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Advanced Binary Cycles for Geothermal Power Generation

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Abstract: The purpose of this study is to examine the technical, economic and environmental aspects of geothermal power generation using the binary cycle. The development of an advanced binary cycle is discussed in the light of the type of geothermal fluid available, efficient utilization of geothermal heat, and the thermodynamics of the power cycle. Using the Imperial Valley as a basis, case studies are developed for various geothermal reservoirs. The economics of power generation using the binary cycle are discussed. Environmental considerations are outlined. Areas in need of future research and development are specified.

Introduction

Historical Background

Geothermal fluids escape from the earth in many thousands of locations throughout the world on both land and sea. These fluids have long had social uses in many ways. Old Faithful has given pleasure to countless millions. Geothermal waters have been used for space heating of residential, commercial, and agricultural structures for many years. Many resorts have been built around hot mineral springs and artesian wells.

Geothermal electric-power generation began in 1904 by utilizing dry steam from the Larderello field in Italy. In the 1950's, power generation began in New Zealand utilizing flashed steam from hot brine wells. In 1960, power generation from the steam fields at The Geysers in Northern California began. Japan, Iceland, and Russia have exploited their geothermal re-

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sources in varying degrees in the last 20 years for power generation, space heating, and agricultural uses.

The current worldwide energy crisis has given increased impetus to the large-scale development of geothermal energy. Active exploration and development programs are under way in many parts of the world, including Algeria, Chile, Columbia, Czechoslovakia, El Salvador, Ethiopia, Hungary, Iceland, Italy, Japan, Kenya, Mexico, the Philippines, Russia, Taiwan, Turkey, and Yugoslavia. Electric-power generation from geothermal sources worldwide is shown in Table 1.

The Potential of Geothermal Energy

Numerous forecasts of geothermal power-generating capacity have been published. The U. S. Geological Survey has stated that the Western United States has a potential generating capacity of 15,000 to 30,000 MW (1). More optimistic estimates come from the Department of the Interior Panel on Geothermal Energy Resources, which, in August 1972, estimated that geothermal energy could supply as much as 132,000 MW in 1985 and 395,000 MW by 2000 (2). Former Secretary of the Interior Walter Hickel has proposed an ambitious $685 million government research and development program which could yield 132,000 MW by 1985 (3). Dr. Robert Rex has estimated the Imperial Valley geothermal deposits could support a generating capacity of 20,000–30,000 MW (4). These figures compare with a present electric-power generating capacity of 300,000 MW in the United States (5) and 35,000 MW in California (6). Muffler and White (7) conclude that the world potential geothermal resource is about equivalent to the energy represented by the world's coal reserves.

Table 1

Geothermal power capacity (1973)

Country	*Capacity (MW)*
Italy	390
United States	300
New Zealand	170
Mexico	75
Japan	33
Soviet Union	6
Iceland	3
Total	977

In forecasting future energy supplies, most energy economists and planners place geothermal energy in a less dominant role. The National Petroleum Council estimates that geothermal energy will supply 7,000–20,000 MW by 1985, mostly in the West (8). The State of California Division of Oil and Gas expects statewide geothermal operating capacity to reach 3,000 MW by 1981 and 7,500 MW by 1991, or about 5% of the state's power needs (9). The President's second energy message to Congress takes a very cautious view of geothermal energy (10). The Administration expects geothermal energy to supply 4,000 MW by 1985 and 30,000 MW by the year 2000, or about 1.5% of the nation's total energy needs.

Another way of looking at geothermal reserves is to calculate the crude-oil equivalent of heat energy. One MW of electrical power generated in an oil-fired power plant for 30 years at 33% thermal efficiency requires the equivalent of 500,000 barrels of crude oil. If the potential generating capacity of the Imperial Valley is indeed 20,000 MW, it is equivalent to 10 billion barrels of crude oil. This is comparable in magnitude with the estimated oil reserves of the Alaskan North Slope.

Conversion of Geothermal Heat to Electrical Energy

Classification of Geothermal Power Plants

Geothermal deposits are commonly classified as vapor-dominated, liquid-dominated, geopressured, dry rock, or magmatic. Since the power-plant technology for utilizing the vapor-dominated and liquid-dominated geothermal deposits is available today, the present study is concerned only with reservoirs of this type. Even with this limitation, however, there are several power-conversion concepts to consider.

All major geothermal power-generating plants operating today use condensing-steam turbines to generate power. At The Geysers, California, and Larderello, Italy, the steam is obtained from vapor-dominated (dry-steam) reservoirs. At Wairakei, New Zealand, and Cerro Prieto, Mexico, the steam is obtained from liquid-dominated reservoirs by flashing the hot brine. In recent years, the binary cycle has been developed to increase plant efficiency and heat utilization. The binary cycle employs a working fluid which is vaporized by heat exchange with hot brine and/or steam. The vaporized fluid drives an expansion turbine. Table 2 lists some of the various power-plant options.

In high-pressure vapor-dominated fields, where the dry steam is low in non-condensable gases, the steam turbine is the most economical means of

Table 2
Classifications of geothermal power plants

Type of geothermal reservoir	*Heat source*	*Power generation*
Vapor dominated (dry steam)	Dry steam	Steam turbines
	Dry steam	Binary cycle
Liquid dominated (hot brine)	Flashed steam	Steam turbines
	Flashed steam	Binary cycle
	Flashed steam and hot brine	Binary cycle
	Flashed steam and hot brine	Hybrid cycle
	Hot brine	Binary cycle
	Hot brine and/or flashed steam	Dual binary cycle

power generation. The use of a binary cycle in vapor-dominated zones may be practical where low-pressure steam is produced or if high concentrations of non-condensable gases are encountered.

In liquid-dominated zones a greater number of options exist. In very hot reservoirs the well is self-producing and a mixture of hot brine and steam will naturally flow to the surface. The steam, if low in non-condensable gases, can be fed directly to turbines and the hot brine can be re-injected to the structure. Alternatively, the steam alone or in combination with hot brine could be used as the heat source to operate a binary-cycle plant. Another possibility is the use of a hybrid cycle where flashed steam is fed directly to a steam turbine and the hot brine is used to operate a binary-cycle plant. In some cases the depth and temperature of the reservoir may be such that the hot fluid can be produced only by pumping. Under these circumstances the hot brine can be used to generate power in a binary cycle. However, even if pumping is required, it may be desirable to flash the liquid and operate with the steam and hot brine.

The dual binary cycle is a variation whereby working fluids with different boiling points are used in two separate binary cycles. The selection of working fluids will depend on the temperature range of the heat source.

It is clear from this discussion that the designer of a geothermal power plant faces a multitude of options. The final design is dictated by the characteristics of the available geothermal fluid, the cost of the geothermal energy, and the price of electric power in a particular geographical region.

The Binary Power Cycle

In this study we are focusing our discussion on the binary power cycle. A flow diagram for a typical binary power cycle is illustrated in Fig. 1. In this case the geothermal fluid is flashed and steam is separated from the hot

Table 2

ns of geothermal power plants

Heat source	Power generation
Dry steam	Steam turbines
Dry steam	Binary cycle
Flashed steam	Steam turbines
Flashed steam	Binary cycle
Flashed steam and hot brine	Binary cycle
Flashed steam and hot brine	Hybrid cycle
Hot brine	Binary cycle
Hot brine and/or flashed steam	Dual binary cycle

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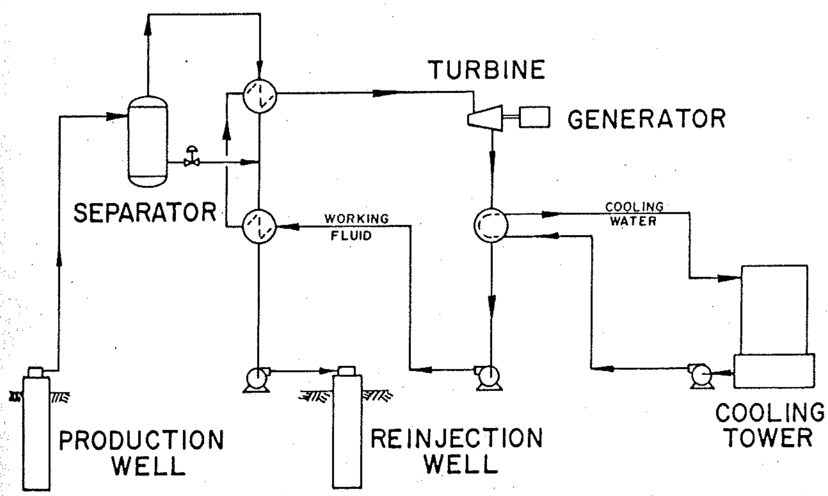

Fig. 1. Typical binary cycle.

brine. Both streams are used to heat and vaporize the power fluid, which is passed through a turboexpander and condensed with cooling water. The power fluid is then pumped to the upper working pressure and reheated to complete the cycle. The brine may be re-injected and the steam condensate used for cooling-tower makeup, sold as fresh water, or re-injected with the brine.

Small binary-cycle plants employing Freon as a working fluid have been built in Russia and Japan. In 1969 the Magma Power Company announced the Magmamax Process in which isobutane is employed as the working fluid. San Diego Gas and Electric Company has announced plans to construct a demonstration plant in the Niland area of the Imperial Valley. This unit will have a nominal capacity of 10 MW. The working fluid is isobutane, which will be heated by flashed steam and brine and condensed with cooling water. Initially, no expansion turbine or generator will be installed. The Hutchinson–Holt Process, developed at The Ben Holt Company, is an advanced binary cycle characterized by high thermal efficiency. The working fluid and operating details are proprietary because the basic patent has not been issued.

Thermodynamics of Binary Power Cycles

The binary power cycle is a term used to describe the application of the Rankine cycle to a geothermal heat source. In order to illustrate the thermodynamics of a binary power cycle, a pressure–enthalpy diagram for isobutane is presented in Fig. 2. In this case it is assumed that the cooling-water temperature limits the condensing pressure and temperature of isobutane to 80 psia and 110°F. Two cycles are illustrated in Fig. 2. In one cycle the isobutane is pumped to 500 psia and heated to 380°F. In the other cycle, a working pressure of 1,000 psia is shown. At higher working pressures, the gross power produced on expansion is higher and the cooling requirement is lower. However, this effect may be offset by higher power requirements for pumping and higher plant costs.

In the evaluation of binary cycles the net thermal efficiency is a useful measure of performance. The net thermal efficiency is defined for present purposes as

$$E_N = \frac{W_N}{Q} \times 100$$

where

$$W_N = W_T - W_P - W_{CT}$$

and E_N is the net thermal efficiency, W_N is the net power generated, W_T is the gross power generated by the turbine/generator assuming an isentropic efficiency of 85%, W_P is the isobutane pump power, W_{CT} is the power required to circulate cooling water (10°F rise) and operate cooling-tower

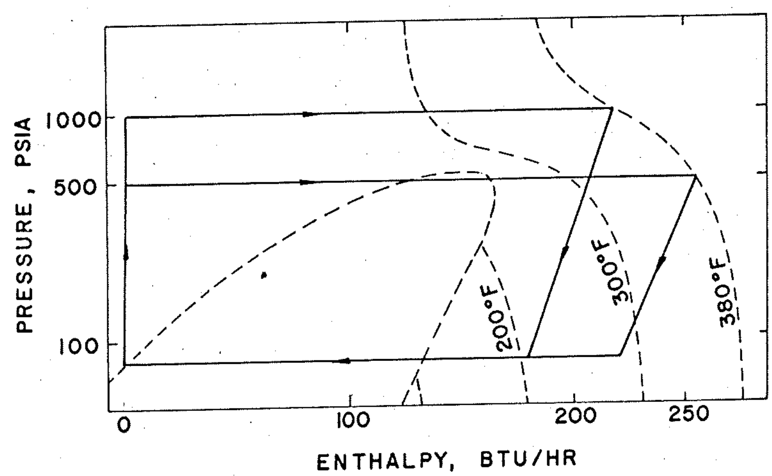

Fig. 2. Typical isobutane power cycles.

fans (12°F approach to 78°F wet bulb), and Q is the heat input to the cycle (enthalpy change of isobutane between 110°F and the turbine inlet conditions).

Net thermal efficiencies have been calculated for the isobutane binary power cycle described in Figs. 1 and 2. Thermodynamic property data published by the American Petroleum Institute were used in this study (11). In power-cycle calculations it is important to use data which are thermodynamically consistent. Surprisingly, some of the popular Mollier diagrams for isobutane do not meet this requirement. The results are shown in Fig. 3 for working temperatures between 300 and 500°F, and working pressures between 400 and 1,500 psia. It is interesting to note that up to about 800 psia higher net thermal efficiencies are achieved at the lower working temperatures. This implies that power plants operating on extremely hot geothermal fluids will be no more efficient than plants operating on moderately hot fluids even though the total power produced would be greater.

An optimal binary cycle plant will generate maximum power from a given well production at a minimum cost. Achieving peak power production requires maximizing both heat input and thermal efficiency. In some cases it may be necessary to sacrifice efficiency to increase heat input and power

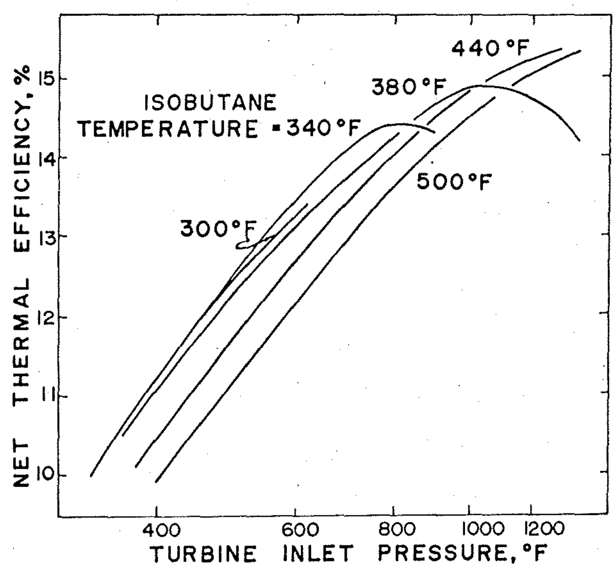

Fig. 3. Effect of turbine inlet conditions on net thermal efficiency.

production. If efficiency drops too low, however, the cooling-sysem cost becomes prohibitive. Higher efficiencies can be achieved at higher working pressures. However, above about 700–800 psia the efficiency curve begins to flatten out and higher pressures become economically impractical. Thus, for the case under discussion, efficiencies much over 14% are not economically attractive.

The above analysis is based on a particular process configuration using isobutane as the working fluid. Other working fluids have been found to yield higher efficiencies and power output per pound of well fluid. Reaching the optimal design for a binary-cycle power plant requires consideration of many interacting factors. However, the procedures are not unlike those used to optimize any process facility or power plant.

Power Plant Design Considerations

The optimum design for a binary-cycle power plant can be reached only if accurate data on the well production are available. Often a flow test of the well is required to determine productivity, pressure, temperature, and composition. The data which should be made available to the engineer include the following: (1) brine and steam properties *versus* production rate and separator pressure; (2) brine properties, including chemical composition, specific gravity, specific heat, and pH at flowing conditions; (3) steam properties, including steam quality, degrees of superheat, and concentration of non-condensable gases, silica, and particulates at flowing conditions; (4) flow rate *versus* wellhead pressure for each injection well; (5) liquid level drawdown *versus* flow rate, if well is pumped; (6) local meteorological data. The method of producing the well and processing the geothermal fluid must be established. Some of the options are the following: (1) pump the well with or without flashing; (2) permit the well to flow naturally (self producing); (3) the number of flashing stages and pressure levels; (4) means for disposal of brine, steam condensate, and non-condensables.

An economic and efficient binary cycle can be designed by the proper selection of the following major independent variables: (1) working fluid to be circulated; (2) the temperature and pressure of the working fluid before and after expansion; (3) the approach to wet bulb and temperature rise of the cooling water; (4) the temperature approaches in the heat exchangers and condensers.

Imperial Valley Case Studies

A set of case studies has been completed assuming an Imperial Valley, California, location for the power plant. The Imperial Valley is one of many areas in the Western United States known to contain large geothermal reserves. This location was selected for the present study because a considerable amount of geothermal data are available (12, 13, 14, 15). Over 50 deep wells have been drilled in the Imperial Valley and the area is undergoing active development.

Imperial Valley Reservoirs

The Imperial Valley reservoirs are of the water-dominated type, and the geothermal fluids have been found to vary widely in temperature and composition. Typical analyses for two areas of the Imperial Valley are shown in Table 3. The Buttes area analysis is representative of the hot hypersaline brines, while the Cerro Prieto analysis is representative of relatively low-temperature, low-salinity brines occurring in the extension of the Imperial Valley in Mexico. Most of the brines in the Western United States and in the rest of the world are lower in salt content than the hypersaline brines in the Buttes area of the Imperial Valley. Thus, these hypersaline brines are most challenging from a design viewpoint.

The presence of calcium bicarbonate may be a problem with some geothermal brines. Flashing these brines under certain conditions results in the evolution of carbon dioxide and shifts the bicarbonate to carbonate. Calcium carbonate will precipitate and deposit on the well casing or heat-exchanger tubes. The concentration of bicarbonates in the Imperial Valley brines is generally low and precipitation has not been a problem.

Two vital properties of the geothermal fluid are the non-condensables and silica concentrations. Unfortunately, very little good data are now available

Table 3

Composition of Imperial Valley brines[a]

	Field	
Analysis	*Buttes area*	*Cerro Prieto*
pH	5.7–6.0	5.8–6.9
Specific gravity	1.20–1.26	1.01
TDS	180,000–340,000	12,800–21,900
Na	30,000–50,000	3,900–6,100
Ca	15,000–28,000	210–390
K	8,000–18,000	500–1,100
Cl^-	92,000–155,000	9,700–11,800
SiO_2	150–1,200	150–770

[a] In ppm except as noted.

on these properties. The reported silica content is frequently low, because by the time the sample is analyzed precipitation has occurred. It is vital to have a good silica analysis in order to design heat exchangers to minimize scaling. Non-condensable gases do not seriously affect the performance of binary-cycle plants, but do seriously affect steam-turbine efficiency and the net power output of a steam-cycle plant. On a worldwide basis the limited data suggest that the non-condensables may be in the range of 0–20 wt % of the flashed steam. The major constituent in the non-condensables is carbon dioxide, the balance being light hydrocarbons and hydrogen sulfide. The hydrogen sulfide is typically in the range of zero to a few mole percent of the total non-condensable gases. Hydrogen sulfide has generally been found to be either absent or present in only trace amounts in Imperial Valley geothermal brines.

Case Study Results

Estimates of binary-cycle performance have been made for typical Imperial Valley reservoirs. The approach was to estimate net power output for reservoir temperatures ranging from 350–600°F. In order to simplify the calculations, some reasonable assumptions were made: (1) brine composition varies uniformly from 10 wt % salt at 350°F to 30 wt % salt at 600°F; (2) non-condensable gases in the flashed steam are 5 wt %; (3) the heat loss in the well casing is negligible; (4) the expander efficiency is 85%; (5) cooling water is available at 90°F (12°F approach to 78°F wet bulb) and a cooling range of 10°F. The cases are divided into pumping and flashing categories. In those cases where the geothermal fluid is flashed, the well may be self flowing or pumped and flashed in a separator.

The heat curves for a typical binary power cycle are shown in Fig. 4. The 400°F reservoir case using isobutane at a working pressure of 500 psia is illustrated. If the well is pumped, the geothermal fluid remains in the liquid state and is cooled from 400°F to 160°F. A lower brine-discharge temperature is not possible without the two heat curves intersecting. By flashing the 400°F brine at 360°F, the steam is condensed, combined with the brine and cooled to 160°F. The same amount of heat is extracted from the geothermal fluid in each case. A greater utilization of the heat could be achieved by reducing the amount of superheat in the isobutane. This, however, reduces the thermal efficiency.

Six case studies have been developed for an isobutane cycle as shown in Fig. 1 and the Hutchinson–Holt Process. The common basis is the availability of 1,000,000 lb/hr of geothermal fluid. This amount of fluid approxi-

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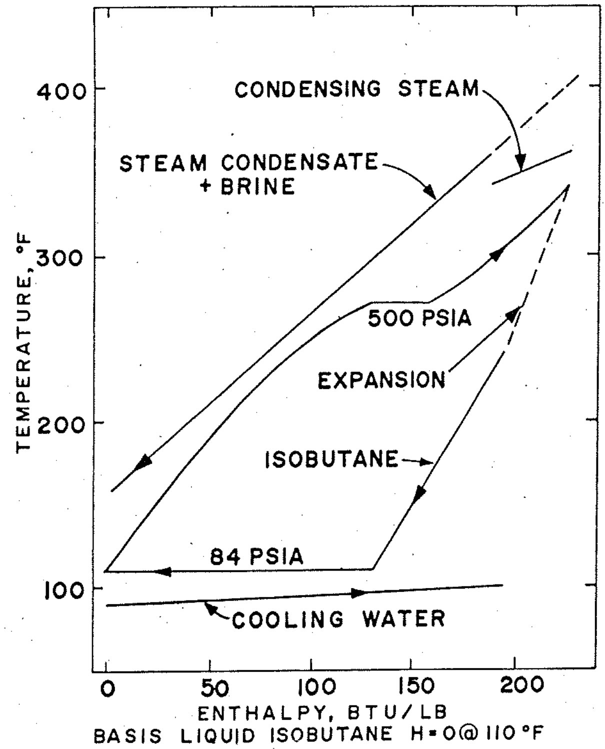

Fig. 4. Typical binary power cycle using isobutane with 400°F brine.

mates the output of two productive wells in the Imperial Valley. A summary of the results is presented in Table 4.

It is assumed that the low-temperature wells will be pumped and that the high-temperature wells will be self flowing. Three pumping cases have been developed at reservoir temperatures of 350, 400, and 450°F, and three self-flowing cases at reservoir temperatures of 400, 500, and 600°F. The temperatures selected are representative of what may be expected in the Imperial Valley, but do not represent the limits of applicability of a binary cycle. In the three high-temperature cases, it is assumed that the separator pressure would be as noted and that the resulting flashed steam and brine would both be heat exchanged with the working fluid.

Net power is the gross output of the generator less the power to pump the working fluid and operate a cooling tower. Power for well pumps has not

Table 4
Binary cycle performance[a]

Reservoir T (°F)	350	400	450	400	500	600
Production	Pump	Pump	Pump	Flash	Flash	Flash
Separator P (psia)	—	—	—	150	220	250
Separator T (°F)	—	—	—	360	380	400
Steam (M lb/hr)	—	—	—	83	128	207
H–H cycle						
Net power (KW)	6,550	8,960	10,830	8,960	12,400	16,100
Cooling duty (MMBTU/hr)	151	170	178	170	199	259
Isobutane cycle						
Net power (KW)	6,250	7,920	8,930	7,920	9,800	11,800
Cooling duty (MMBTU/hr)	161	204	230	204	254	304

[a] Imperial Valley case studies (basis: 1,000M lb/hr geothermal fluid).

been deducted since the differential head will vary widely depending on the well location and reservoir porosity. For the pumping cases an additional allowance for pumping power is required. Except for this allowance, the net power shown in Table 4 represents the power input to the transmission line. The net power for the Hutchinson–Holt Process increases from 6,550 KW at 350°F to 16,000 KW at 600°F, while the comparable figures for the isobutane cycle are 6,250 KW and 11,800 KW. The net power for the Hutchinson–Holt Process is, therefore, 4.8 to 36.4% greater than the isobutane cycle. Cooling duties for the Hutchinson–Holt Process range from 151 to 259 MMBTU/hr or 6.2 to 28% lower than the isobutane cycle. Net thermal efficiency for the Hutchinson–Holt Process varies from 15 to 17%, compared with 11 to 12% for the isobutane cycle. The increased power production, lower cooling requirement, and resulting higher thermal efficiency are critical to economic feasibility of binary-cycle power plants. The cooling tower is an expensive part of the power plant and the thermal efficiency is critical to placing a value on geothermal properties.

Figure 5 is a graphic presentation of the net power generated *versus* reservoir temperature. The power production from the low-temperature brines falls off sharply with temperature. This is due to a drop in both heat input and thermal efficiency. At reservoir temperatures below 350°F, selection of another working fluid should be considered.

The foregoing values are representative of the Imperial Valley conditions. In many other areas, such as the colder climates of the western states, efficiencies would be significantly higher because cooling water is available

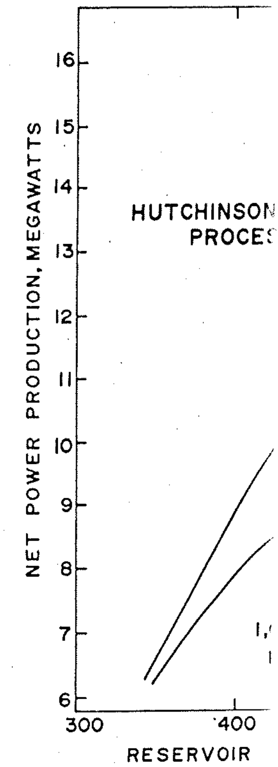

Fig. 5. Binary cycle performance.

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Economics

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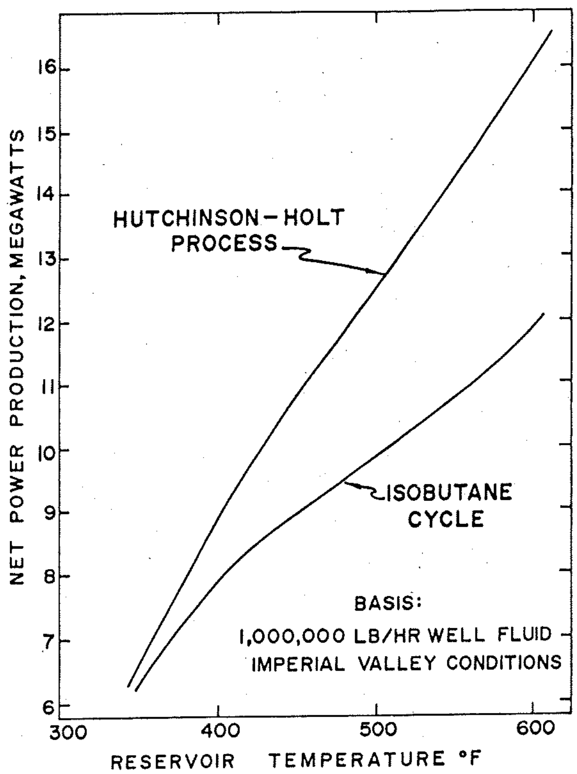

Fig. 5. Binary cycle performance.

at lower temperatures. It should also be pointed out that the hypersaline brines of the Imperial Valley have a lower specific heat than mineral-free water. Brines with a lower salt content will generate significantly more power than that shown in Table 4, owing to the higher heat content.

Economics

The large-scale development of geothermal power rests on the demonstration of economic feasibility. For most geothermal fluids, the technology exists for processing the fluid and generating power. Establishing economic feasibility requires the integration of power-plant economics and geothermal field production economics. On a larger scale, the cost of geothermal power must be weighed against the cost of alternative energy sources.

Binary Power Plant Economics

In the present state of the art, a 50 MW binary-cycle module appears to be optimum. Little economy of scale is achieved in larger modules. Above 50 MW it becomes necessary to use multiple-expansion turbines. Over about 10 MW, parallel heat-exchanger banks are required.

The typical installed cost of a 50 MW module, including the generator and cooling tower, but excluding the wells, field piping and power transmission lines, is estimated to be $250 per kilowatt or about $12,500,000. Many factors will influence the cost of a particular installation, especially the location and the composition and temperature of the geothermal fluid. Under favorable conditions the cost might be as low as $200 per kilowatt, and under unfavorable conditions as high as $300 per kilowatt. For a given location the Hutchinson–Holt Process can be expected to cost less than the comparable isobutane cycle on a dollars per kilowatt basis.

Binary versus Steam Cycle

A comparative study of all the power-plant cycles listed in Table 2 is beyond the scope of the present study. However, the relative advantages of the binary and steam cycles can be stated.

In general, a steam-cycle plant is less expensive than the binary-cycle plant for very hot geothermal reservoirs where large quantities of flashed steam are produced. However, since the steam cycle is inherently less efficient than the binary cycle, greater quantities of well fluid are required. Thus, even in those cases where the capital investment for a steam-cycle plant is less than the binary-cycle plant, the additional cost for developing the geothermal field may offset this advantage.

The hydrocarbon-expansion turbine used in the binary-cycle plant has several advantages over the steam turbine. The condensing steam turbine has a lower isentropic efficiency and is more expensive per gross kilowatt. The non-condensing hydrocarbon turbine has a low weight-to-power ratio and is constructed of less expensive materials. The presence of non-condensables has an adverse effect on the steam cycle, but has little effect on the binary cycle. Carbon dioxide and hydrogen sulfide in the presence of steam are corrosive and necessitate more exotic materials of construction. If a steam surface condenser is used, the fixed gases increase its cost owing to reduced rate of heat transfer and the need for corrosion-resistant materials. A vacuum compressor or steam ejector is required to evacuate the fixed gases consuming more power or steam.

For a given geothermal field, an evaluation of each power-plant cycle using the case study approach is desirable. The steam cycle, hybrid cycle, and dual binary cycle each have economic advantages in certain geothermal fields.

The Value of Geothermal Energy

The value of geothermal energy can be estimated by deducting the conversion cost from the price of electric power. In the usual situation, the property, the wells, and the distribution piping will be under the control of an operator who will sell thermal energy to a public utility. The public utility will own and operate the generating plant. The cost to a public utility would be the sum of direct operating cost and fixed charges.

Direct operating costs for a 50 MW plant including labor, supervision, maintenance, and supplies are estimated to be about $500,000 per year. Fixed charges, which include depreciation, interest, taxes, and insurance return on investment would typically be about 18%, or about $2,250,000 per year. On the basis of an average annual generation of 50 MW, the conversion cost would be 0.63¢/KWh. To this must be added the cost of the energy supplied to the unit. The operator wants to sell his energy at as high a rate as possible, while a utility would not be likely to go into geothermal energy if the cost of electricity from this source were higher than from alternative sources. This places an upper limit on what an operator would receive for his energy. Assuming that the utility would accept a total generating cost of 1.0¢/KWh, the field operator would receive 0.37¢/KWh from the utility. At a net thermal efficiency of 18%, this would amount to selling geothermal energy at about 20¢/MMBTU. Geothermal energy values at other plant efficiencies and electrical energy prices are presented in Table 5.

Table 5

Value of geothermal energy[a]

Price of electrical power at the generating station (¢/KWh)	*Power plant net thermal efficiency*			
	12%	*15%*	*18%*	*20%*
1.0	13	16	20	22
1.5	31	38	46	51
2.0	48	60	72	80

[a] Cents per MMBTU.

Actual production costs from a given proved reserve are likely to be on the order of a few cents per MMBTU. What a utility can afford to pay or what a producer can afford to accept are matters beyond the scope of this paper. However, the problem of pricing geothermal energy is not unlike the problem of pricing crude oil. While the cost of producing any given field may be low, account must be taken of the overall costs of exploration and development to the producer as well as the costs of alternative fuel sources. On balance it appears that geothermal energy is less costly than nuclear energy or fossil-fuel energy on a cents per BTU basis. However, the cost of fossil fuels and nuclear fuel will rise as well as the cost to generate the electric power in an environmentally acceptable manner. This will provide the leverage that will greatly enhance the value of geothermal properties.

Development Costs

The capital required to prove up a geothermal reserve and demonstrate a power plant on a commercial scale is small compared with the capital required to develop the breeder reactor, coal liquefication, and other power-generation concepts with long payout periods. Since the economic module for geothermal power plant is 10–50 MW, a small plant is sufficient to demonstrate the technology. Once a single module has been tested there is little risk in expanding the plant. Additional modules can be added as quickly as the field is developed.

A 25 MW binary-cycle demonstration plant could be built for \$6–7 million. An estimated \$2–3 million is required for drilling and production of the geothermal reservoir. A test period of 3–6 months would be sufficient to generate the needed data on the plant and reservoir operation. Thus, the commercial potential of a field could be proven for an investment of about \$10 million before, say, \$100 million is spent to develop its full potential.

Environmental Impact

Geothermal energy will have minimal impact on the environment. In comparison with fossil-fuel and nuclear power plants, geothermal energy has clear environmental advantages. However, any large-scale development of this type will have some influence on the environment. The important factors requiring consideration are discussed below.

Air Pollution

Many geothermal fluids contain dissolved gases. In a pumped system in which no flashing occurs, the dissolved gases would be returned to the field with the re-injected brine. When steam flashing occurs at the wellhead, the non-condensables will concentrate in the steam and will be removed in a separator following the steam condenser. If hydrogen sulfide is not present, the non-condensables are vented to the atmosphere. Demonstrated methods for removing hydrogen sulfide are available if required. Alternatively, the non-condensable could be compressed and dissolved in the rejected brine.

Cooling Water

Large quantities of cooling water may be required for efficient power generation. One MW of continuous power requires about 70 acre-feet of cooling tower makeup water annually. However, substantially less cooling-water requirements are possible. In a flashed-steam process, mineral-free steam condensate is produced. In some cases, all the cooling-water requirements can be satisfied by this source. Under these circumstances, the cooling-water makeup and blowdown are negligible.

In some areas, it may be possible to use the cooled geothermal brine as cooling-tower makeup if the salt content is low. The use of dry cooling towers may also be used if water is in short supply. In most areas of the world, however, where geothermal reservoirs are present, water is plentiful and not a restraining factor on power generation.

Water Pollution

The cooled brine from a geothermal power plant must be re-injected to avoid water pollution or disposal problems. In highly porous reservoirs, the cold brine can be re-injected without additional pumping owing to its higher density. In other cases injection pumps will be required.

Cooling-tower blowdown is the only other potential source of water pollution. If steam condensate is used as makeup water, little blowdown is required. Cooling water will be treated in conventional ways to comply with water-quality regulations. Alternatively, the blowdown may be re-injected into the reservoir with the brine.

Subsidence

Excessive depletion of the reservoir could lead to land subsidence and possibly cause minor earthquakes. In most cases, all or part of the well production will be re-injected as a means of disposal and to prevent subsidence. Some geothermal reservoirs are quite porous and have active water drives. The reservoir is continuously replenished from surface water sources. Under these conditions subsidence will not be a problem. In the rare case where the problem exists, extraneous water could be injected, as is common practice in petroleum-reservoir engineering.

Noise Pollution

Noise emanating from a normally operating field and power plant is nominal and there should be no problem in designing to comply with applicable standards.

Blowout

An accidental blowout could be a temporary source of air, water, and noise pollution. If hydrogen sulfide is present, a blowout could be hazardous. Stopping a blowout should not be more difficult than stopping an oil-well blowout using demonstrated techniques. The hazard would be nowhere as great because the fluid is not flammable.

Aesthetics

Binary-cycle plants will probably be limited in capacity for a few years to about 50 MW. A plant of this size will occupy a space of about 3 acres and will have a low profile. The maximum height of any equipment will not be more than 35 ft. It will be a simple matter to blend a plant into the landscape with suitable plants, trees and bushes. If need be, the plant could be located entirely below ground level. Alternatively, it could be located 15 ft below ground level, with the excavated earth forming a landscaped dike surrounding the plant.

Typically, a 50 MW plant might be served by 8–10 wells (production and injection) on 80 acres of land. The wells and distribution piping are all low profile and landscaping could be provided to blend the facilities into the surrounding countryside. Present land uses would be unaffected.

Technological Challenges

A number of unsolved technical problems remain in the geothermal power industry. The opportunities for contributions by process engineers, reservoir engineers, and geologists are great. In many cases the industry is dealing not so much with problems as it is with uncertainties. These uncertainties will undoubtedly be cleared up as more operating experience is acquired. Important areas requiring additional research and development are discussed below.

Geological

Steam fields such as The Geysers and Larderello have long lives. In The Geysers field, for example, pressure reduction after 15 years' operation seems to be negligible. Some water-dominated fields, such as those in Iceland, appear to have indefinite lives. By contrast, the Wairakei field in New Zealand has shown a decline in productivity. This may be due to the fact that the brine is not re-injected.

It appears that there will be an optimum production rate for each field depending on its size, the rate of replenishment of the water into the reservoir, the extent to which re-injection is practiced, and other factors. Re-injection has been successfully practiced at The Geysers field and in the Imperial Valley. Long-term flow tests and injection tests are now being planned for the Imperial Valley. These tests will provide valuable information on the life of the fields and the long-term effects of re-injection.

Well Drilling

Thousands of geothermal wells have been drilled throughout the world. The drilling industry has demonstrated their capability at depths to 8,600 ft. Drilling techniques are expected to improve with experience.

Pumping

It may be necessary to pump water-dominated reservoirs having bottom-hole temperatures of less than 400°F. This, however, is not always the case as numerous artesian wells have been found which are self flowing. Pumping may also be required to prevent flashing of the liquid and to increase productivity. The design of a deep-well pump must take into consideration the pressure drop through the formation, well casing, and pump suction. Adequate static head is required to prevent pump cavitation.

Other problems to consider include materials of construction, thermal expansion, and shaft lubrication. We have recently conducted an in-depth study of deep-well pumps for geothermal production, which concluded that suitable pumps can be designed to operate at depths up to 1,100 ft.

The hotter the reservoir, the more difficult is the pumping job and the less need for pumping. At a reservoir temperature of 400°F, good productivity might be expected at a wellhead pressure of 150 psig and a temperature of 360°F, high enough for efficient power production from a binary cycle.

Materials of Construction

The selection of materials of construction for geothermal brine applications will depend on several factors. It is important to distinguish between the problems of corrosion and scaling. Corrosion is the destruction of metals by a chemical or electrochemical reaction. Scaling is the formation or deposition of a solid film on the metal surface. Scaling may be a result of corrosion products formed at the surface or the adherence of solid material formed in the surrounding fluid. Precipitated salts, for example, may form a scale without chemically corroding the metal surface. It is well known that chloride brines are highly corrosive in the presence of oxygen. Since geothermal brines are in a reducing environment, the problems of corrosion may not be as great as some have stated. If required, corrosion resistant alloys may be used. However, we expect that carbon steel will be a satisfactory material of construction for geothermal brine service. For heat exchangers condensing steam in the presence of CO_2 and H_2S, stainless steel will be required. After non-condensables have been removed, however, carbon steel should be adequate for steam service.

Scaling

Scaling of equipment may be a problem with some geothermal fluids. The scaling can be attributed to the presence of certain constituents in the brine. Silica, bicarbonates, and entrained sand can contribute to scaling tendencies. If bicarbonates are present, a reduction in pressure will result in the evolution of carbon dioxide and the precipitation of calcium carbonate. This can be prevented by pumping the well under pressure to maintain the carbon dioxide in solution.

Geothermal brines generally contain varying amounts of silica. Some hypersaline brines in the Imperial Valley contain as much as 1,200 ppm silica. Under flashing conditions, the silica will precipitate as silica or silicates. It may deposit on the well casing or may be carried on as a flocculent. Insoluble salts in the brine may act as binding agents for the silica and sand in the formation of scale. In most instances, the scale is insoluble in acid, exceedingly hard, and difficult to remove. Tests are required to determine the magnitude of the scaling problem in any particular field. A 90-day production test of the Imperial Irrigation District No. 1 well in the Imperial Valley in 1961 showed no scale in the well casing or steam separator.

The deposition of silica and particulates on brine heat-exchanger surfaces will seriously reduce heat-transfer rates. Very little is known about these phenomena. The Office of Saline Water is supporting one research effort. San Diego Gas and Electric Company and the Southern California Edison-Southern Pacific–Phillips Joint Venture are each planning to research the subject using Imperial Valley brines. We have developed process schemes for eliminating or sharply reducing the problem of scaling in geothermal power plants.

Flashed steam may contain silica which could deposit on exchanger surfaces or turbine blades. In this case, the silica can be removed by washing

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the flashed steam with silica-free condensate. We have developed an effective device for removing dissolved silica from steam.

Non-condensables

As previously observed, non-condensables have only a minor effect on the performance of a binary cycle, but could have a major effect on the performance of a steam cycle. Very little data are available with regard to the quantity of non-condensables in most geothermal fluids. They tend to be predominantly CO_2, with smaller quantities of H_2S and hydrocarbons. Reliable data on non-condensables both as to quantity and composition are essential.

Conclusions

The geothermal resources of the world are comparable in magnitude to fossil-fuel and nuclear-energy resources. An advanced binary cycle has been developed to permit the practical utilization of the vast amount of geothermal energy existing as water-dominated reservoirs. This technology exists today for generating significant quantities of geothermal power at competitive prices.

When compared with other alternative energy sources, geothermal energy has several distinct advantages. Geothermal energy is essentially a low-cost, non-polluting source of power. The technical problems associated with geothermal energy are orders of magnitude less than those associated with breeder reactors, shale-oil production or coal liquefaction.

When evaluating alternative energy sources, it is necessary to consider factors that go beyond the battery limits of a power plant. The impact of transportation and fuel-processing facilities must be considered. International factors, such as the balance of payments, are also involved. After considering all of these factors, it is apparent that geothermal energy is a valuable source of energy and should be developed without delay.

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