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TECHNICAL AND ECONOMIC EVALUATION OF A BRAYTON-RANKINE COMBINE-CYCLE SOLAR-THERMAL POWER PLANT

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NOTICE

TECHNICAL AND ECONOMIC EVALUATION OF A BRAYTON-RANKINE COMBINED-CYCLE SOLAR-THERMAL POWER PLANT

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ABSTRACT

Solar central receiver systems are capable of producing temperatures on the same order as those used in gas turbines. A system capable of taking advantage of the low cost of gas turbine equipment, while retaining the benefits of molten salt storage and long-duration Rankine cycle operation is the combined cycle. The combined-cycle plant has a high thermal efficiency (45.4%) and a unit capital cost competitive with a standard molten salt-steam Rankine solar thermal plant. In the combined cycle plant, inlet ambient air is compressed, preheated by the exhaust air, then heated to 815°C (1500 F) in the receiver. After passing through the turbine, exhaust air at 600°C (1110 F) is passed through a direct contact heat exchanger where it cools from 600°C to 300°C and raises the temperature of counter flowing drops of molten salt from 288°C to 565°C. The salt is then circulated through a steam generator to provide the energy input for a Rankine cycle plant, or stored to fire the generator at a later time. The technical feasibility of the direct contact heat exchanger system is examined. The cost and value of energy from the plant are calculated and compared with that of competing systems.

1. INTRODUCTION

Central receiver systems are among the most attractive methods of large-scale solar power generation. They are capable of producing temperatures on the same order [1100°C (2000 F)] as those used in gas turbines. One promising generation system that takes advantage of this high-temperature capability is the combined cycle (Brayton/Rankine), which offers very high thermal efficiency and low power-conversion costs.

Solar combined cycles have been studied previously by Bechtel (1). Bechtel uses solar collectors and an oil combustor in series to heat air to the turbine inlet temperature. This system is deemed less attractive since it requires continuous burning of oil to achieve the rated output.

Thermal storage has been shown to be advantageous in solar power plants (2). It extends operation into evening, nighttime, and cloudy periods, reducing the need for fossil fuels. Thermal energy may be stored either as sensible or latent heat, and efficiencies of over 95% may be achieved. At the high temperatures typical of gas-cycle applications, energy is stored in beds of ceramic bricks. Many concepts have been proposed for thermal storage for steam Rankine cycles. A promising system is the molten-draw salt receiver and storage. In this system, molten salt is heated from 288° to 565°C (550 to 1050 F) in the central receiver. The salt is then pumped either to the steam generator, or is stored directly in large tanks. Unfortunately, draw salt storage can not be used at higher temperatures where it exhibits unacceptably high rates of decomposition.

This study describes a unique solar thermal system which combines the high conversion efficiency of a combined cycle with the low cost of draw salt storage. The following sections briefly discuss the alternative central receiver systems, describe the proposed combined-cycle system, and evaluate its technical and economic merit.

1.1 Assessment of Solar Thermal Central Receiver Systems

Day (2) determined the cost and value of liquid metal/molten salt (LM/MS), water/steam, closed-cycle Brayton, and combined-cycle power plants operating both with storage and oil auxiliary. The most attractive system was LM/MS operating with storage as a stand-alone plant, followed by the LM/MS oil burning hybrid. The solar/oil combined cycle, water/steam, and closed-cycle Brayton hybrid were marginally attractive compared to fossil fuels.

Day also studied the effect of storage duration on the cost/value ratio of LM/MS stand-alone plants. For all regions of the country, an optimum storage duration on the order of 3 hr was identified. This corresponds to a capacity factor of approximately 0.4 in a southwestern location.

The cost of energy produced by various stand-alone plants is presented in Fig. 1 (3). The data are for optimized plants with 0, 3, 6, and 9 hr of thermal storage. For the no storage case, there is

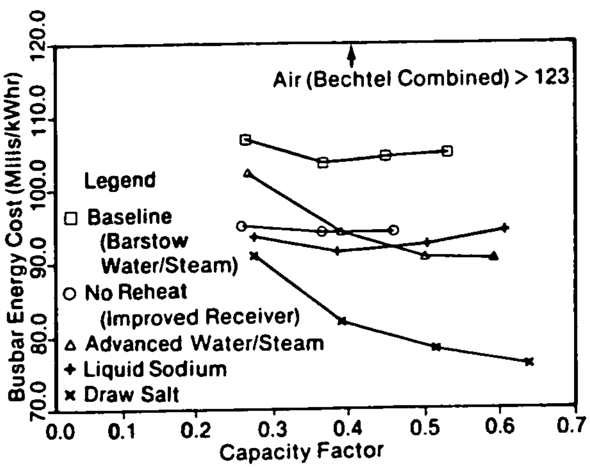

Fig. 1. Comparison of stand-alone solar central receiver systems.

no significant difference between the costs of the no-reheat water/steam, liquid sodium, and draw salt systems. However, for storage capacities above 3 hr (CF 0.4) there is a distinct advantage to the molten salt system.

These data indicate that solar thermal power systems can compete with fossil fuels, that molten salt systems are among the most promising alternatives, and that storage (particularly around 3 hr) can improve their economics.

1.2 Objective of the Study

The objective of this study is to conduct an assessment of gas-liquid direct-contact heat exchange and of a new storage-coupled system (the open-cycle Brayton/steam Rankine combined cycle). Both technical and economic issues are evaluated. Specifically, the storage-coupled combined cycle is compared with a molten salt system. The open Brayton cycle system is used as a topping cycle, and the reject heat powers the molten salt/Rankine system. In this study the molten salt system is left unmodified, the Brayton cycle is integrated on top of a Martin Marietta description of an existing molten salt plant. This compares a nonoptimized combined cycle with an optimized molten salt system. Therefore, if the economics of the new system are as good as or better than those of the molten salt system, further study and optimization would be expected to show the new system to be more favorable than indicated here.

2. DESCRIPTION OF SYSTEMS

This section describes both the base case molten salt system and the combined cycle modification. The design of the combined cycle is based on the basic Martin Marietta molten salt system (4) because sufficient design detail was available, and because it represents one of the best systems under consideration. The combined cycle employs the same equipment as the molten salt system wherever possible (the collector field, receiver height, cavity design, and Rankine subsystem are common to both designs).

2.1 Martin Marietta System

The base system has a net electrical output of 300 MW_e and is designed to run at rated output for 24 hr on June 21. The system has nine heliostat fields, each with a peak output of 194 MW_t. The flux from each field is directed at a receiver on top of a 155-m (510-ft) tower. Molten salt is circulated through the receivers and heated from 288° to 565°C (550 to 1050 F). Hot salt from the nine individual fields is piped to the centrally located power plant, where it is routed to the steam generator or stored in a thermocline salt storage tank for later use. The Rankine cycle exhibits a gross cycle efficiency of 40.3%.

2.2 Storage-Coupled Combined Cycle

A schematic of the combined-cycle system is presented in Fig. 2 and the state points of the fluids as they pass through the cycle are shown in Table 1. The steam Rankine and molten salt systems are identical to the Martin design, except that heat enters the salt system through an air-salt heat exchanger instead of through the receiver. The air Brayton cycle equipment is all mounted on the individual receiver towers. Transport of thermal energy to the central Rankine plant is still by molten salt.

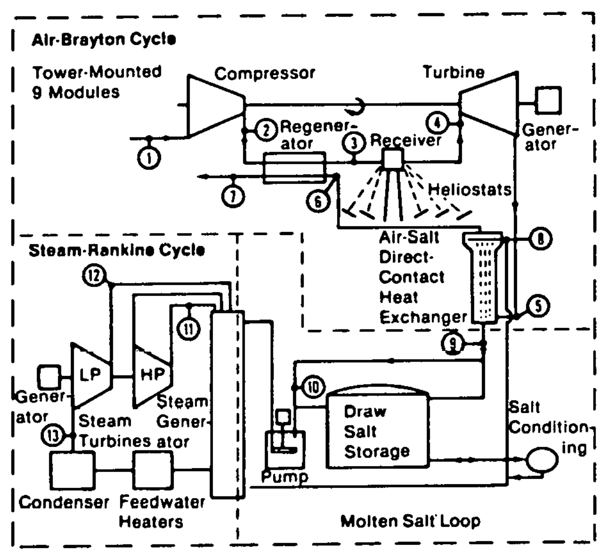

Fig. 2. Combined-cycle solar thermal power plant.

In the air cycle, ambient air is compressed to 0.25 MPa (2.5 atm), preheated to 288°C in the regenerator, and then raised to 816°C (1500 F) in a sodium/air fin tube heat exchanger. The air then is expanded through the turbine to produce electricity and exits the turbine at 593°C (1100 F).

exchangers the cross sectional area, fluid velocities, and heat transfer coefficients are set according to the allowable pressure drop.

TABLE 1. COMBINED CYCLE STATE POINTS

State Point	Fluid	Pressure		Temperature	
		Atm	Psia	°C	F
1	Air	1.000	14.7	21	70
2	Air	2.500	36.75	131	267
3	Air	2.495	36.68	288	550
4	Air	2.445	36.0	816	1500
5	Air	1.020	15.0	593	1100
6	Air	1.013	14.9	316	600
7	Air	1.0	14.7	158	317
8	Draw salt	1.014	14.9	288	550
9	Draw salt	1.02	15.0	566	1050
10	Draw salt	1.0	14.7	566	1050
11	Steam	163.3	2400.	510	950
12	Steam	30.6	450.	510	950
13	Steam	0.0069	0.102	38	100

Here it enters the air/salt heat exchanger where it heats the salt from 288° to 565°C. This could be either a direct-contact exchanger, or an indirect compact heat exchanger. The air then passes through the recuperator and is exhausted to the atmosphere. A schematic of the tower and gas-cycle equipment is presented in Fig. 3.

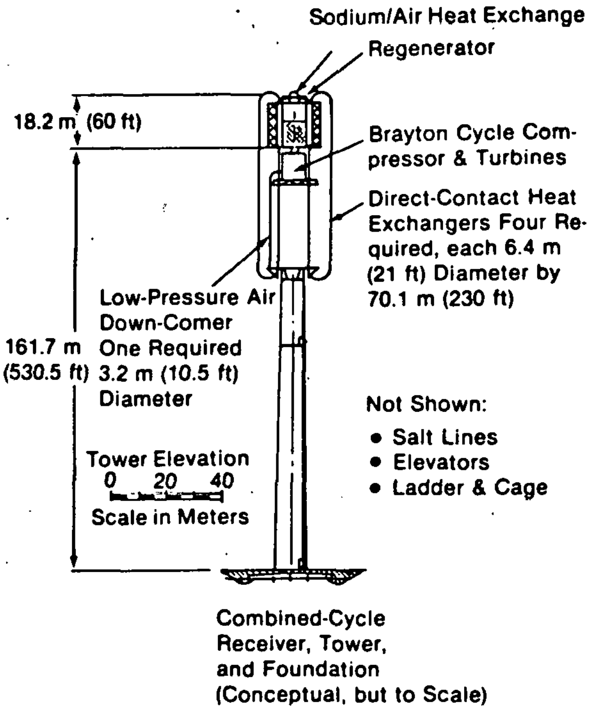

Fig. 3. Storage-coupled combined-cycle tower, receiver, and gas-cycle components.

Two of the air-cycle components warrant further description: the receiver and the direct-contact heat exchanger. The compressor and turbine are standard items. Compact heat exchangers are used in the regenerator and for the air/salt indirect heat exchangers. In these compact exchangers the cross sectional area, fluid velocities, and heat transfer coefficients are set according to the allowable pressure drop.

2.2.1 Combined-Cycle Receiver

The combined-cycle receiver has the same outward appearance as the molten salt receiver; cavity openings, receiver size, Incoloy construction. Panel location and size are indentical. The principal changes are replacement of the molten salt with liquid sodium and the addition of a fin-tube sodium-air heat exchanger.

The higher thermal conductivity and lower viscosity of the sodium result in a 100-fold improvement in the heat-transfer coefficient. Due to the high heat-transfer coefficient between the tube wall and sodium, the tube wall is virtually isothermal around the circumference. This reduces the wall stress, and allows the use of Incoloy at high temperature. As panel design, manifolding, and tube layout are similar for the two receivers, their costs are assumed to be equal.

The sodium/air heat exchanger was sized to accept the peak output of the receiver. The total temperature drop across the receiver and sodium-air exchanger equals the temperature drop (tube wall to fluid) across the salt receiver. Due to the low air-side heat-transfer coefficient, the air-side area is more than 50 times that of the receiver panels. The exchanger is a combination compact heat exchanger/fin tube design located in the center of the receiver, and is arranged as a cylinder with the air flowing radially inward to a central duct. Air-cooled panels and a heat-pipe receiver were considered, but discarded due to excessive temperature drop on the air receiver and large frictional losses in the heat-pipe receiver.

2.2.2 Direct-Contact Heat Exchanger

The air-salt direct-contact heat exchanger is shown in Fig. 4. It is essentially a large column in which hot air flows upward, while drops of molten salt absorb heat as they fall through the air. These exchangers are both simple and inexpensive, but quite large. The height and diameter of the columns are determined by the drop size, air flow rates, and heat-exchange duty. When small drops are used, the contact time required to transfer a given amount of heat is reduced, and the terminal velocity of the drops is decreased. However, as the drop terminal velocity decreases, the air velocity must decrease to prevent the drops from being carried upward. Thus, small drops require short, large diameter columns, while large drops dictate tall, thin columns. The air flows up through the column at 60% of the drop terminal velocity. This reduces the net downward velocity of the drops, and therefore, the height of the tower. The drop diameter chosen was 1.25 mm. This size results in a terminal velocity of 8.3 m/s and a column height of 70 m.

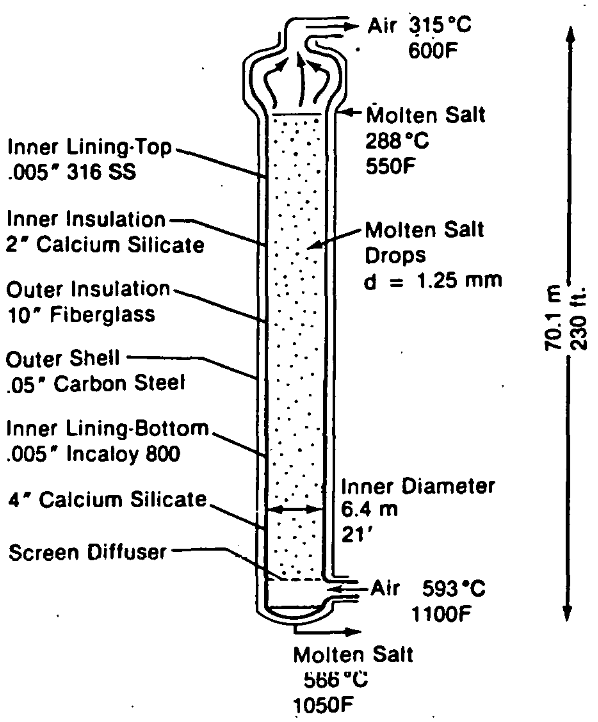

Fig. 4. Molten salt direct-contact heat exchanger.

The columns are carbon steel, internally insulated with fiberglass and calcium silicate. The insulation is protected from the salt by a metal foil liner. In spite of their large size, the simplicity of construction and thin wall gauge make them relatively inexpensive. The installed cost of the 36 columns (4 per receiver) is $5.5 M, compared with $27.7 M for compact heat exchangers for the same duty.

Direct contact between air and the molten salt raises the possibility of salt degradation. The sodium nitrate and potassium nitrate in the draw salt can react with the carbon dioxide and water vapor in the air to produce sodium and potassium carbonate and hydroxide, nitric acid, and nitrous oxide. The degradation problem may be solved by treating with nitric acid to reverse the reaction. The cost of salt treatment was estimated by computing the present worth of the nitric acid required to treat the salt during the life of the plant. Even with this $11.4 M penalty, direct-contact heat exchange is less costly than indirect heat exchange. It is likely that the cost of removing the CO_2 and H_2O from the air stream by thermally regenerated absorption on calcium oxide would be less expensive. However, this possibility was not studied in detail.

3. TECHNICAL EVALUATION

Because gas turbines are considerably less expensive than boilers and steam turbines, a Brayton topping cycle is essentially a way of increasing the plant electrical rating for a small capital outlay.

The effect of the maximum cycle temperature on receiver, Brayton, and Rankine cycle efficiency is shown in Fig. 5. In order to best illustrate the effect, the output of a plant without storage (sized to handle peak solar input) is plotted. As the receiver temperature is increased (compression ratio increases), the receiver losses slowly increase. The conversion efficiency of the overall cycle increases, but the amount of heat rejected to the Rankine cycle (and hence the output of the Rankine cycle) decreases. Over the range studied, the total annual energy delivered by the combined cycle is greater than that delivered by a Rankine cycle. For the case analyzed, the output of the combined cycle was 10% greater. The overall output of the cycle increases with increasing temperature up to approximately 1950 F. However, a compression ratio of 2.5 [maximum receiver temperature of 816°C (1500 F)] was chosen because it does not push the limits of present receiver materials technology.

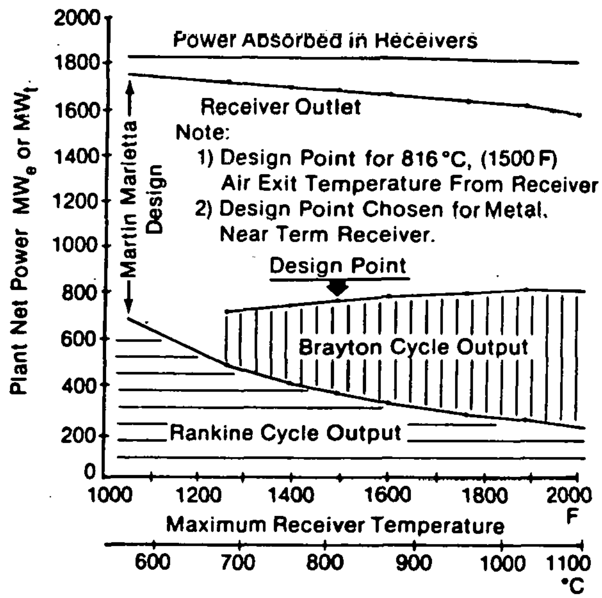

Fig. 5. Output vs. maximum receiver temperature.

4. ECONOMIC EVALUATION

The capital costs of Rankine and combined cycles with direct contact heat exchange and a capacity factor of 0.38 are presented in Table 2. Whenever possible, cost data from the Martin report were used. When these data were not available, every effort was made to use consistent data. The capacity factor of 0.38 was chosen because it corresponds to the optimum storage size. The plants were required to have equivalent capacity factors and dispatch profiles.

The combined-cycle plants cost more than the straight Rankine cycle plants, but also produce more energy on both a peak and annual basis. The cost of the combined-cycle plants is greater because, even though gas turbines cost considerably less than Rankine units of similar capacity, they require expensive heat exchangers in the receiver and regenerator. The cost of the direct-contact cycle is lower than that of the indirect system, as the capital cost of the indirect contact heat exchanger is larger than the sum of the capital cost of the direct-contact heat exchanger and the present worth of the salt treatment.

TABLE 2. COST BREAKDOWN OF COMBINED CYCLE AND MOLTEN SALT PLANT AT A 0.38 CAPACITY FACTOR

Item	Cost, Millions, (1978$) Martin	Combined Cycle
Heliostats	208.9	208.9
Indirects	13.5	13.5
Land, Site, Structures	7.9	4.5
Tower, Receiver, Piping, and Pumps	45.3	62.1
Draw Salt Storage	16.0	17.2
Salt/Steam Heat Exchangers	10.3	4.9
Controls	1.1	1.1
Steam Power Plant	63.1	30.1
Gas Turbines	–	15.6
Regenerator	–	18.2
Direct Contact Heat Exchangers	–	5.5
Salt Conditioning	–	11.4
TOTAL	366.1	393.0

Figure 6, presents the busbar energy cost for the three cycles as a function of capacity factor, normalized to the cost of the basis molten salt cycle at a capacity factor of 0.65. The direct-contact combined cycle shows an advantage at low capacity factors but not at high capacity factors. While the differences in cost are less than the uncertainties in the calculations, it must be remembered that the combined cycle is not optimized and has a large potential for improvement. It is also seen that the use of gas turbines without storage gives the combined cycle an inherently low capacity factor, unless oil burners are used to extend its operation. However, use of oil is an option with this system, not a required feature.

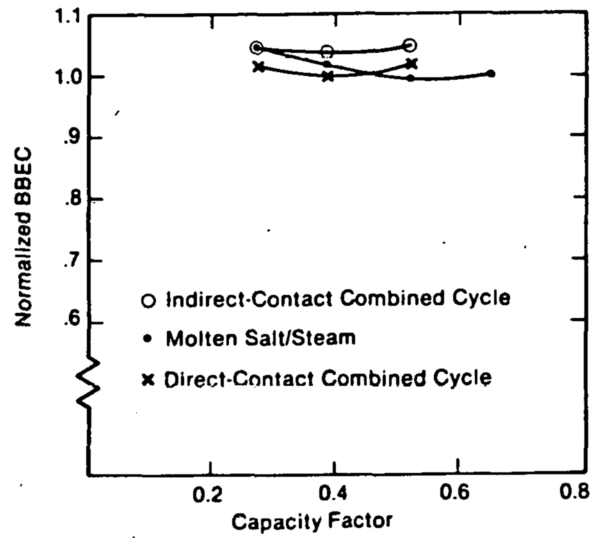

Fig. 6. Normalized busbar energy cost vs. capacity factor for 1500 F turbine inlet on combined cycles.

5. POTENTIAL IMPROVEMENTS

The combined cycle system described was not optimized. Possible improvements to the solar section include terminal concentrators and receiver and field size optimization. Use of a high-pressure closed Brayton cycle with helium as a working fluid would reduce heat exchanger costs and eliminate the need for salt treatment. Optimizing the size and effectiveness of the regenerator and receiver heat exchanger would also lower their cost. Raising the turbine inlet temperature would increase cycle efficiency. Lowering the temperature at which heat is rejected to the Rankine cycle would also improve net efficiency by allowing increased regeneration.

6. CONCLUSIONS AND RECOMMENDATIONS

A storage-coupled stand-alone combined-cycle power plant has been described. The cost and performance have been determined and compared with molten salt. Based on this data, the following conclusions seem reasonable:

1) The combined-cycle system is competitive with molten salt. Potential improvements identified may make the concept even more attractive.
2) Direct-contact heat exchange provides significant cost advantages over conventional compact heat exchangers.
3) At solar capacity factors over 0.5, an all-molten salt cycle is preferred to a combined cycle.

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