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## INVESTMENT AND OPERATING COSTS OF BINARY CYCLE GEOTHERMAL POWER PLANTS

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The purpose of this paper is to present typical investment and operating costs for geothermal power plants employing binary cycle technology and utilizing the heat energy in liquid-dominated reservoirs. These costs are developed as a function of reservoir temperature. The factors involved in optimizing plant design are discussed. A relationship between the value of electrical energy and the value of the heat energy in the reservoir is suggested.

### I. INTRODUCTION

Interest in the production of electric power from geothermal resources is increasing exponentially. Much of this interest, both private and public, is focused on the exploitation of liquid-dominated reservoirs for the simple reason that there is only one exploitable vapor-dominated reservoir (the Geysers) in the United States, while the rest are liquid-dominated. These latter reservoirs are simply superheated bodies of hot water lying deep below the surface and containing varying quantities of salts, minerals, and noncondensable gases.

It appears that binary cycle plants will be used extensively to produce power from hot water reservoirs. The problems inhibiting rapid development of such reservoirs appear to be solved or well on the way to solution.

Our firm has been participating in the development of three hot-water reservoirs in California. These are Mammoth (Long Valley), Niland (Imperial Valley) and Heber (Imperial Valley). Any one of them could be the first in the United States to be a source of electric power from a hot-water reservoir.

The status of these projects will be discussed briefly, but the main purpose of this paper is to present capital and operating cost figures for binary cycle power plants based upon the ABC process developed by members of our firm, to discuss the factors involved in optimizing a plant design, and to suggest a relationship between the value of electrical energy produced and the value of the heat energy in the hot water.

## II. THE BINARY CYCLE

The binary cycle has been described in two earlier papers (Refs. 1 and 2) presented by members of our firm, and has been described by others as well (Ref. 3). The industry seems to have firmly adopted the term "binary cycle", although the term "organic Rankine cycle" is more explicit, since it is exactly what it is. Figure 1 is a flow diagram of a typical binary cycle. The working fluid is heated and vaporized by exchange with the hot water, expanded in a turbine, condensed to a liquid with a cooling medium and pumped to the exchanger, thereby completing the cycle.

One variation of the binary cycle is the patented Magmamax process owned by Magma Energy, Inc. Another is the ABC process developed by members of my firm. In the latter case patents have been applied for but not yet granted. The ABC process patent applications include methods of scale control and prevention as well as innovative concepts in the binary cycle itself. To the best of our knowledge none of our claims conflict with the Magmamax patent.

## III. SCALING

The major problem inhibiting the construction of binary cycle plants has to do with the prevention or control of scaling in the tubular exchangers transferring heat between the hot water and the working fluid. In order to gain insight into this problem, Magma Energy, Inc. at Mammoth and San Diego Gas & Electric Company (SDG&E) at Heber are operating heat exchange test units which we designed and fabricated. These units closely simulate the conditions expected in commercial size heat exchangers. Both units have been operating in recent weeks. Some reduction in heat transfer rates has occurred in both units, but it is too early to evaluate the magnitude of the problem or to decide what to do about it. We believe that an economical solution will not be difficult to find.

The solution to the scaling problem at Niland is to heat the working fluid with flashed steam rather than hot water. It is necessary to remove the entrained solids from the steam and this has been done successfully employing a proprietary scrubber patented by our Mr. Hutchinson.

Direct contact heat exchange between the hot water and the working fluid has been suggested as a means of eliminating scale deposition. Members of our firm have two patent applications covering two direct contact concepts. Claims for both applications have been allowed. We are seeking NSF support to develop our Mr. Sheinbaum's concept which is similar to the concept proposed by R. F. Boehm, et al., in a recent paper (Ref. 4). SDG&E have the hardware on hand for demonstrating the concept invented by our Mr. Hutchinson and plan to operate a pilot plant in connection with the operation of their geothermal test facility at Niland.

Earlier this year we completed a conceptual design and cost estimate for Magma Energy's proposed installation at Mammoth. It is our understanding that authorization for construction is awaiting completion of their field testing

program. More recently we received an assignment from SDG&E to redesign their Niland geothermal test facility based on using flashed steam and our proprietary scrubber. Both installations will employ binary cycle technology.

#### IV. ECONOMICS

As one would anticipate, the economic viability of a geothermal development is clearly related to the reservoir temperature, higher temperatures resulting in lower capital costs and decreased hot water consumption.

##### A. Capital Cost

The relationship between reservoir temperature and capital cost is illustrated graphically in the upper curve of Figure 2 for a 50 MW installation. At 250°F the capital cost is about \$475/kW, declining to \$250/kW at a 500°F reservoir temperature. These capital costs are representative of costs prevailing during the second quarter of 1974. They represent the installed cost of a battery limits plant. They do not include land cost, working capital, royalties, nor costs associated with the production, transmission to the plant, and reinjection of the hot water. The assumption is made that the hot water is nonfouling, that steel may be used in the hot water exchangers, and that H<sub>2</sub>S is present in negligible amounts. A further assumption is made that reservoirs are pumped at temperatures up to 400°F and are self-flowing at temperatures above 400°F, producing at the surface a mixture of steam and hot water. At 500°F, the well-head mixture of steam and hot water is at a pressure of 200 psig and a temperature of 390°F.

These cost figures should be used with caution and the basis of the estimates should be kept clearly in mind, because local conditions can have a major effect on capital cost.

There is a significant economy of scale in comparing the installed cost of a 10-MW unit and a 50-MW unit. A 10-MW unit will cost 25% to 35% more per kilowatt than a 50-MW unit.

##### B. Optimization

In concept the binary cycle is simplicity itself. It is a relatively simple matter to design a plant that will work, but not so simple to provide an optimum design, that is one which will give maximum return on invested capital.

In the typical case, a public utility will own and operate the power plant and will buy heat energy from the developer of the field. In order to design an optimum plant the utility must furnish the engineer the value of the electricity to be produced and the utility's method of economic analysis. The developer must furnish composition, pressure, temperature, and flow rates of the available hot water. With the foregoing data in hand the engineer can produce an optimum design and can estimate realistic capital investment and operating costs.

In the process of optimization the engineer must make many decisions including:

- (1) Selection of a working fluid. The optimum fluid varies with the temperature of the reservoir. Propane (boiling point =  $-44^{\circ}\text{F}$ ) might be used in a low-temperature reservoir, while hexane (B.P. =  $+156^{\circ}\text{F}$ ) might be the best fluid in a high-temperature reservoir.
- (2) Selection of turbine inlet pressure and temperature. Optimum turbine inlet pressures will range from 400 psig to 800 psig, and inlet temperatures may be  $20^{\circ}\text{F}$  to  $40^{\circ}\text{F}$  lower than the incoming hot water.
- (3) Selection of condensing temperature. This will vary with the method of cooling as well as local climatic conditions. The lower the condensing temperature the higher the efficiency of the plant. In cold climates air cooling may be the best selection. In other areas, a cooling tower is usually best, and local weather conditions will dictate the optimum cooling water temperature and condenser temperature. Condensing temperatures may vary from  $50^{\circ}\text{F}$  in very cold climates to  $120^{\circ}\text{F}$  in very hot climates.
- (4) Selection of turbine. It is most important to select a hydrocarbon turbine having the highest possible efficiency. At the present state of development, the radial inflow type appears to be the front runner. The established manufacturers quote thermodynamic efficiencies in the range of 85%. The reason that high efficiency is important is that the capital cost and operating cost of a power plant are inversely proportional to turbine efficiency. For example, a plant with a 75% efficient turbine will cost just about  $85/75 = 1.13$  times a plant with an 85% efficient turbine.
- (5) Selection of heat exchangers and condensers. Large fixed-tube-sheet tubular exchangers built in accordance with the Standards of The Tubular Exchanger Manufacturers Association are recommended. Careful attention to design is necessary because heat exchangers are the single most expensive item in the plant. Single units are available having diameters up to six feet, lengths up to 80 feet and weighing up to 300 tons. Such designs have been developed and proven over a period of years by the hydrocarbon processing industry. Optimum temperature approaches must be determined in exchangers, condensers and cooling towers.

We have developed a computer program which we use in our optimization studies. The program makes it possible to determine the effect on net power output easily and quickly by making changes in the previously outlined variables.

We would like to emphasize that the major equipment is all "state-of-the-art" and "off-the-shelf" equipment. The exchangers, pumps, turbine, generator, cooling tower, and pressure vessels may be purchased from established

vendors on a guaranteed performance basis. The physical and thermodynamic properties of the working fluids may be estimated with precision. Thus the technical risk in constructing a power plant of this type is minimal, except for the uncertainty in the design of the hot water/working fluid heat exchanger.

A binary cycle plant bears more resemblance to a chemical process or a natural gas processing installation than it does to a conventional fossil-fueled power plant.

This is not to say that there will not be new hardware, techniques, and processes developed in the future which will improve performance and economics.

### C. Performance of the ABC Process

The performance of the ABC process is shown in the lower curve of Figure 2. Hot water consumption in pounds per net kWh is plotted against reservoir temperature. The reservoir fluid is assumed to be water, and the cooling water temperature is assumed to be 65° F. A net kWh is the salable power and takes into account the power required to operate the cooling system and the working fluid pumps, together with realistic estimates of the mechanical and electrical efficiency of the components of the finished plant.

Each point on the curve represents the results of a number of optimization studies made with respect to choice of working fluid, turbine operating conditions, and heat exchanger temperature approaches. The quality of hot water required varies from about 400 lb/kWh at 250° F to about 55 lb/kWh at 500° F. For practical purposes, this curve is independent of capacity.

### D. Operating Costs

The cost of operating a geothermal power plant is the sum of fixed charges and other direct operating costs. We have taken annual fixed charges to be 22% of the capital cost of the plant. This figure includes the following:

- (1) Capital return and interest.
- (2) Income taxes.
- (3) Property taxes.
- (4) Depreciation.
- (5) Insurance.
- (6) General and administrative expense.
- (7) Maintenance labor and materials.

Since the cost of maintenance is a capital related item, this cost has been included in the fixed charges.

We estimate that other direct operating costs will be about 1.4 mills/kWh. Such costs include operating labor, supervision, chemicals and supplies and plant overhead. This cost can vary quite a lot depending on local conditions.

On the basis that the plant operates 8,000 hr/yr, the relationship among the value of the hot water, the reservoir temperature and the value of the electricity is presented in Figure 3. These variables are related by the following equation:

$$P = F + O + W$$

where

P = value of electricity produced in mills/kWh

F = fixed charges in mills/kWh

O = direct operating costs in mills/kWh

W = value of hot water produced in mills/kWh

At 20 mills, the value of 500° F water is about 12 mills/kWh declining to about 5.5 mills/kWh at 250° F. The value of Btu's extracted from the hot water may also be estimated. For example with 20 mill power, the heat extracted is estimated to be about 36¢/MM Btu at 350° F and about 51¢/MM Btu at 500° F. The corresponding numbers for 30 mil power are 75¢/MM Btu and 94¢/MM Btu.

A recent paper by R. A. Walter, et al., entitled "Evaluation of Small Power Systems for use with Geothermal Reservoirs" (Ref. 5) studies the effect of capacity and reservoir temperature on capital costs and operating costs for both binary and steam flash cycles. We note significant differences between their estimates and ours.

We believe these differences stem largely from the fact that our curves are based upon optimized cycles, whereas their curves are based upon employing a single fluid over the whole range of temperatures considered.

The data presented herein indicate what a utility might afford to pay for energy under various assumed conditions. No consideration is given to whether such payment would provide the developer with an adequate return on his investment.

This presentation is intended to provide useful economic guidelines to government, utilities, developers, and others. Each group can apply its own method of economic analysis to prepare similar estimates.

We may have raised more questions that we have answered, including:

- (1) On what basis should a developer sell and a utility buy the energy in a hot water reservoir?
- (2) Under what conditions do the economics favor a steam flash cycle or a hybrid cycle rather than a binary cycle?
- (3) How do the economics compare with other new sources of electric power?
- (4) Should optimization studies include the costs associated with the production and reinjection of the water and, if so, how do you go about it?

We would welcome your response to these questions.

#### REFERENCES

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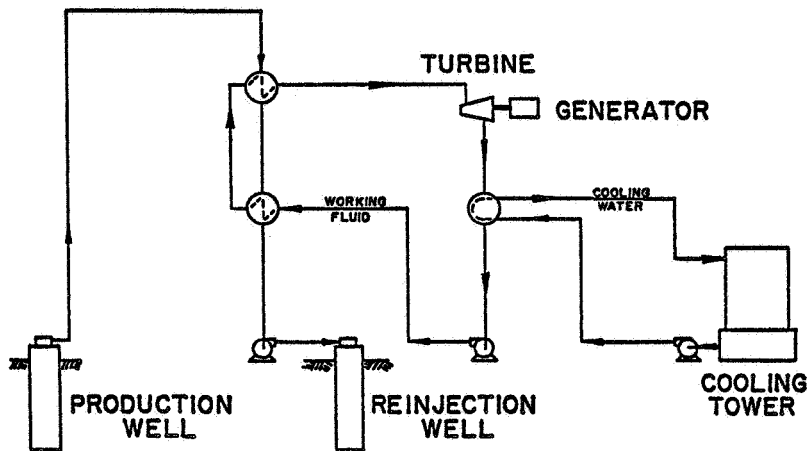


Fig. 1. Typical binary cycle

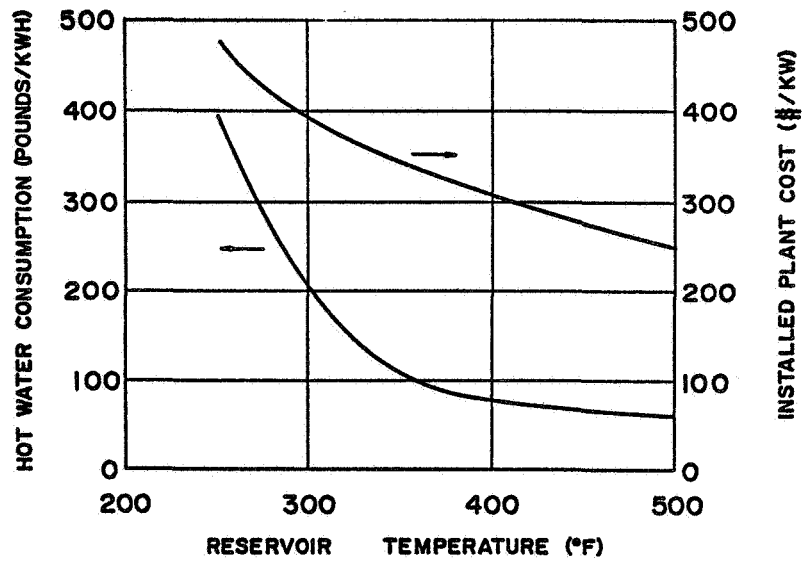


Fig. 2. Effect of reservoir temperature on water consumption and installed plant cost (basis: 50-MW plant)



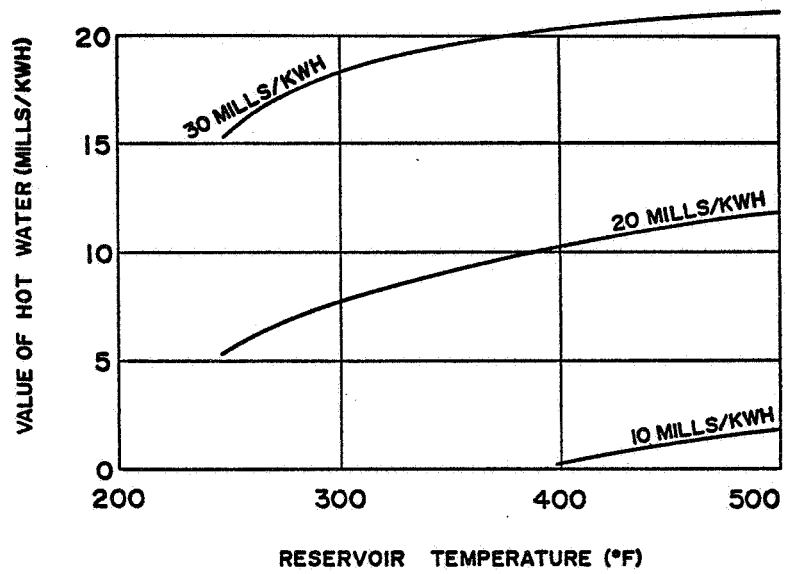


Fig. 3. Effect of reservoir temperature on value of hot water at varying values of power