fans thereby increasing the net station output.

Alternatively in Figure 2(b), the ambient wet bulb exceeds the design wet bulb for a percentage of the day. Therefore there will be periods of the day when gross turbine output is not maintained. Alternative generating capacity must be found to compensate for this diurnal variation in station output. To incorporate the cost of this alternative power source in the study so as to compare selected design conditions, marginal' intermediate peak and base rates are required. Figure 3 shows the relationship of marginal base and peak load generation with station output for variations in ambient wet bulb temperature.

2.5 Effect of Variation in Design Cooling Tower Range

The design cooling water flow is inversely proportional to design range. As design range increases cooling water flow decreases resulting in lower cooling water can pump cost, power consumption and cooling water pipework cost.

The cooling water can pump power consumption reduces the net station power output, and the operating value will slightly vary as cooling water flow varies with condenser pressure. For the purpose of comparing the varioue design conditions in the optimisation study, the can pump power consumption is valued at the marginal base load rate and the marginal peak rate as shown in Figure 3

2.6 Interactive Effects of Variations in Design Parameters

Sections 2.2 to 2.5 examined the effect of varying one design parameter in isolation. In actual fact variation of one design parameter will have an interactive effect on the other design parameters. It is possible to visualise these interactive effects by using the temperature scale shown in Figure 4

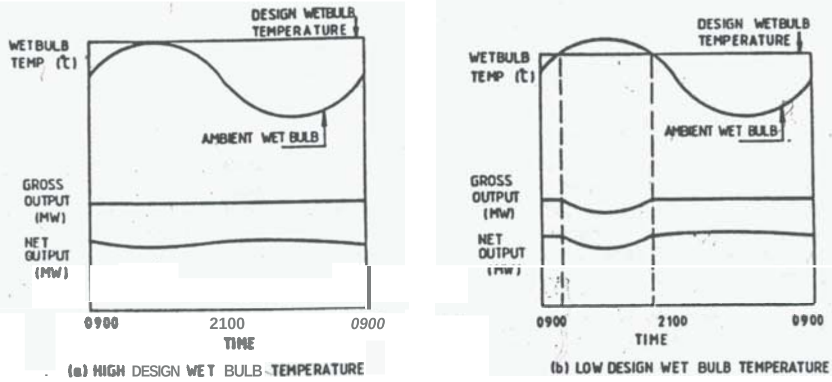

FIGURE 2 : STATION OUTPUT AS A FUNCTION OF DESIGN WETBULB TEMPERATURE.

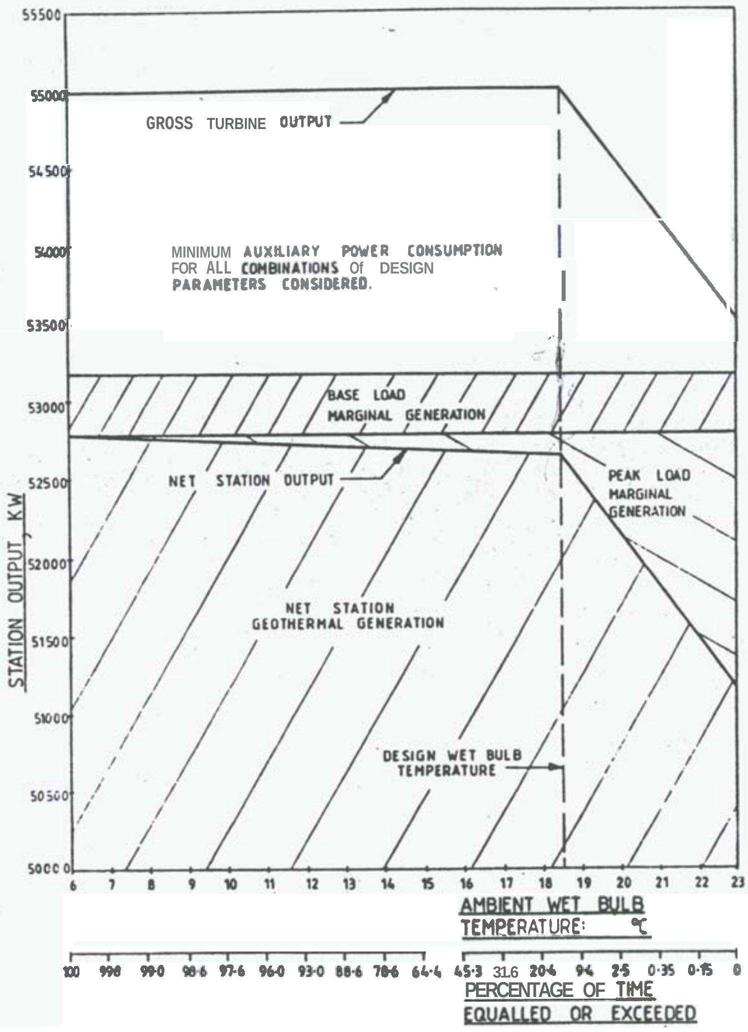

FIGURE 3 : THE EFFECT OF AMBIENT WET BULB TEMPERATURE ON NET STATION OUTPUT FOR A 55MW PLANT

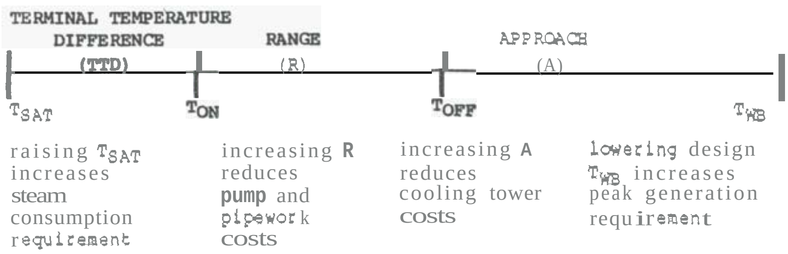

FIGURE 4 : TEMPERATURE SCALE SHOWING COOLING SYSTEM TEMPERATURES FROM STEAM CONDENSATION TEMPERATURE TO AMBIENT WET BULB TEMPERATURES

Figure 4 illustrates that no one cost *can* be reduced without simultaneously increasing all the other costs. Therefore an optimum combination of T_{SAT}, R, A and T_{WB} exists when the total cost is a minimum.

3. Optimisation Flow Chart

The economic opthisation procedure is shown diagramatically in the flaw chart in Figure 5. This flow chart was derived from an earlier flaw chart outlined by Lorentz and Van de Wydeven 1980.

The procedure used to identify the optimum combination of design parameters (P, T_{WB}, A) was to carry out an independent economic analysis for several possible combination of the design parameters within a selected range. The optimum combination of design parameters is that with the minimum unit cost ($/kWh).

APPLICATION OF OPTIHISATION PROCEDURES TO THE KAMOJANG GEOTHERMAL POWER PLANT, UNITS, 2 & 3, INDONESIA

1. Cooling System Description

The cooling system selected for the Kamojang Geothermal Power Plant, Units 2 and 3, (2 x 55 MW) is illustrated in Figure 1.

2. Assumptions in Programme

The following values have been assumed in order to facilitate modelling of the Kamojang cooling system:

(i) Steam supply,
- % weight gas, 0.5 at 6.5 bar abs

(ii) Turbo-generator,
- work from 3kg gas equals that fram 1kg steam
- isentropic efficiency, 78%
- mechanical and electrical losses (including leaving losses), 4%

(iii) Condenser and gas extraction system
- condenser pressure drop, 0.007 bar
- TTD, 3°C
- temperature difference between condenser gas outlet and cooling water inlet, 2°C
- insignificant variation in the inter and after condenser cooler water flaws with condenser pressure
- intercooler heat load constant

(iv) Cooling water pumps,
- pump efficiency, 80%
- motor efficiency, 92%

(v) Taxes and inflation,
- taxes were not included
- inflation was assumed constant through-out the evaluation period and therefore was not included.

(vi) Operation and Maintenance Costs,
- operation and maintenance costs were not included as they would be the same for all combinations of design parameters and therefore would not affect the selection of the optimum. (An exception to 'this would be the maintenance cost associated with excessive erosion of the ultimate turbine blade stage as described in Section 6).

3. Input Parameters

(i) Steam Price

Steam is purchased at Kamojang 'across the fence'. At the time of this study the steam price was still under negotiation therefore it was calculated by two different methods. Firstly by basing the steam price on its value for oil substitution, a price of US$6.29 per tonne was calculated. Secondly, by basing the steam price on the steamfield cost, a price of US$1.83 per tonne was calculated.

Based on information available at the time, a value of US$3.50 per tonne was used. (Following completion of this study, the stem price was confirmed to be about US$4.50 per tonne).

(ii) Marginal Generation Costs

A separate computer programme was developed to calculate the marginal generation intermediate peak and base load costs, based on an oil and coal power plant respectively at the same capacity as Kamojang. Capacity utilisation factors of 40% and 70% were used for-the oil and coal power plants respectively.

The calculated marginal costs for intermediate peak generation and base load generation were 9.28c/kWh and 4.75c/kWh respectively.

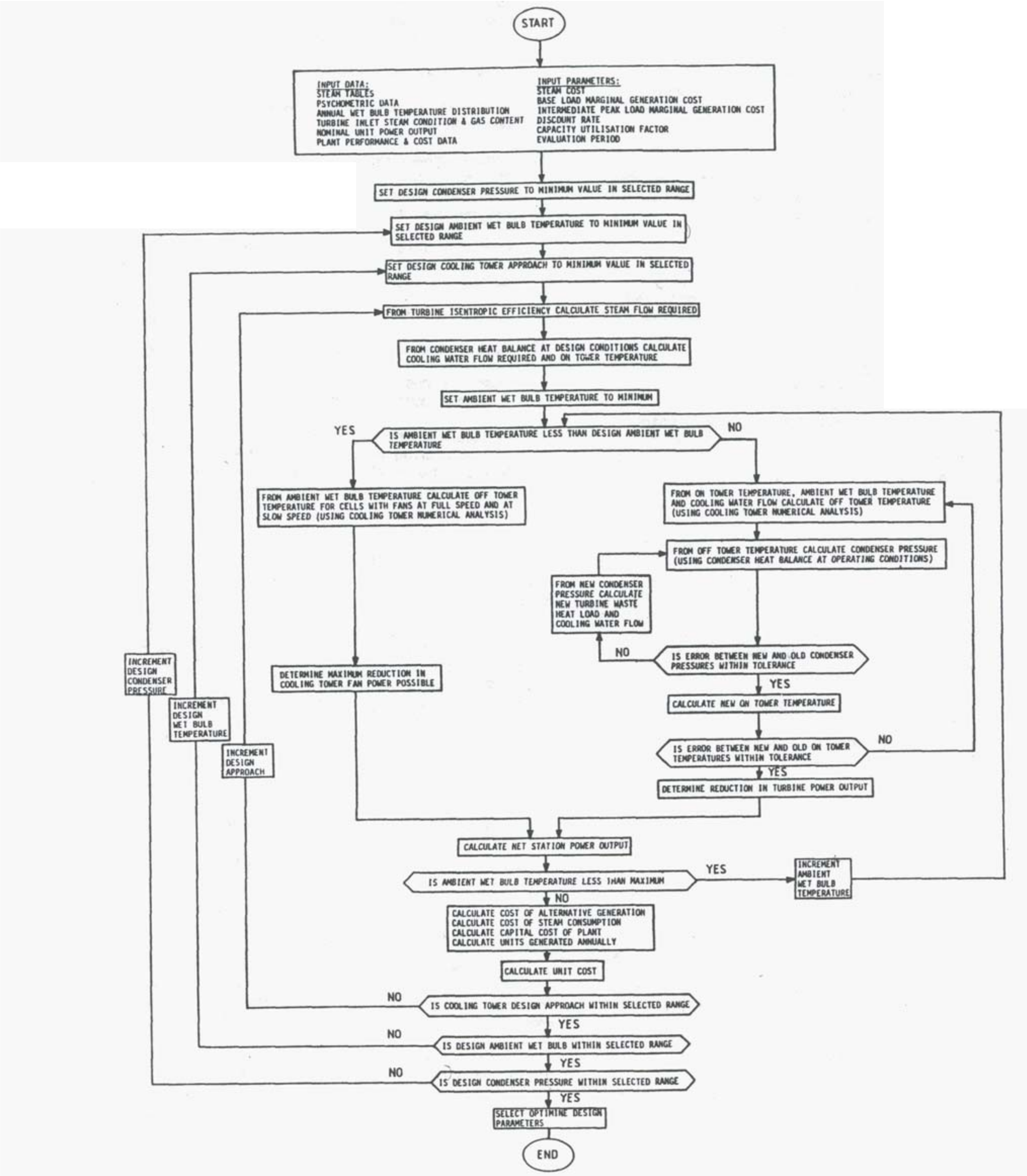

FIGURE 5 : OPTIMISATION FLOW DIAGRAM

(iii) Discount Rate

A 12% p.a. discount rate was used for this project.

(iv) Capacity Utilization Factor

The capacity utilization factor was conservatively estimated to be 80% throughout the life of the plant.

(v) Plant Evaluation Period

A plant evaluation period of 25 years was used. This assumed that the plant had no residual value at the end of the evaluation period.

4. Optimisation Programme Equations

Specific data and relationships for the capital investment costs were included. These costs made up the total capital cost component, CTOT, of the unit cost in which :

CTOT = CTURBINE + CCONDENSER + CEJECTOR + CPIPEWORK + CPUMP + CTOWER.

The derivation of the following equations which represent the capital cost for 1 x 55 MW unit were obtained from budgetary costs from several manufacturers and are represented in 1982 US dollars :

(i) Turbo-generator Cost (CTURBINE)

An average cost for a double-flow turbo-generator of US$8.5 million was used. A cost index from one manufacturer enabled the costs of different physical sized turbines to be determined as the exhaust annulus area varies with the design condenser pressure. The cost indices for the various design pressures were incorporated into the programme in matrix form.

(ii) Condenser Cost (CCONDENSER)

A relationship for a 316L stainless steel clad carbon steel shell direct contact condenser was derived as follows :

$$CCONDENSER = BCOST(0.172 + 2.4 \times 10^{-4}\ MWI)\ US\$$$

Where MWI is the cooling water flow, kg/s, and BCOST is the base condenser cost of US$2.444 million.

(iii) Steam Ejector Costs (CEJECTOR)

Conservative cost data for various design conditions were obtained for two 100% two stage steam ejectors, with inter and after condensers, and constructed from 316L stainless steel. The data was incorporated into the programme in matrix form. A base cost of US$1.333 million was used.

(iv) Pipework Costs (CPIPEWORK)

A conservative cost for the supply and installation of 316L stainless steel and fibre reinforced polyester pipework was derived based on a water velocity of 2.5 m/s.

$$CPIPEWORK = 3300 \times MWI^{1/2}\ US\$.$$

(v) Pump Costs (CPUMP)

Prices obtained for two 50% can pumps yielded the following relationship :

$$CPUMP = 141.36 \times MWP + 680\,000\ US\$.$$

where MWP is the water flow through each pump, kg/s.

(vi) Cooling Tower Costs (CTOWER)

The cost relationship of different sized cooling towers for varying design conditions was derived as follows :

$$COST\ 1 = 3.75 - 0.5715A + 0.0404A^2 - 0.001076A^3$$

$$COST\ 2 = 0.561 + 0.28\ T_{ON} - 0.0155\ T_{ON}^2 + 3.01 \times 10^{-4}\ T_{ON}^3 - 2 \times 10^{-6}\ T_{ON}^4$$

$$COST\ 3 = 2.44 - 0.125\ T_{WB} + 2.5 \times 10^{-3}\ T_{WB}^2$$

$$COST = COST\ 1 \times COST\ 2 \times COST\ 3$$

$$CTOWER = COST \times BCOST$$

A basecost (BCOST) of US$3 million was used corresponding to the cooling tower cost for A = 10, T_{ON} = 45.8 and T_{WB} = 18. In addition, the cooling tower fan power was derived as :

$$\text{Fan power} = -0.003 + 11500\ COST - 14050\ COST^2 + 7816\ COST^3 - 1598\ COST^4$$

5. Results

Plots of combinations of the specific design parameters, i.e. comparative unit cost versus P, T_{WB} and A, yielded definite trends towards the optimum parameters. The results were plotted in the form of Figure 6 and the optimum design parameters derived. Table 1 gives the optimum design parameters.

Condenser pressure, mbar	:	100
Wet bulb temperature, °C	:	18.5
Approach temperature, °C	:	8.5
Comparative unit cost, mills/kWh	:	35.46

TABLE 1 : OPTIMUM DESIGN PARAMETERS (1 mill = US$0.001)

The comparative unit cost only facilitates selection of the optimum parameters and is not indicative of the true unit cost because not only have costs such as powerhouse, civil works, switch-yard and transmission not been included, but the base load cost for the minimum auxiliary power consumption, as shown in Figure 3, has also not been included.

Comparative unit cost components for the optimum design parameters in 1983 US dollars are tabulated in Table 2.

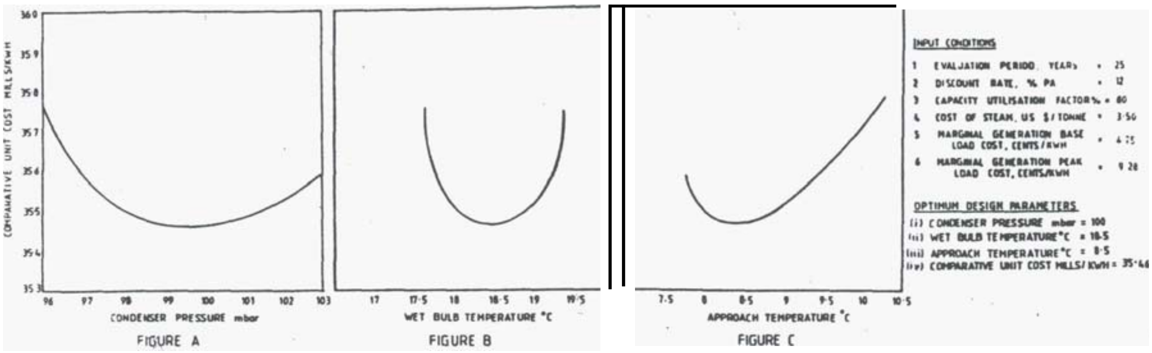

FIGURE 6 : SELECTION OF OPTIMUM DESIGN PARAMETERS

	mills/kWh	Percentage
Capital investment	6.06	17.1
Steam price	28.78	81.2
Marginal generation		
charges; base load	0.36	1.0
peak load	0.26	0.7
	35.46	100.0

TABLE 2 : COMPONENTS OF COMPARATIVE UNIT COST FOR THE OPTIMUM DESIGN PARAMETERS

6. Sensitivity Analysis

The input conditions, or Base Case, for the sensitivity analysis are given in Table 3. The corresponding base case optimum design pararaters and comparative unit cost are given in Table 1.

Discount rate, % p.a.	:	12
Capacity utilistion factor, %	:	80
Steam price, US$/tonne	:	3.50
Marginal generation base load cost, cents/kWh		4.75
Marginal generation peak load cost, cents/kWh	:	9.28

TABLE 3 : BASE CASE INPUT CONDITIONS

In this study five input conditions were investigated. These included variations in steam price, discount rate, capacity utilisation factor and marginal generation base and peak load coats. Each condition included 3 variables giving a total of 15 separate variables. Optimum design parameters and unit costs were derived for each variable. Graphical representation of these results are given in the form of Figure 7.

A sensitivity analysis was not performed on the capital investment because the investment costs obtained from various manufacturers far this study were conservative budgetary costs. Any decrease in the capital investment would increase the steam price portion of the unit cost, thereby raking the steam price a more sensitive parameter.

Table 4 summarises the sensitivity of the decision for the selection of the base case optimum design parameters to changes in specific variables. The conclusion drawn from Table 4 is that the steam price is the only variable that significantly affects the decision for the selection of the base case optimum design parameters.

Economic operation of the power station for increased steam prices would require-reduotione in steam consumption while trying to maintain the required electrical production. Reductions in steam consumption are achieved by reducing the condenser pressure. However, thio increases the risks of unacceptably high erosion rates occurring in the ultimate and penultimate turbine blade stages due to increasing wetness.

Although a variety of parameters affect erosion rate, the only design parameters at' the control of the Purchaser are the steam inlet conditions and the condenser pressure. In order to select a turbine with minimal blade erosion rates it is therefore necessary to select a conservative condenser pressure bearing in mind the other parameters that are outside the Purchaser's control but also affect erosion rates.

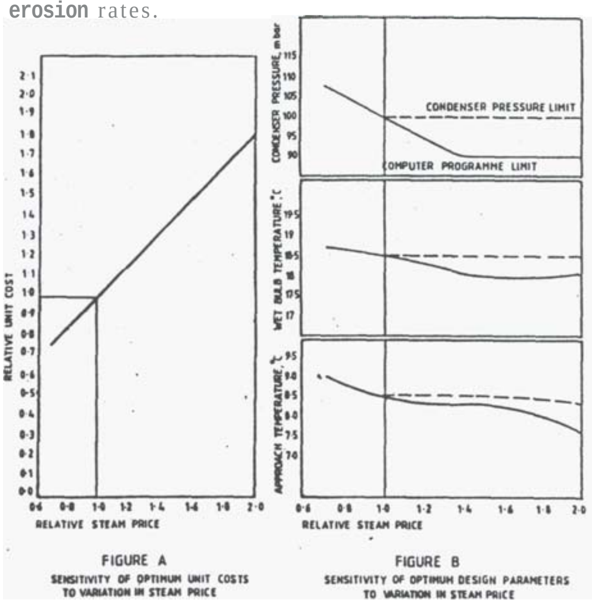

FIGURE 7 : SENSITIVITY ANALYSIS FOR STEAM PRICE

Variable	Sensitivity	
	Comparative Unit Cost (mills/kWh)	Design Parameters (P, T_{WB}, A)
Steam Price	Very sensitive	Very sensitive
Discount Rate	Marginally sensitive	Not sensitive
Capacity utilisation factor	Marginally sensitive	Not sensitive
Marginal generation cost:		
base load	Not sensitive	Not sensitive
peak load	Not sensitive	Not sensitive

TABLE 4 : SENSITIVITY OF THE BASE CASE OPTIMUM DESIGN PARAMETERS TO CHANGES IN SPECIFIC VARIABLES

In light of recent information from turbine manufacturers regarding turbine operating conditions, and in view of the current world wide operating experience with geothermal power stations similar to that proposed for Kamojang, Units 2 and 3, it does not appear prudent to operate at condenser preseures below 100 mbar, irrespective of any increase in steam price. The consequences of operation at lower condenser pressures could eventually be borne out by higher erosion rates in the ultimate and penultimate blade stages resulting in shorter blade lives. Although a variety of factors which affect turbine blade erosion rates may not be readily quantifiable in condenser pressure terms? the information available to date suggests that 100 mbar would be a conservative lower limit for condenser pressure at Kamojang.

Thus by limiting the condenser pressure to 100 mbar, the decision for the selection of the base case optimum design parameters becomes insensitive to increases in steam price as shown in Figure 7B.

DISCUSSION

It is apparent that the steam price component has the largest contribution to the calculated optimum unit cost. In addition, the sensitivity analysis shows that the steam price is the only variable that significantly affects the decision on the selection of the optimum design parameters.

The price of steam selected for the optimisation programme affected the optimum design condenser pressure. In general, any reduction in this price will increase the optimum design condenser pressure. Alternatively, any increase in the steam price will reduce the optimum condenser pressure unless there is a preselected minimum design condenser pressure to reduce the risk of unacceptably high erosion rates occurring in the ultimate and penultimate turbine blade stages.

It is possible to refine the optimisation programme by changing two assumptions; isentropic efficiency, and terminal temperature difference. Instead of assuming constant values for each of these parameters, the following manufacturers' relationships could be incorporated into the programme. for design and operating conditions;

(i) the variation of isentropic efficiency with turbine exhaust steam wetness

(ii) the variation of terminal temperature difference with cooling water flaw

Unfortunately due to the lead time required for manufacturers to provide these relationships and due to the short time allocated for the completion of this study, these relationships were not included.

CONCLUSIONS

Optimisation procedures have been developed and used for a geothermal power plant with a direct contact condenser, can pumps, steam ejector gas extractors and mechanical draught cooling towers. However? appropriate modifications to the relevant sections of the procedures will facilitate application to any type of geothermal atmospheric cooling system.

Utilisation of the optimisation procedures for the Kamojang Geothermal Power Plant, Units 2 and 3, Indonesia, has yielded optimum design parameters for condenser pressure, wet bulb temperature and approach temperature.

A sensitivity analysis for discount rate, capacity utilisation factor, marginal generation base and peak load costs, and steam price established that the steam price was the only variable that significantly affected the decision for the selection of the optimum design parameters. However by limiting the condenser pressure to a specific lower limit in order to prevent unacceptably high erosion rates occurring in the ultimate and penultimate turbine blade stages, then the decision for the selection of the optimum design parameters became insensitive to increases in steam price.

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