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EVALUATION OF HYBRID SOLAR/FOSSIL
RANKINE-COOLING CONCEPT

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H.M. Curran, Ph.D., P.E.

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Prepared by:

Hittman Associates, Inc.
9190 Red Branch Road
Columbia, Maryland 21045

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EVALUATION OF HYBRID SOLAR/FOSSIL FUEL RANKINE COOLING CONCEPT

Introduction

The hybrid solar/fossil fuel Rankine cooling concept involves the use of the output of a solar thermal collector, or other low-quality thermal resource, to evaporate the working fluid in a Rankine engine at a moderate temperature and the use of high-quality fossil fuel to superheat the fluid to a high temperature. This has the beneficial effects of (1) a much higher Rankine cycle efficiency than is attainable with only the energy input from moderate temperature solar collectors, and (2) matching the qualities of the energy resources to the quality requirements of the cycle components. Because of the high superheat temperature, on the order of 1000°F, water is the only practical working fluid. In the cooling application the shaft power of the Rankine expander is used to operate a vapor compression refrigeration cycle.

The development of a steam turbine for this concept was initiated by Energy Technology Inc. (ETI) in 1972, and a patent was obtained in 1976 [1]. The concept was evaluated by Curran and Miller [2] in connection with a National Science Foundation contract, and by Lior [3].

In 1977, the U.S. Department of Energy awarded contracts to ETI and to the University of Pennsylvania for the design, construction and testing of steam turbines suitable for use in hybrid solar/fossil fuel Rankine cooling systems. Table 1 provides details of these two contracts. In the case of the ETI contract, as of August 1980 the turbine had been completed and successfully tested to a speed of 60,000 rpm and steam

TABLE 1. DETAILS OF ETI AND UNIVERSITY OF PENNSYLVANIA PROJECTS

	<u>ETI</u>	<u>University of Penn.</u>
<u>Turbine</u>		
Type	Radial outflow	Counter-rotation radial outflow
Blading	4 stages	10 rows
<u>Turbine Design Point</u>		
Speed, rpm	75,000	15,300
Shaft power, hp	31	30
Boiler temp., °F	300	212
Boiler press., psia	67	15
Superheater Temp., °F	1,000	1,112
Condensing temp., °F	115	115
Mass flow, lbm/hr	250	357
Turbine efficiency	~0.75	~0.75
Cycle efficiency	0.217	0.195
<u>Vapor Compressor</u>		
Make/Type	_____	Trane/Model 2F5050
Speed, rpm	_____	1749
Capacity, tons	_____	25
<u>Drive Arrangement</u>	_____	Reduction gearing
<u>Auxiliary Power</u>	_____	Induction motor

inlet conditions of 55 psia and 825°F. Due to liquidation of ETI in September 1980, no further testing of this turbine is planned.

As of November 1980 the University of Pennsylvania turbine had not been completed. Most of the design work had been completed and some of the parts had been fabricated. The project completion is scheduled for mid-1981.

Similar concepts are under consideration for large hybrid fossil/geothermal power plants [4, 5, 6, 7]. Two approaches have been found to be technically feasible. In one approach a hot geothermal brine is used to provide feed-water heating for a closed cycle power plant, with fossil fuel being used for evaporation and superheating. In the other approach, a hot geothermal liquid is flashed to obtain steam for an open cycle power plant and fossil fuel is used to superheat the steam. In the fossil/geothermal system analyses coal is usually assumed to be the fossil fuel used. No fossil/geothermal power plant has yet been built, but one has been under consideration for Burbank, CA [8].

Objective

The objective of this study is to provide a new assessment of the hybrid solar/fossil Rankine cooling concept in support of the U.S. Department of Energy Solar Cooling Program. This study was performed as an item of work under U.S. Department of Energy Contract No. DE-AC-03-79CS-30202. The assessment covers the areas of technical evaluation and economic evaluation.

Technical Evaluation

The hybrid solar/fossil Rankine cycle is a closed cycle using water as the working fluid. In a closed Rankine cycle the energy input is supplied in three stages. These are sensible preheating of the liquid, isothermal evaporation, and superheating of the vapor. Of these three, the largest energy input corresponds to the isothermal evaporation stage.

Figure 1(a) shows a schematic diagram for a superheated Rankine cycle. As shown, the cycle includes two regenerators for recovery of part of the enthalpy in the expanded vapor. Figure 1(b) shows the corresponding ideal cycle pressure enthalpy diagram. The evaporation enthalpy, q_{HS} , is added in the boiler between state points 3 and 4, and the superheat enthalpy, q_{HF} , is added in the superheater between state points 5 and 6. Figure 2 shows an approximate actual cycle temperature-entropy diagram, indicating the expansion and regeneration irreversibilities. The evaporation process is isothermal, whereas the vapor temperature is increased in the vapor to vapor regenerator and the superheater.

Since the boiler, superheater, and condenser conditions may be independently chosen the number of possible cycles is infinite. However, the temperature range of possible cycles is limited by practical constraints. The state-of-the-art limit for the highest cycle temperature in steam power plants is generally considered to be about 1000°F, on the basis of metallurgical, economic and reliability considerations. The practical limit for the lowest cycle temperature is on the order of 100°F, depending on ambient conditions and condenser design.

Figure 1. System Schematic and Ideal Cycle Pressure-Enthalpy Diagram for Superheated Rankine Cycle

Assuming that the highest and lowest cycle temperatures are selected at or near the limiting values in order to maximize the cycle efficiency, the boiler temperature becomes the principal cycle parameter. As the boiler temperature increases, the cycle efficiency increases gradually, but the pressure increases rapidly. In the hybrid solar/fossil concept the upper limit for the boiler temperature is determined by the output temperature of the solar collector.

Also, as the boiler temperature is increased, with the maximum cycle temperature remaining fixed, a limiting value is reached at which vapor-to-vapor regeneration becomes infeasible. This occurs when the temperature at state point 4 becomes equal to the temperature at state point 5 in Figure 2. This limiting value depends primarily on the maximum cycle temperature, the isentropic efficiency of the expander, the regenerator effectiveness, and the minimum temperature difference in the regenerator. For a 1000°F maximum cycle temperature and state-of-the-art values for the other factors, this limiting value is about 290°F.

The prior performance analyses [2,3] of the hybrid solar/fossil concept established the Rankine cycle efficiency in terms of the state point enthalpies and as a parametric function of the cycle temperatures. The relative enthalpy inputs of the solar and fossil energy resources were also determined as a parametric function of the cycle temperatures. These analyses indicated the technical superiority of the hybrid solar/fossil concept relative to the use of an organic fluid Rankine cycle operated by only the thermal energy from a low- or medium-temperature solar collector.

Figure 3 provides a comparison of the ideal cycle efficiencies as functions of evaporation temperature for super-

Figure 3. Comparison of Ideal Cycle Efficiency Versus Evaporation Temperature for Superheated Steam and Organic Fluid Rankine Cycles.

heated steam and organic fluid Rankine cycles. The superheated steam cycle efficiency is about 1.5 times the organic fluid cycle efficiency at an evaporation temperature of 300°F. Because of irreversibilities the actual cycle efficiencies for both cases would be much lower, on the order of 75 percent of the ideal values, but the ratio would be about the same order of magnitude. The primary effect of this cycle efficiency ratio of 1.5 is that, for otherwise equivalent solar cooling systems, the superheated steam Rankine system could be expected to require about two-thirds as much collector area as an organic fluid Rankine system for the cooling function. For a specific site requiring both heating and cooling, this area reduction would be feasible only if the collector area is determined by the cooling load, rather than by the heating load.

For the ideal cycle conditions specified in Figure 3 the fossil energy fraction is in the 0.21 to 0.25 range over the 200 to 320°F evaporation temperature range. This is the fraction of the total enthalpy input to the cycle provided by the fossil energy resource. The variation in the fossil energy fraction is caused by a combination of factors related to the increase in evaporation temperature. These include the decrease in the specific enthalpy of evaporation, the increase in pressure, and the decrease in regenerative superheating. In an actual cycle the fossil energy fraction would be practically the same as in the ideal case, since the relative energy inputs for evaporation and superheating are not significantly affected by cycle irreversibilities.

The constraint on evaporation temperature imposed by the use of moderate temperature solar collectors results in a limitation of the actual hybrid solar fossil cycle efficiency to a maximum of about 22 percent. However, modern state-of-

the-art steam power plants using a more complex Rankine cycle can achieve actual cycle efficiencies of over 40 percent. This raises the question of whether or not the hybrid solar/fossil Rankine cycle is desirable from the standpoint of optimum utilization of fossil fuel. An analysis in Reference 2 showed that a hybrid solar/fossil Rankine engine with given solar and fossil fuel energy input rates would provide a higher overall efficiency in converting the energy inputs to shaft power than would a combination of an organic Rankine engine with the same solar energy input rate and an electric motor receiving electricity from a power plant with the same fossil fuel energy input rate. However, this applies only when solar energy is available directly or from storage. When solar energy is not available the hybrid engine becomes a fuel-only engine with a lower fuel-to-shaft power conversion efficiency than a power plant-electric motor system.

Thus, from the point of view of national conservation of fossil fuel, the hybrid solar/fossil concept is only desirable in applications where the operating duration in the solar/fossil mode is substantially greater than in the fossil fuel-only auxiliary mode. In the solar cooling application this indicates that sites with a high percentage of sunny weather are preferable. Alternatively, applications for which interruptible power is acceptable, such as water pumping, would be suitable.

In comparing solar and geothermal applications the geothermal resource is not intermittent as is the solar resource, no storage is required, and continuous operation in the hybrid mode is possible. Thus, the use of fossil fuel superheating in hybrid flashed steam geothermal/fossil power plants generally represents a favorable use of fossil fuel in comparison with conventional power plants [9].

In comparison with a solar organic Rankine system which uses fossil fuel in the auxiliary mode the hybrid solar/fossil Rankine system would use about two-thirds as much fuel in the auxiliary mode because of the higher cycle efficiency. This advantage would be largely offset by the need to use fossil fuel in the hybrid mode versus no fuel use for the organic Rankine system in the solar mode, especially since the solar mode would be predominant. On a seasonal basis the fuel use of the two systems could be expected to be about the same.

Economic Evaluation

From an economic point of view the use of a hybrid solar/ fossil Rankine engine would result in a reduction in the capital cost of a solar cooling system relative to the use of an organic Rankine engine in an otherwise equivalent system. This cost reduction would be primarily due to the reduction in collector area as a result of the higher Rankine cycle thermal efficiency. Offsetting this first cost advantage is the annual operational cost imposed by the need to purchase the fossil fuel to operate the superheater. This fossil fuel input to the superheater is required in both the solar mode and the auxiliary mode.

The basic procedure is to compare the present value of the superheater fuel cost over the system lifetime with the first cost reduction obtained by substituting a hybrid solar/fossil Rankine engine for an organic Rankine engine. This involves the use of two cost factors. The first of these two cost factors is the unit cost of solar collectors. Considerable research and development efforts are in progress to reduce the unit cost of collectors in order to make solar

systems economically competitive with conventional systems. To the extent that these efforts are successful the first cost advantage of the hybrid solar/fossil Rankine cooling system will tend to decrease. The other cost factor is the unit cost of fossil fuel. This is expected to continue to increase at a rate greater than general inflation. Increasing fuel costs tend to make solar systems more economically competitive with conventional systems. However, as fuel costs increase the operational cost for the superheater in the hybrid solar/fossil system more easily overcomes the first cost advantages.

Thus the two major economic factors which will determine the eventual marketability of solar heating and cooling systems, namely system first cost and fuel cost, both have trends which tend to reduce the economic desirability of the hybrid solar/fossil concept. Because of their opposite trends the comparison of the superheater fuel cost with the first cost reduction will eventually become unfavorable for the hybrid concept. The cost of the fossil fuel required to operate the superheater in the k^{th} year after installation is a function of the average annual cooling load, the fuel combustion efficiency, the coefficient of performance of the cooling unit, the superheater fraction of the total energy input rate to the Rankine cycle, unit cost of the fuel in the year of installation, and the fuel cost escalation rate. This superheater fuel cost is given by the equation

$$C_k = \frac{12,000}{10^6} \frac{H_f c_f}{\eta_f} \frac{(1+e)^k}{COP_s} \quad (1)$$

8. Burbank, City of, "Continuing Site-Specific and Design Analysis of Hybrid Geothermal/Fossil Power Plants," Report prepared for the U.S. DOE/DGE, 1978.
9. Kestin, J., et al, editors, Sourcebook on the Production of Electricity from Geothermal Energy, U.S. DOE/DGE, March 1980.
10. OMB Circular A-94.
11. "Federal Energy Management and Planning Programs; Methodology and Procedures for Life Cycle Cost Analysis (Average Fuel Costs)," Federal Register, Part XII, 27 October 1980.
12. United Technologies Research Center, "Design, Development and Testing of a Solar-Powered Multi-Family Residential Prototype Turbocompressor Heat Pump," Interim Technical Report, R79-953050-1, Prepared for U.S. Department of Energy, September 1979.

where

C_k = superheater fuel cost in k^{th} year, \$/ton-year

c_f = initial unit cost of fuel, \$/10⁶ Btu

f = superheater fraction of total energy input rate to Rankine cycle

η_f = fuel combustion efficiency

COP_s = coefficient of performance of hybrid solar/fossil chiller (product of actual Rankine cycle efficiency and vapor compressor coefficient of performance)

e = fuel unit cost real annual escalation rate

H = hours of cooling per year

12,000 = Btu/ton - hr

The present value of the superheater fuel cost for n years is

$$\begin{aligned}
 P &= 1.2 (10^{-2}) \frac{H f c_f}{\eta_f COP_s} \sum_{k=1}^n \left[\frac{1+e}{1+d} \right]^k \\
 &= 1.2 (10^{-2}) \frac{H f c_f}{\eta_f COP_s} r \frac{1-r^n}{1-r}
 \end{aligned} \tag{2}$$

where P = present value, \$/ton

d = real discount rate

$$r = \frac{1 + e}{1 + d}$$

$$r \frac{1 - r^n}{1 - r} = \text{uniform present worth factor modified for fuel escalation}$$

The real fuel escalation rate and the real discount rate are used in this analysis, that is, inflation has been excluded. These rates are assumed not to vary with time in order to simplify the present analysis. The U.S. Office of Management and Budget (OMB) requires federal agencies to use a real discount rate of 10 percent in the evaluation of government investments [10]. The U.S. Department of Energy currently uses a real discount rate of 7 percent [11]. Private investors and economists evaluating investments use a real discount rate based on the after-tax return on the best alternative investment.

Assuming that the organic Rankine and the hybrid solar/fossil Rankine cooling systems are essentially equivalent except in collector area,* which is a reasonable first approximation, and assuming that the collector area is determined by the cooling load, the first cost differential is

$$\Delta FC = c_c (A_o - A_s) \quad (3)$$

*This equivalence includes the use of fossil fuel auxiliary in the organic Rankine system. An example is the United Technologies System (12).

where ΔFC = difference in first cost, \$/ton

c_c = solar collector installed cost, \$/ft²

A_o = collector area required for organic Rankine system, ft²/ton

A_s = collector area required for hybrid solar/fossil system, ft²/ton

For specified parameter values the number of years, n , at which $\Delta FC = P$ is a measure of the economic desirability of the hybrid solar/fossil Rankine system relative to the organic Rankine system. Values of n greater than the probable system life, say 20 years, indicate that the hybrid system would be economically preferable, and vice versa. Combining Equations (2) and (3) and solving for n gives

$$n = \frac{\ln[1 - V \frac{1-r}{r}]}{\ln r}, \quad r < 1$$

$$n = V, \quad r = 1 \quad (4)$$

$$n = \frac{\ln[V \frac{r-1}{r} + 1]}{\ln r}, \quad r > 1$$

where
$$V = \frac{c_c (A_o - A_s) \eta_f \text{COP}_s}{1.2 (10^{-2}) H f c_f}$$

Mathematically, the range of possible values for n is 1 to ∞ . The corresponding limits on V are:

n	V	
	$r < 1$	$r > 1$
1	r	r
∞	$\frac{r}{1-r}$	∞

Figure 4 shows a graphical plot of Equations (4). For the case $r=1$ the linear function corresponds to the real fuel escalation rate being equal to the real discount rate, $e=d$. This line is independent of the absolute values of e and d , and it divides the graph into two regions, one in which $r<1$ ($e<d$), and the other in which $r>1$ ($e>d$). In the region $r<1$, the curve shown is for $e=0.05$ and $d=0.10$. In the region $r>1$, the curve shown is for $e=0.15$ and $d=0.10$. Because of the nature of the function r , these curves are not independent of the absolute values of e and d , but they are close approximations for $e/d=0.5$ and $e/d=1.5$, as noted on the graph.

If a probable system lifetime, say $n=20$ years, is selected, Figure 4 shows that as e increases relative to d , increasing values of V are required to satisfy this condition.

The function V may be considered as the product of two groups of parameters, one made up of parameters which have values dependent on the hybrid solar/fossil cooling unit, and the other made up of economic and site-specific parameters:

$$V = \frac{\eta_f \text{COP}_s}{1.2(10^{-2}) f} \cdot \frac{c_c (A_o - A_s)}{c_f H} \quad (5)$$

Table 2 shows appropriate values for the first group of parameters for an evaporation temperature of 320°F , a super-heat temperature of $1,000^\circ\text{F}$, and a condensing temperature of 120°F . Inserting these values into Equation (5) gives

$$V = 268 \frac{c_c (A_o - A_s)}{c_f H} \quad (6)$$

Figure 4. Plot of n as a function of V for $r = \frac{1+e}{1+d}$.

TABLE 2. HYBRID SOLAR/FOSSIL CHILLER PARAMETER VALUES*

$$\text{COP}_s = 1.10$$

$$\text{COP}_s / \text{COP}_o = 1.45 = A_o / A_s$$

$$\text{COP}_o^{**} = 0.76$$

$$\eta_f = 0.70$$

$$f = 0.24$$

*Temperature Basis:	Evaporation	320°F
	Superheat	1,000°F
	Condensing	120°F

**COP_o = coefficient of performance of organic Rankine chiller

Assuming that the cooling load, rather than the heating load, determines the collector area, the value of A_o is site-dependent, but is generally in the range of 125 to 200 ft^2/ton . Using the area ratio of 1.45 given in Table 2, the value of $(A_o - A_s)$ falls in the range of 39 to 62 ft^2/ton .

The number of hours of cooling per year, H , is site dependent. The following table gives values used in the United Technologies project [12]:

<u>City</u>	<u>H, hrs/yr</u>
New York	1136 to 1526
Phoenix	3216 to 3817
Fort Worth	3414
Santa Maria	1259
Madison	1435
Apalachicola	3575

The remaining two parameters are the unit cost for the solar collector, c_c , and the initial unit cost for fossil fuel, c_f . Both of these are time-dependent, that is, the values used in computing V should be those which apply for the year of installation of the solar cooling system. Given that a marketable hybrid solar/fossil cooling system has not yet been developed and that a significant solar cooling market does not yet exist, the first feasible installation year for a hybrid solar/fossil system as a commercial product is unknown.

The installed collector unit cost, c_c , depends on the collector type and the manufacturer. For collectors capable of a 350°F output temperature at high efficiency, a representative current installed cost is about \$30/ ft^2 . With

continued efforts at cost reduction and the attainment of mass production, future costs for solar collectors are generally expected to be much lower than the current costs, in constant dollars. Assuming that a 50 percent reduction is attainable, a value of \$15/ft² (1980 dollars) is assumed for the first feasible installation year.

Natural gas is the most probable fossil fuel for the hybrid solar/fossil system. The mid-1980 U.S average cost for the residential sector, as reported by the U.S. Department of Energy, is \$3.83/10⁶ Btu [11]. The U.S. DOE projected 1990 U.S. average is \$4.83/10⁶ Btu (1980 dollars), and the projected U.S. average escalation rate for natural gas in the residential sector for 1990 and beyond is 1.24 percent/ year [11]. These projections are based on a large-scale econometric model. This model is an approximation of the actual situation that may be influenced by changing relationships and government policies that change with time. Thus these projections are based on the model's representation of relevant economic relationships and are not necessarily accurate forecasts of what future costs are expected to be.

Various economic studies of solar heating and cooling systems have indicated that initial fuel costs of \$10/10⁶ Btu or higher and high escalation rates are necessary for these systems to be economically competitive with conventional systems using fossil fuel. If the projected 1990 values quoted above for natural gas should prove to be correct, then the time at which solar heating and cooling systems become commercially marketable in large quantities may not occur for many years after 1990.

For the present analysis the fuel cost in the year of installation is assumed to be $\$10/10^6$ Btu and the escalation is assumed to be 5 percent.

The above values are summarized in Table 3. The real discount rate is assumed to be 10 percent. Using the values in Table 3 in Equation 6 and rounding to the nearest integer gives $4 < V < 23$.

For the values given in Tables 2 and 3, Figure 5 shows the range of V for which the hybrid solar/fossil Rankine cooling system is preferable to a solar organic Rankine cooling system, assuming a minimum service life of 20 years. This indicates that only about one-half the possible range, namely $13 < V < 23$, satisfies the minimum service life condition. This limits the range of preferability to combinations of high collector area reduction and low cooling season duration, which, in turn, imposes limitations on system design and on feasible sites.

The values used in the above analysis are assumed to exist for the first year in which the two compared systems could be installed as commercial products competitive with fossil fuel conventional systems. Assuming a continuation of real fuel escalation at 5 percent per year, the unit fuel cost would double in about 15 years, reducing the possible range to $2 < V < 12$, and none of this range would make the hybrid system preferable for a 20 year service life.

Of course, the actual values for fuel cost and escalation rate are unknown. However, there is a very high probability that the escalation will continue, so that, regardless of the actual escalation rate, the fuel cost will eventually increase to a value such that the first cost reduction will

TABLE 3. ECONOMIC AND SITE-SPECIFIC PARAMETER VALUES

$$A_o - A_s = 39 \text{ to } 62 \text{ ft}^2/\text{ton}$$

$$H = 1,100 \text{ to } 3,800 \text{ hrs/year}$$

$$c_c = \$15/\text{ft}^2 \text{ (1980 dollars) in installation year}$$

$$c_f = \$10/10^6 \text{ Btu (1980 dollars) in installation year}$$

$$e = 0.05$$

$$d = 0.10$$

Figure 5. Range of V for which Hybrid Solar/Fossil Rankine Cooling System is Preferable to Solar Organic Rankine Cooling System. Parameter Values Are Assumed for First Installation Year.

not cover the cost of superheater fuel for the service life of the system.

Conclusions

The economic analysis indicates that even if the hybrid solar/fossil Rankine cooling system were developed to the point of being a commercial product with an economic advantage over an otherwise equivalent solar organic Rankine cooling system it would gradually lose that advantage with rising fuel costs and decreasing collector costs (in constant dollars). At best, the production and marketing period for hybrid solar/fossil systems might be on the order of two decades, which is probably inadequate to justify the development effort and the formation of a production plant and a marketing organization.

The technical evaluation indicates that from the point of view of national conservation of fossil fuel, the hybrid solar/fossil Rankine concept would be preferable only in applications where the operating duration in the solar/fossil mode would be substantially greater than in the fossil fuel-only auxiliary mode. In comparison with a solar organic Rankine cooling system the hybrid system would require less collector area because of its higher COP, but would require about the same amount of fuel on a seasonal basis because the fuel usage in the solar/fossil mode offsets the lesser fuel usage in the auxiliary mode.

In summary, the limited technical advantages and the probable short duration of any economic advantage indicate that further government investment in the hybrid solar/Rankine cooling concept would not produce compensating benefits.

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