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ECONOMIC PERFORMANCE OF GEOTHERMAL POWER PLANTS USING THE KALINA CYCLE TECHNOLOGY

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Abstract

The economics of geothermal power using liquid-dominated resources in the 300°F to 350°F (149°C to 177°C) range is substantially improved using an ammonia/water Kalina cycle, designated as System 12 (KCS12). The best features of flash steam systems and the binary Rankine cycle are combined to produce a plant design that is 40 percent less expensive per unit of installed capacity than current commercial binary plants.

A plant design is presented for a 30MW unit. Plant costs are developed using vendor quotations and factored estimates for construction and installation. Based on unit costs of capacity, i.e. $/kW, project returns to the equity investor are presented.

Economics of Existing Systems are Poor in Today's Power Market

Most liquid-dominated resources, as yet undeveloped, are at temperatures equal to or below 350°F (177°C). In this range, both flash and binary organic Rankine cycles are not economic at current competitive electricity prices, e.g. $.05 to $.06 per kWh.

A. Flash Steam

Flash steam systems perform reasonably well at higher temperatures, say 400°F (204°C) by virtue of their simplicity and low capital cost. Very little heat exchange equipment is required, except for the condenser, and conventional steam turbines are specified. These turbines, except for some blade treatment to protect against the solids carryover in the steam such as H_2S, are identical to those that have been used in utility and industrial steam plants for the past century. In large sizes, these turbines sell for less than $200/kW. However, as the source temperature decreases, the production of steam per unit of brine decreases precipitously. Remember that the production of flashed steam is a function of the temperature difference between the <u>source</u> and <u>flash</u> temperature, not the absolute temperature of the source. For example, a 65 psia (4 bar) single flash plant consumes more than three times the amount of brine at a 330°F (166°C) source temperature than one at 400°F (204°C).

B. Binary Rankine

The other competing technology that has been developed specifically for lower temperature sources suffers for different reasons. The thermodynamic process of transferring heat from the source to the organic (hydrocarbon or chlorofluorocarbon) working fluid is inefficient. Except for experimental supercritical plants operating with hydrocarbon mixtures,[1] commercial binary plants employ a single-component working fluid which is vaporized in a subcritical boiler. The result is a thermodynamic mismatch between the hot brine as it enters the evaporator and the much cooler working fluid leaving the evaporator. This is an irreversible thermodynamic loss that manifests itself as lower efficiency and higher brine consumption.

Further, the hydrocarbons used in binary plants, such as pentane, impose a much different turbine specification, making them more expensive than conventional steam turbines. There is a much smaller enthalpy drop during the expansion of hydrocarbons compared to steam. So, in order to produce the same amount of power, the hydrocarbon mass flowrate must be increased proportionately. This makes the turbine very large, albeit with few stages of expansion. With such a departure from conventional steam turbine practice, relatively few vendors offer these machines and, accordingly, at a higher price. At present, commercial binary plants have turbines limited to 5MW modules. The vast majority have one-megawatt modules. Building a plant with ten or more modules may improve on-line availability somewhat, but it certainly results in much higher capital cost. For example, twenty hydrocarbon turbines at one megawatt are three to five times more expensive per kilowatt than one twenty-megawatt steam turbine.

Finally, hydrocarbons exhibit poor heat transport properties. Their specific heat is less than one-half of that of water. Thus, heat exchange surface is increased, further adding to cost.

An Alternative: KCS12

The design features of the Kalina Cycle System 12 (KCS12) were first reported in 1989[2]. It achieves a thermodynamic efficiency (brine effectiveness) that is approximately 50% greater than binary Rankine plants while using standard steam turbines to produce a plant design that is economically superior to either the flash or hydrocarbon binary designs for resources in the 300°F to 350°F (149°C to 177°C) range. The design of KCS12 is shown in Figure 1. The working fluid is a mixture of ammonia and water having a concentration of 0.85 ammonia.

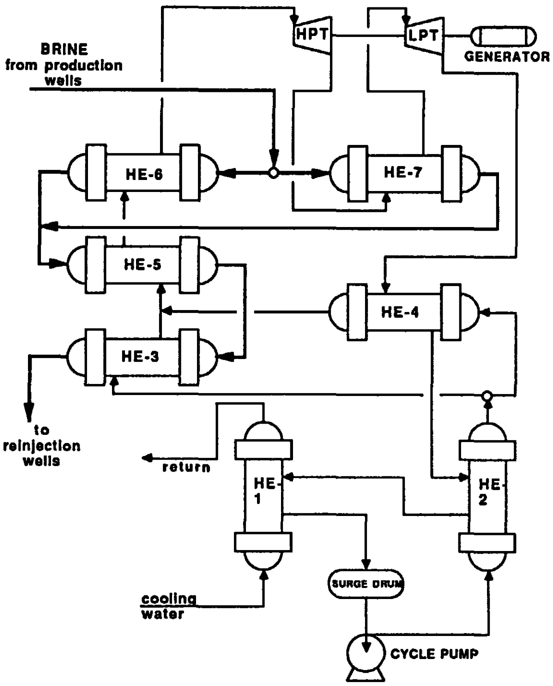

FIGURE 1

KCS12 Plant Design

Upon entering the plant, the brine is split into two streams; one is used to superheat the working fluid vapor in HE-6 and the other to reheat the vapor in HE-7. After leaving these two exchangers, the brine streams are merged and then used for evaporation and preheat duty in HE-5 and HE-3. After leaving the preheater, the brine is reinjected to ground. On the working fluid side, the vapor is condensed against cooling water in HE-1 and pumped to boiler inlet pressure. From there, the liquid is preheated recuperatively in HE-2 and HE-4 and then on to the main boiler, HE-3, 5 and 6. After leaving HE-6 in a superheated state, the vapor is expanded through the high-pressure turbine stages, then reheated in HE-7 before entering the low-pressure turbine stage. After completing the second expansion, the saturated vapor enters the recuperative boiler, HE-4, where it begins to condense. As the vapor condenses, its heat is given up to vaporize a stream of the oncoming working fluid.

The features that distinguish KCS12 from the flash and hydrocarbon binary Rankine plants are:

1. Variable Boiling Temperature

The .85 ammonia/water mixture boils along a variable temperature process in a conventional subcritical boiler. At a pressure of 453 psia (31.2 bar), the working fluid begins to boil (bubble point) at 165°F (74°C) and completes boiling (dew point) at 300°F (149°C). This produces a very good working fluid/brine match. See Figure 2. Thermodynamic losses are reduced.

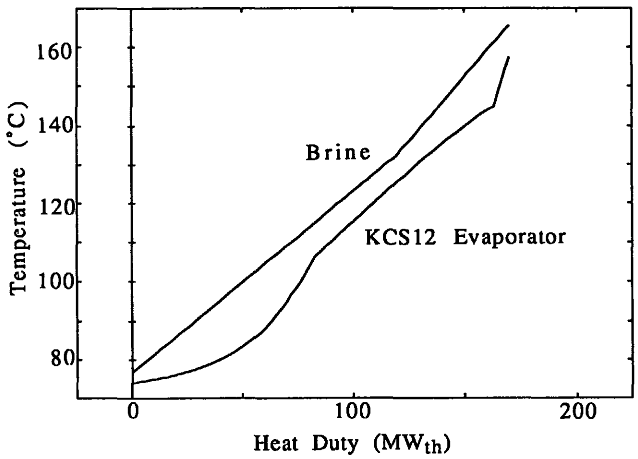

FIGURE 2

Heat Acquisition

2. Highly Recuperative

The two recuperative heat exchangers (HE-4 and HE-2) provide approximately 38 percent of the total heat transferred to the working fluid. This improves the net brine effectiveness, i.e. Wh/kg. Only through the use of mixtures is it possible to transfer heat from the turbine's exhaust at 134 psia (9.2 bar) to the oncoming working fluid at 453 psia (31.2 bar). Even though the turbine exhaust pressure is lower than in the boiler, the temperature at which the exhaust vapor begins to condense (dew point) is approximately 63°F (35°C) higher than the temperature at which the working fluid begins to boil. By contrast, the turbine exhaust in conventional binary plants cannot be used for boiling. The recuperation is limited to the small amounts of superheat remaining in the exhaust, which may be used for minor liquid preheat duty.

3. Standard Steam Turbines

The molecular weight of ammonia is very similar to that of water, 17 vs. 18. Thus, standard steam turbines may be used for ammonia/water duty. Molecular weight determines the fluid's sonic velocity which, in turn, sets the blade heights and rotational speed. Except for a zero leakage mechanical seal, the ammonia/water turbine is identical to conventional steam turbines. Furthermore, KCS12 operates at above-one atmosphere at all times. This eliminates the need for the large, expensive condensing stages that are used in all steam power plants, including flash geothermal. Erosion protection is also unnecessary because the exhaust is clean, dry saturated vapor.

4. Heat Exchangers

The specific heat of ammonia/water mixtures is more than twice that of hydrocarbons or chlorofluorocarbons, albeit mixtures have lower conductances than pure components. Surface per unit of heat transferred is reduced proportionately. Carbon steel is specified throughout.

The improvements described in 1 and 2 above result in superior thermodynamic performance. Net brine effectiveness for KCS12 is approximately 40 to 60 percent better than comparable hydrocarbon binary Rankine plants. KCS12 performance is presented in Figure 3. The combined effect of improved performance and the ability to use a centrally located, conventional steam turbine and small heat exchanger surfaces (items 3 and 4) play a major role in reducing the plant's capital cost.

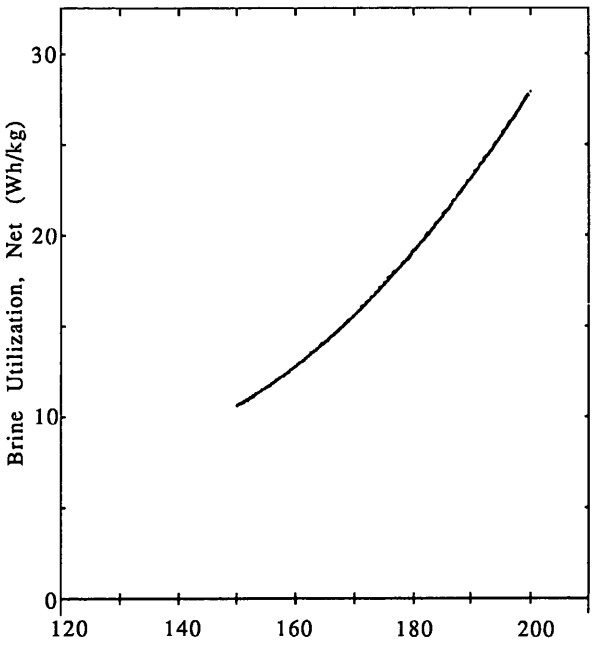

FIGURE 3

KCS12 Performance

Capital Cost

A study was conducted to estimate the installed capacity cost of KCS12 under the following conditions:

Site: Central Nevada
Brine Inlet Temperature/Reinjection Temperature: 330°F (166°C)/170°F (77°C)
Brine Flowrate: 4,000,000 lb/hr (1.82 kg x 10^6/hr)
Cooling Water Inlet Temperature: 55°F (13°C)

Based on the above conditions, the KCS12 plant's performance is summarized below:

Net Output of the Power Island: 32.2MW
Net Output Delivered to the Grid: 25.5MW
Working Fluid: .85 ammonia/water
Turbine Inlet: 435 psia (30 bar)/315°F (157°C)
Turbine Exhaust: 110 psia (7.6 bar)/220°F (104°C)

Based on the conditions cited above and heat exchanger specifications shown in Table 1, an estimate of equipment and construction costs was made. A plot plan is shown in Figure 4.

Major Equipment	Cost ($000)
Heat Exchangers	5,260
Vessels and Tanks	620
Pumps	2,050
Turbine Generator	6,450
Subtotal	14,380
Construction	
Cooling Tower	3,600
Piping	3,200
Power and Lighting	2,300
Foundations	1,000
Structures	1,100
Buildings	330
Instruments	1,000
Insulation	760
Miscellaneous	850
Subtotal	14,140
Engineering and Home Office	2,600
Field Labor and Indirects	4,000
Subtotal	6,600
Total	35,120
Resource development*	18,000
Total In-Ground Costs	53,120
Legal and Project Fees @ 3%	1,600
Total Project Cost	$54,720
Net Power to Grid	25,500kW
Capacity Cost	$2146/kW

* Estimate by Calpine Corporation.

KCS12 vs. Binary Rankine Economic Analysis

To demonstrate the benefit of the KCS12 from the investor's perspective, a simple cash flow analysis was performed comparing the KCS12 to the binary Rankine cycle (BRC). Based on published(3,4) data for commercial installations, the capacity cost of saleable net power for a BRC was estimated to be $3800/kW.

Table 1

Summary of KCS12 Heat Exchangers

Heat Exchanger	Duty 10^6 Btu/hr (MW_{th})	LMTD °F (°C)	ΔP psi (bar) Shell	Tube
1	539 (157.9)	10.7 (5.9)	3.58 (.25)	cooling water
2	144 (42.2)	20.8 (11.5)	2.84 (.20)	5.0 (.34)
3	253 (74.1)	17.2 (9.5)	2.80 (.19)	brine
4	198 (58.0)	14.1 (7.8)	2.80 (.19)	3.80 (.26)
5	123 (36.0)	14.8 (8.2)	4.30 (.30)	brine
6	194 (56.8)	18.5 (10.3)	7.80 (.54)	brine
7	83 (24.3)	22.3 (12.4)	5.40 (.37)	brine

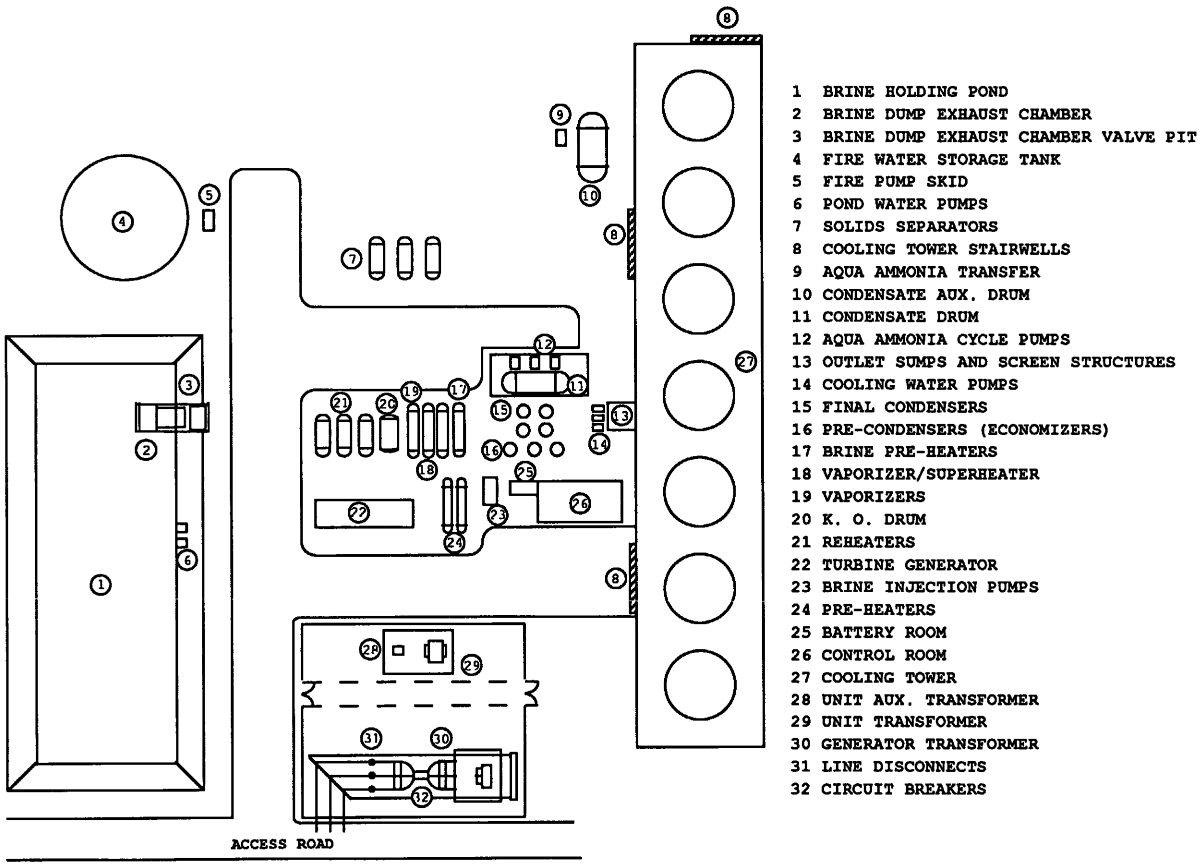

FIGURE 4

KCS12 Plot Plan

A. Methodology and Assumptions

The identical model was run for two plants, a KCS12 and a BRC, each costing $60 million. The output of each plant was estimated from the per-kW price. Thus, the KCS12 was assumed to produce 27.9MW based on an underlying cost of $2150/kW, whereas the BRC delivered 15.8MW using a cost of $3800/kW.

All other assumptions were held constant for both plants so that even if one or more of the individual assumptions is not representative of a particular project, the relative comparison of the two technologies should remain valid.

Major assumptions:

- Sales price of energy: 5.5¢/kWh
- Annual utilization: 7800 hours
- Operating costs: 0.5¢/kWh
- Debt ratio: 85% of combincd plant and and resource cost
- Debt repayment: Straight line amortization
- Interest rate: 12%
- Plant life: 30 years
- Insurance: 1% of power train
- Property tax: 1% of power train and resource
- Tax dcprcciation: Straight line
- Tax benefits: Used as incurred
- Development period: One year
- Resource acquisition costs and transmission lines: Not included
- Technology licensing fees: Not included

It is worthwhile noting that the tax depreciation assumption is very conservative. Under the appropriate circumstances, U.S. regulations may permit depreciation over a much shorter life, which would generate substantial tax benefits for a qualified investor.

B. Results

1. Internal Rate of Return

The impact of the much lower cost per kW for the KCS12 is a dramatically higher return. Whereas the BRC plant generates an after-tax internal rate of return of only 7%, the KCS12 yields 22%. Driving these results is the fact that the two plants have almost identical cost structures, but the KCS12 produces 77% more revenue. Assuming a 15% investment threshold, the BRC plant described in this example would not be built.

2. Cumulative Cash Flows

The comparison plants are of identical total cost so that the absolute cash flows can be compared. In both cases, the 15% initial equity investment plus interest during the one-year development period results in an initial $11.1 million cash outlay at the time of plant operation. In contrast to the KCS12, which generates positive cash flow in the first year, the BRC does not have a positive cash flow until the eighth year of operation. Over the estimated 30-year life of the two projects, the KCS12 yields nct after-tax cash flow of $191 million versus only $56 million for the BRC plant.

3. Interest Coverage

Lenders to thesc projects are generally concerned that they have adequate sccurity for the payment of principal and interest on their loan. One frequently used test is the ratio of a project's earnings before interest and taxes to the required interest payment. A ratio of one means that there is exactly enough cash flow to pay the interest. Although a geothermal project with a power salc contract from a strong utility may be a relatively securc risk, it would be typical for a lender to require an interest coverage ratio of somewhat greater than one.

In this example, the KCS12 has an initial interest coverage ratio of 1.61, which is sufficiently high that lenders may be willing to increase the leverage on the project. Alternatively, the BRC has an interest coverage ratio of only 0.84. In this case, it is possible that the lender would not procced with an 85% loan without additional security of some type.

C Sensitivity Analysis

The results presented abovc wcre tested for their sensitivity to changes in some of the most important assumptions.

1. Sale Price

The single most critical variable is the price at which electric power can be sold. The graph in Figure 5 (and the accompanying data points in Table 2) demonstrates the relationship between the internal rate of return and the sale price of power for both plants.

If the cost of equity capital for these projects is assumed to be 15%, then the KCS12 creates a viable investment alternative at a sales pricc of 4.5¢ per kWh whereas the BRC requires a sales price of 7.5¢ per kWh to meet the same threshold. During the early 1980s, when public utilities were granting Standard Offer 04 (SO-4) power sales contracts, the energy sales price frequently was betwecn 7¢ and 9¢ per kWh. At these prices, the existing BRC technology offered an economically sound alternative for developing geothermal resources. Sincc the expiration of the SO-4 contracts, sales prices have fallen. The KCS12 is one way to provide an adequate return to attract equity investment for geothermal development.

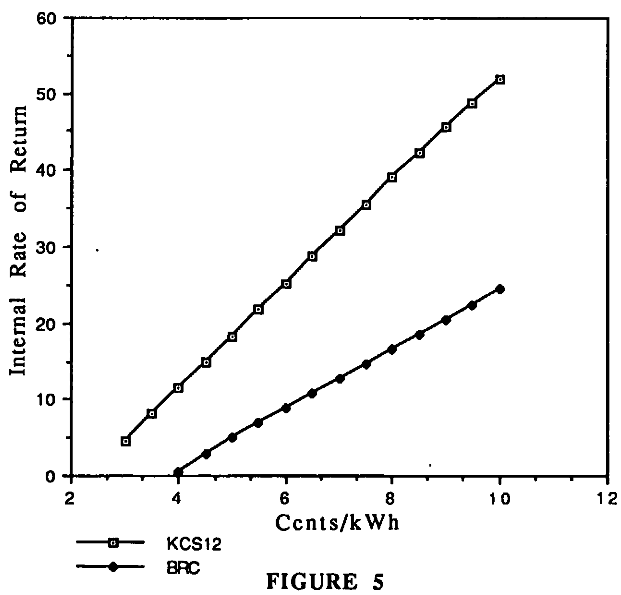

FIGURE 5

Internal Rate of Return vs. Electricity Sales Price

Table 2

Data Points:
Internal Rate of Return vs. Electricity Sales Price

Sales Price (Cents/kWh)	KCS12	BRC
3.0¢	5%	
3.5¢	8%	
4.0¢	12%	0%
4.5¢	15%	3%
5.0¢	18%	5%
5.5¢	22%	7%
6.0¢	25%	9%
6.5¢	29%	11%
7.0¢	32%	13%
7.5¢	36%	15%
8.0¢	39%	17%
8.5¢	42%	19%
9.0¢	46%	20%
9.5¢	49%	22%
10.0¢	52%	24%

2. Cost per kW

The costs of developing a resource and building a plant can vary over a wide range. Table 3 contains the rates of return which result if the cost per kW is varied while all other assumptions remain constant. The percentage of the total cost allocated to development of the resource was unchanged. In the case of the KCS12, a 20% increase in the cost per kW to $2600 still yields a 16% return to the equity investor.

Table 3

Internal Rate of Return vs. Cost per kW

KCS12		BRC	
$/kW	Return	$/kW	Return
$1,800	29%	$3,500	9%
1,900	26%	3,600	8%
2,000	24%	3,700	8%
2,100	23%	3,800	7%
2,200	21%	3,900	6%
2,300	20%	4,000	6%
2,400	18%	4,100	6%
2,500	17%	4,200	5%
2,600	16%	4,300	5%

3. Leverage

In general, the more debt the lender is willing to provide, the higher the return to the investor. Table 4 shows the impact on the internal rate of return of 10% increments in permissible leverage over the range of 90% to 50%.

The KCS12 demonstrates the traditional relationship of a falling return as the leverage decreases. In the BRC case, the return on assets is approximately the same as the after-tax cost of debt, resulting in very little benefit from increasing leverage. At higher sales prices, where the return on assets exceeds the cost of debt, the BRC would exhibit the typical characteristic of higher return with increasing leverage.

Table 4

Leverage vs. Internal Rate of Return

Percentage Debt	KCS12	BRC
90%	25%	7%
80%	20%	7%
70%	17%	7%
60%	16%	7%
50%	15%	7%

Conclusions

The KCS12 offers an economically superior alternative. It improves thermodynamic efficiency and also lowers cost through the use of standard steam turbines. It is estimated that the cost per kW for the KCS12 is approximately 40% less than for a binary system. With this dramatic decrease, even at current electricity prices, equity returns provided by the KCS12 are quite attractive, even at 20% over the estimated cost.

Acknowledgements

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