Base-Load and Peak Electricity from a Combined Nuclear Heat and Fossil Combined-Cycle Plant

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A combined-cycle power plant is proposed that uses heat from a high-temperature reactor and fossil fuel to meet base-load and peak electrical demands. The high-temperature gas turbine produces shaft power to turn an electric generator. The hot exhaust is then fed to a heat recovery steam generator (HRSG) that provides steam to a steam turbine for added electrical power production. A simplified computational model of the thermal power conversion system was developed in order to parametrically investigate two different steady-state operation conditions: base load nuclear heat only from an Advanced High Temperature Reactor (AHTR), and combined nuclear heat with fossil heat to increase the turbine inlet temperature. These two cases bracket the expected range of power levels, where any intermediate power level can result during electrical load following. The computed results indicate that combined nuclear-fossil systems have the potential to offer both low-cost base-load electricity and lower-cost peak power relative to the existing combination of base-load nuclear plants and separate fossil-fired peak-electricity production units. In addition, electric grid stability, reduced greenhouse gases, and operational flexibility can also result with using the conventional technology presented here for the thermal power conversion system coupled with the AHTR.

I. INTRODUCTION

A combined-cycle power plant is proposed that uses heat from a high-temperature reactor and natural gas to meet base-load and peak electrical demands. For base-load electricity production, heat from a high-temperature reactor is delivered through heat exchangers to a high-temperature air-breathing gas turbine to raise the compressed air inlet temperatures to between 700 and 850°C. The high-temperature gas turbine produces shaft power to turn an electric generator. The hot exhaust is then fed to a heat recovery steam generator (HRSG) that provides steam to a steam turbine for added electrical power production.

To meet peak electrical demand, natural gas or jet fuel is burnt after the nuclear heating of the compressed air to increase power levels. Because nuclear heat raises air temperatures above the auto-ignition temperatures of the fossil fuels and also powers the air compressor, the net power output can be varied rapidly compared to fossil-fired turbines to meet spinning reserve requirements and stabilize the grid. This process raises the inlet temperatures to both the gas turbine and the steam turbine. In this mode of operation, the peak gas-turbine inlet temperature is ~1300°C─about the same temperatures and operating conditions of a standard natural-gas-fired utility Brayton-cycle gas turbine that exhausts heat to a bottoming Rankine steam turbine.

A simplified computational model of the thermal power conversion system was developed in order to parametrically investigate different steady-state operation conditions. The two main operating conditions are for nuclear heat only, and combined nuclear heat with fossil heat added to bring the working fluid to a maximal turbine inlet temperature. These two cases bracket the expected range of power levels, where any intermediate power level can result during electrical load following. The nuclear reactor is expected to be at full power for all operating conditions.

II. INCENTIVES FOR THE POWER CYCLE

The nuclear-fossil combined-cycle power plant offers six potential advantages.

1. Higher efficiency. Gas turbines, with technologies such as actively cooled hollow blades, can operate at much higher temperatures than nuclear reactors. The combined nuclear-fossil system allows higher temperatures and thus higher efficiencies than nuclear-only systems.

2. Small reactors for small electrical grids. The developing world has small electrical grids with highly variable energy demands. There is a need for small reactors that are economic and can load follow. This combined power cycle is the same as that used worldwide for natural gas and oil-fired power plants. Thus, many developing countries have experience in the operation and maintenance of such systems.

3. Reduced carbon dioxide emissions. Fossil fuels are universally used to provide peak electrical power because they are storable and the cost of equipment to convert the fuel to electricity is low relative to the cost of the fuel. A long-term constraint is the release of greenhouse gases. For peak power production, the nuclear heat preheats the air approximately half way to its peak

temperature and thus can reduce up to a factor of 2 the use of fossil energy for peak electrical production.

4. Improved economics. The system has the potential for improved economics by combining low-cost base-load nuclear heat production that allows full utilization of the nuclear heat source with peak power production using low-capital-cost combined-cycle systems.

5. Available technology. The power conversion technology is an existing technology that can be coupled to high-temperature reactors. Thus, the development of high-temperature reactors is not coupled to development of new power conversion systems with the exception of the heat exchanger necessary to transfer the nuclear heat to the compressed air.

6. Operating flexibility. Although required nuclear reactor maintenance or refueling would be scheduled during turbine maintenance periods, fossil fuel heat only can be used to provide electricity to the grid if the nuclear reactor experiences an extended or unexpected outage.

III. TECHNOLOGY CONSIDERATIONS

The general concept of combining nuclear and fossil heat sources is not a new idea. The Indian Point I pressurized-water reactor in New York had a high-temperature steam cycle in which the reactor provided saturated steam that was then superheated with a fossil-fired superheater. Recent studies[1] have examined a nuclear-fossil combined cycle for steady-state electricity production. The technology to combine nuclear heat sources with Brayton thermal power conversion systems is also not new. The billion-dollar Aircraft Nuclear Propulsion program[2] of the 1960s, which had its goal the development of a nuclear-powered aircraft, developed designs and conducted non-nuclear tests that integrated heat from a secondary liquid heat-transport loop into a gas turbine.

The proposed power cycle here would be coupled to the Advanced High-Temperature Reactor (AHTR), a liquid-salt-cooled high-temperature reactor[3] that uses the same coated-particle fuels as are used in helium-cooled high-temperature reactors. The AHTR has an intermediate liquid heat-transport loop that allows for the efficient transport of heat from the reactor to the power cycle. The intermediate heat transfer loop also allows for separation of the reactor from the partly fossil-fueled power cycle to ensure safety and to avoid the need for nuclear-plant security for the power conversion system. A high-temperature reactor is required because heat input into a Brayton cycle must be >600°C for the base-load Brayton cycle operations.

IV. THERMAL POWER CONVERSION SYSTEM MODELING

The preliminary study was initiated here to map the options for such a system. A wide variety of system configurations exist (e.g., steam injection into the gas turbine after air compression but before nuclear heating or final heating of the superheated steam with nuclear heat in the HRSG system) to boost base-load or peak power levels, boost efficiency, or increase the nuclear heat fraction when the plant is operating in a peak power production mode. A schematic of the proposed combined cycle thermal power conversion system is shown in Fig. 1.

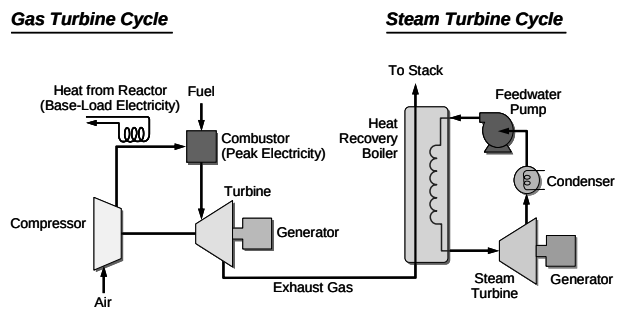

Fig. 1. Combined Cycle Schematic.

A very simplified model of the gas turbine, heat recovery steam generator, and steam turbine was developed. The Brayton cycle is first heated by an air-to-salt heat exchanger for a base load circumstance, then additional heat is added by a fuel burner for additional power production as might be needed for peaking power production or electrical load following. Note that the additional heat added by the fossil fuel combustion will add increased shaft power to the first generator almost instantaneously because none of the additional expansion work would need to be invested in additional compressor work. The exhaust from the gas turbine would then pass to the Heat Recovery Steam Generator (HSRG) where the steam working fluid would generate additional electricity in a conventional Rankine cycle. For the scoping feasibility study presented here, simplified models of the individual components of the gas turbine, HSRG, and Rankine cycle will be developed individually, then combined sequentially to show a combined performance of the thermal power conversion system. Only steady-state conditions are considered, thus energy storage or mass storage dynamic effects are not included.

IV.A. Gas Turbine Cycle Modeling

In order to calculate the state points of the combined thermal conversion power cycle, the gas turbine portion is developed first. For the first step of the combined cycle model, heat is added only at the compressor outlet for the simple Brayton cycle. To start with the system model, the design parameters of a conventional combined cycle device were chosen to utilize realistic existing hardware.

The algorithms for gas turbine performance are those given by Wilson and Korakianitis[4]. The parameters of most significant interest to calculate the cycle state points are the compressor pressure ratio, the turbine inlet temperature, the compressor inlet temperature, the compressor and turbine polytropic efficiencies, and total fractional pressure loss. Before determining the performance of the proposed AHTR/burner gas turbine, the performance calculations for a simple gas turbine cycle for various parameter variations were verified against those presented by Wilson and Korakianitis[4].

For an initial estimate of gas turbine performance, the following parameters were chosen. The ambient pressure was set to 100 kPa as appropriate for an open cycle air machine. The turbomachine polytropic efficiencies are typical for the class of machines (large, axial flow) under consideration. The polytropic efficiencies, which are functions of the physical size and mass flow rate, can be updated as appropriate in the future.

Compressor inlet temperature = 25°C
AHTR salt temperature = 800°C
Burner outlet temperature = 1425°C
Turbine polytropic efficiency = 0.875
Compressor polytropic efficiency = 0.85
Total fractional pressure drop ($\Delta P/P$) = 0.06

Because the reactor heat is transferred to the compressed air leaving the compressor by a heat exchanger, an additional parameter of the effectiveness of the salt-to-air heat exchanger was set to 0.95. All these parameters can easily be varied as appropriate. The computed results as shown on the following plots will be affected (some significantly, some not) by the values of these cycle parameters. Because the compressor pressure ratio is a major design parameter for specifying the turbomachinery, a number of important results are calculated as a function of compressor pressure ratio.

The first, perhaps most significant result is the thermal efficiency, simply calculated here as the net shaft power ($W_{turbine}$–$W_{compressor}$) divided by the total heat transferred from the AHTR heat exchanger and burner. Another important parameter is the specific work, defined as net shaft power divided by the product of the working fluid heat capacity rate and the compressor inlet temperature (mC_pT_{inlet}). The thermal efficiency as a function of the specific power is given in the following Fig. 2 for the given cycle parameters for various compressor pressure ratios. The calculations were initiated at a pressure ratio of 2, and the plotted points are in increments of 2 up to a pressure ratio of 30.

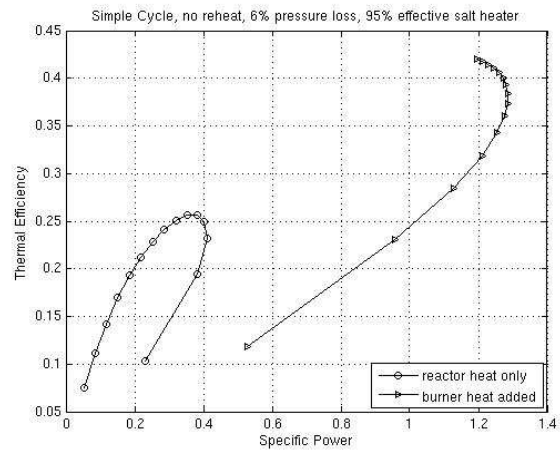

Fig. 2. Efficiency vs specific work as a function of pressure ratio.

For the case of reactor heat only, the pressure ratio for maximum work is 6 and for maximum efficiency is 11. When additional heat from the burner is added, the maximum work pressure ratio increases to 15 and the maximum efficiency occurs at a pressure ratio greater than 30. This plot shows the profound effect of turbine inlet temperature on the efficiency and specific work, but it also shows the noticeable effect of pressure ratio. For the postulated use of this combined cycle machine, these results are promising because the pressure ratio yielding the maximum efficiency when operating under reactor heat also yields a maximal amount of power when burner heat is added. Also, some of the existing designs of combined cycle gas turbine power plants currently operating on the grid have compressor pressure ratios of approximately 15 (Ref. 5).

An important result for the combined cycle is the turbine exhaust temperature, which is the inlet temperature to the heat recovery steam generator of the bottoming Rankine steam cycle. This temperature is plotted in Fig. 3 as a function of compressor ratio for the two cases of unfired and fired heat addition.

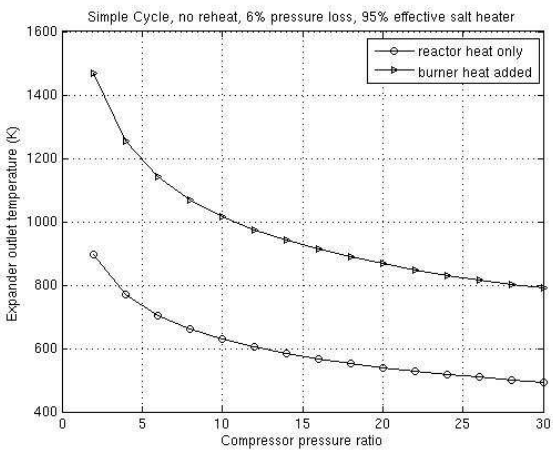

Fig. 3. Turbine outlet temperature.

Note that the turbine exit temperature for the reactor heat only operating at the pressure ratio for maximal thermal efficiency is 600 K. This temperature is rather cold for steam generation, and would limit the pressure of the water in the steam generator to 12.3 MPa. The turbine exit temperature for the fired case with maximal work would be ~900 K, which would increase the allowable pressure in the steam generator for additional Rankine cycle power. The effect of this exit temperature on the power generated by the steam Rankine portion will be presented in a following section.

Another result of interest for the combined cycle is the fractional amount of the total heat transferred to the compressed air by the burner during burner operation. This is presented in Fig. 4. Note that for the maximal efficiency pressure ratio of 12, 61% of the total heat is provided by the burner, and 64% for the maximal work pressure ratio of 16. This increasing fraction is due simply to the compressor exit temperature increasing as the pressure ratio increases as the unfired temperature remains limited by the salt-to-air heat exchanger.

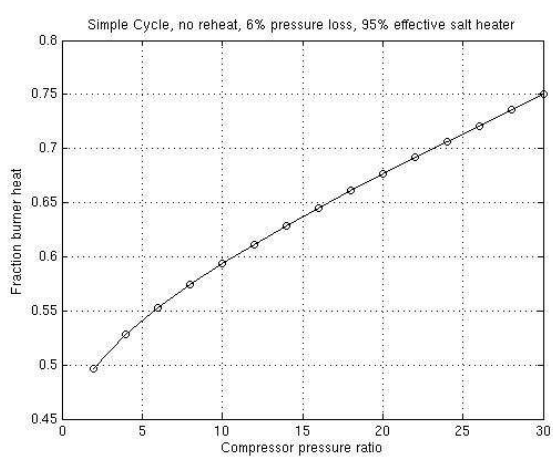

Fig. 4. Fractional burner heat.

IV.B. Steam Turbine Cycle Modeling

The steam turbine cycle portion of the proposed combined cycle has two interrelated subsystems of the heat recovery steam generator (HRSG) and the steam turbine (ST). To model the HRSG, the simplest configuration was that of a simple heat balance of the gas side and the water side. The GT outlet conditions of mass flow and temperature specify the HRSG gas side mass flow and inlet temperature. To complete the gas side of the HRSG, a stack temperature was specified as 120°C in order to exhaust the water content as a vapor and avoid "wet stacking." Air ambient temperature is also specified as a parameter as the GT inlet conditions. The corresponding inlet and outlet temperatures of the water side were specified as approach temperature differences of the gas side temperatures.

The HRSG outlet temperature and flow are set equal to the steam turbine inlet temperature and flow. The shaft power extracted by the steam turbine is simply the product of the steam mass flow, the isentropic enthalpy change from the inlet conditions to the condenser conditions, and the adiabatic efficiency of the turbine.

For simplicity, only one pressure level was modeled in the heat recovery steam generator where only the approach temperatures were specified. The value of the pinch point minimum temperature difference was monitored to ensure physically realistic values. The steam turbine model was also as simple as possible, where only the exit steam quality need be specified. In addition, no regenerative feedwater heaters (i.e., no steam extraction during expansion) were modeled. Because of this simplistic approximation of no feedheating, the efficiencies calculated will be lower than those resulting from the more common and realistic feedwater heater regeneration train configuration. This very simple model should be improved in the future, as this study is just a first step in a feasibility analysis of the concept.

One very important parameter of steam generator design is the "pinch-point," or closest approach between the hot gas temperature process line and the water-steam temperature process line. During these parameter studies, various seemingly physically realistic HRSG approach temperatures and turbine exit quality resulted in pinch-points approaching zero, which would result in a very large HRSG. Indeed, some parameters resulted in physically non-realistic negative pinch-point temperature differences. This close approach pinch-point is definitely a problem in combined cycle HRSG design because usually a high evaporating pressure is desired to increase the power of the turbine. This high evaporating pressure with its concomitant high evaporating temperature, however, results in a small pinch-point which requires a large heat transfer area with resulting high costs of manufacture. This pinch-point was monitored during parameter variations, as was the HRSG effectiveness. If

either were physically unrealistic, a cycle free parameter was changed until these were reasonable.

Another parameter of importance is the HRSG effectiveness, defined as the actual heat transfer divided by the theoretically maximum heat transfer. An effectiveness of unity represents a heat exchanger of infinite extent, so this effectiveness must be less than one for physically realistic heat exchangers. One simplistic modeling assumption was that the HRSG approach temperatures used in computing the HRSG effectiveness were specified for both the AHTR and fossil operating peaking power condition and the AHTR only base load power condition. An improved modeling assumption would be to specify the physical (and heat transfer) size of the HRSG and then analyze the heat transfer process in order to compute the actual approach and pinch-point temperatures for all power levels. But for the purposes of this study, the simplistic assumption of specified approach temperatures was used for expedience.

The thermophysical properties of water were computed by the algorithms of the IFC1997 formulation, and the air and combustion gas properties were computed by those of Collona and Silva [6].

IV.C. Base Load and Peaking Power Results

Initial studies indicate that the turbine conditions will be similar to the existing General Electric model MS7001FA gas turbine in terms of gas pressure ratios and peak temperatures[5]. The operating points for base-load electricity production are near the peak efficiency operating conditions for the gas turbine at the lower inlet temperatures, whereas the operating points for peak power production are near the maximum power output condition for the gas turbine at the higher inlet temperatures. A combined-cycle system was simplistically modeled with a single gas turbine having the same pressure ratio and gas flow rates as the GE turbine and a steam cycle representative of the commercial GE combined-cycle machine.

The calculations showed a base-load power output (both gas and steam turbine) of 68.0 MW(e) and a peak-load power output of 276.1 MW(e). For base-load operations, the reactor provides 175 MW(t) at 800°C. For peak power production, the fossil fuel provides an additional 323 MW(t) at a peak gas-turbine inlet temperature of 1300°C.

Table 1. Parameter listing.

Parameter	Peaking (AHTR + fossil	Base (AHTR only)
GT compressor polytropic efficiency (%)	85	85
GT turbine polytropic efficiency (%)	90	85
Steam turbine adiabatic efficiency (%)	90	90
Steam turbine exit quality (%)	100	90
Ambient temperature (°C)	10	10
Condenser approach temperature diff. (°C)	10	10
HRSG hot side approach temperature diff. (°C)	30	30
Gas turbine inlet temperature (°C)	1300	780
GT air mass flow rate (kg/s)	445	445
Compressor pressure ratio	16	16
GT pressure loss (%)	8	8

Table 2. Calculated results and comparison.

Parameter	Peaking	Base
HRSG effectiveness (%)	85	62
HRSG pinch point (°C)	25	16
HRSG evaporating pressure (MPa)	1.5	0.27
Gas turbine outlet temperature (°C)	626	283
Gas turbine power (MW)	188.5	50.2
Steam turbine power (MW)	83.6	17.8
Total power (MW)	272.1	68.0
GT thermal efficiency (%)	37.9	28.8
ST thermal efficiency (%)	29.0	14.3
Total thermal efficiency (%)	54.7	39

From inspection of Table 2, the free parameters chosen in Table 1 yield good agreement between published and computed performance, as well as very reasonable values of parameters not given in Ref. 5. When inspecting Table 1, bear in mind that the computational model used here is very simple (e.g., no feedwater heaters, …). Based on this comparison, this simple model should yield sufficiently accurate values for the scoping studies here.

During these computations, the pinch-point temperature difference was very sensitive to the specified turbine exit quality. When a more realistic value of 90% or 95% was tried, close or negative pinch-point temperature differences were calculated, the results of which were of course discarded. The increased evaporator pressure resulting from this wet turbine exhaust, which is desirable, unfortunately set up the undesirable low or negative pinch point. This pinch-point problem is, and has

always been, a concern in HRSG and steam turbine design.

Another parameter of importance that arose during the model evaluations was the exhaust moisture content. Because the compared gas turbine[5] used methane, the exhaust would have moisture from combustion. For the lean conditions postulated here, this moisture content was approximately 10% of the exhaust gases. This moisture content added additional power from the gas turbine because it increased the specific heat by 20%. This increased gas flow capacity rate also advantageously increased the pinch-point temperature difference in the HRSG. During postulated operation with heat only from the AHTR, the gas turbine power will decrease and the pinch point will decrease when this combustion moisture is not present.

V. CONCLUSIONS

Combined nuclear-fossil systems have the potential to offer the best of both worlds: low-cost base-load electricity and lower-cost peak power relative to the existing combination of base-load nuclear plants and separate fossil-fired peak-electricity production units. In addition, electric grid stability, reduced greenhouse gases, and operational flexibility can also result with using the conventional technology presented here for the thermal power conversion system coupled with the AHTR. The results presented here are very encouraging, because realistic results were obtained with the very simplistic modeling assumptions used. Improved and more detailed modeling should result with even more encouraging results. Significant work is required to fully understand and develop this new electricity generation option.

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