CANDU COMBINED CYCLES FEATURING GAS-TURBINE ENGINES

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ABSTRACT

In the present study, a power-plant analysis is conducted to evaluate the thermodynamic merit of various CANDU combined cycles in which continuously operating gas-turbine engines are employed as a source of class IV power restoration. It is proposed to utilize gas turbines in future CANDU power plants, for sites (such as Indonesia) where natural gas or other combustible fuels are abundant. The primary objective is to eliminate the standby diesel-generators (which serve as a backup supply of class III power) since they are nonproductive and expensive.

In the proposed concept, the gas turbines would: (1) normally operate on a continuous basis and (2) serve as a reliable backup supply of class IV power (the Gentilly-2 nuclear power plant uses standby gas turbines for this purpose). The backup class IV power enables the plant to operate in poison-prevent mode until normal class IV power is restored. This feature is particularly beneficial to countries with relatively small and less stable grids.

Thermodynamically, the advantage of the proposed concept is twofold. Firstly, the operation of the gas-turbine engines would directly increase the net (electrical) power output and the overall thermal efficiency of a CANDU power plant. Secondly, the hot exhaust gases from the gas turbines could be employed to heat water in the CANDU Balance Of Plant (BOP) and therefore improve the thermodynamic performance of the BOP. This may be accomplished via several different combined-cycle configurations, with no impact on the current CANDU Nuclear Steam Supply System (NSSS) full-power operating conditions when each gas turbine is at maximum power. For instance, the hot exhaust gases may be employed for feedwater preheating and steam reheating and/or superheating; heat exchange could be accomplished in a heat recovery steam generator, as in conventional gas-turbine combined-cycle plants.

The commercially available GateCycle power plant analysis program was applied to conduct a thermodynamic evaluation of various CANDU gas-turbine combined cycles. For the evaluation, a minimal number and size of gas-turbine engines were considered, specifically, 4×50 MWe (based on CANDU 6). With this set of gas turbines, it is calculated that a relatively high level of reliability of class IV power restoration can be attained. The results from the GateCycle analysis indicate that certain CANDU combined cycles can generate over 940 MWe (net) with an overall thermal efficiency of up to 37% (which is about 4 percentage points higher than that of the current CANDU 6). Hence, the proposed concept may significantly enhance the competitiveness of future CANDU plants. This is especially important in light of: (a) advancements in combined-cycle technology and (b) recent studies on the thermal coupling of gas turbines with future light water reactors.

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1. INTRODUCTION

In a conventional CANDU® plant, the power supplies for station services are classified according to required levels of reliability. Class IV power (available from the grid or the turbine-generator) is the main power supply to the station; long-term interruption of Class IV power can be tolerated. Class III power is defined as the power supply for essential station loads (that is, auxiliaries which are necessary for the safe shutdown of the reactor) with a maximum interruption time of a few minutes. Class III power is normally provided from the Class IV system; standby diesel-generators serve as a backup supply of Class III power. The primary function of the diesel-generators is to restore Class III power with a relatively high level of reliability in the event of a loss of Class IV power. However, the diesel-generators incur a considerable capital cost, require maintenance, and are nonproductive since they do not provide power during normal plant operation.

As an alternative concept for future CANDU plants, it is proposed to utilize continuously operating gas-turbine engines as a reliable backup supply of Class IV power. In so doing, one could eliminate the aforementioned standby diesel-generators and maintain the nuclear plant in a poison-prevent mode following a loss of Class IV power. Furthermore, the addition of gas-turbine engines would improve the thermodynamic performance of a CANDU plant. Firstly, the net (electrical) power output would increase by virtue of the continuous operation of the gas-turbine engines. Secondly, the transfer of gas-turbine exhaust heat to the steam cycle in the CANDU Balance Of Plant (BOP) would lead to a further increase in the net power output as well as the overall thermal efficiency. From an economic perspective, the proposed concept may be most suitable for countries, such as Indonesia and certain parts of China, where nuclear power is desired and there is an abundance of combustible fuels (for example, natural gas).

By definition, the thermal coupling of gas-turbine engines with the CANDU BOP constitutes a type of combined cycle. Theoretically, numerous combined-cycle configurations are possible. For instance, the gas-turbine exhaust gases could be used to preheat feedwater or to reheat steam from the high-pressure steam turbine.

The primary objective of the present study is to evaluate the potential thermodynamic merit of CANDU gas-turbine combined cycles. In this evaluation, the number and size of the gas-turbine engines are limited to the minimum required for a relatively high level of reliability of Class IV power restoration. The present study represents a joint effort between Atomic Energy of Canada Limited and BPPT (the Agency for the Assessment and Application of Technology), Indonesia.

The concept of using gas-turbine engines as a reliable supply of backup Class IV power in CANDU plants has already been implemented. At present, the Gentilly-2 nuclear power plant is electrically coupled to the Bécancour gas-turbine power station, which is located within the exclusion zone of the nuclear plant. The Bécancour station houses four General Electric MS-7001 series gas-turbine engines (86 MWe each). Normally, these engines

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are not operating on a continuous basis. Instead, the gas-turbine engines are predominantly utilized for (1) peaking service (less than 200 hours per year) and (2) restoration of Class IV power to the Gentilly-2 nuclear plant. The calculated reliability of Class IV power restoration is greater than 97%.

Gas-turbine combined-cycle plants are widely used throughout the world. A typical plant is schematically shown in Figure 1. Basically, the exhaust gases from one or more gas turbines are used to produce superheated steam in a heat recovery steam generator (HRSG), and the steam is subsequently employed to generate power in a steam turbine. As shown in Table 1, the overall thermal efficiency of an advanced gas-turbine combined-cycle plant is in the range of about 55% to 60%. Table 1 indicates that such efficiency levels are attainable when the ratio of gas-turbine power to steam-turbine power is roughly on the order of 2 to 1. With multiple-unit designs, gas-turbine combined-cycle plants can generate over 2500 MWe.

There have also been considerations on the use of gas-turbine combined cycles with pressurized water reactors (PWRs). For example, the Battelle Institute has developed a patented concept for increasing the thermal efficiency of a PWR. The concept is referred to as the Tsikl-Durst cycle or the TD cycle [2]. The basic idea in the TD cycle is to superheat the saturated steam from the reactor by mixing the saturated steam with superheated steam produced using gas-turbine exhaust gases in a HRSG (with the option of supplementary fuel firing upstream of the HRSG). Both Toshiba and Mitsubishi have expressed an interest in the TD cycle [2].

2. ENGINEERING PHILOSOPHY FOR CANDU COMBINED CYCLE

In principle, as the amount of gas-turbine power is increased in the proposed CANDU combined cycle, the overall thermal efficiency approaches that of a conventional gas-turbine combined cycle. Recall that, in order to achieve an overall thermal efficiency of about 55% to 60% in a gas-turbine combined cycle, the gas-turbine power must be roughly equal to twice the steam-turbine power. It is not sensible to adopt this target ratio for the proposed CANDU combined cycle since the majority of the thermal power in the combined cycle would be provided by combustible fuel, as opposed to nuclear fuel. As the NSSS (Nuclear Steam Supply System) supplier of CANDU reactors, AECL's main interest is to design and construct nuclear power plants for countries that choose the nuclear option.

The premise of the proposed concept is that the primary function of the gas-turbine engines is to provide Class IV power restoration. The predominant source of thermal power in the CANDU combined cycle should be nuclear (say, at least 80%). This criterion may be satisfied if:

(a) Only the minimum number of gas-turbine engines required for sufficient reliability of Class IV power restoration are employed.

(b) The power output of each gas-turbine engine is limited to the Class IV power load.

With respect to (a), the results from a detailed reliability assessment show that a minimum of <u>four</u> gas-turbine engines are needed for the proposed concept. This is the number required to provide both Class III and Class IV reliability levels that are similar to the reliability level which the diesel-generators currently provide for backup Class III power in a CANDU 6 plant on loss of grid. The reliability assessment accounts for planned outages due to routine maintenance as well as unplanned forced outages.

Regarding (b), each gas-turbine engine in the CANDU combined-cycle plant should have the capacity to deliver the total Class IV power load. This is in keeping with the aforementioned primary function of the gas-turbine engines. Additional engine power is not necessary. Thus, the maximum power output from each gas-turbine engine is specified to be the total Class IV power load, which is approximately 50 MWe.

3. THERMODYNAMIC ANALYSIS OF CANDU COMBINED CYCLES

3.1 Methodology

As mentioned earlier, the focus of the present study is on the thermodynamic evaluation of CANDU gas-turbine combined cycles. Several configurations were considered. The specific objective was to determine the potential merit of the CANDU combined cycles in terms of net power output and overall thermal efficiency. These performance values were compared with the those corresponding to the conventional CANDU 6 power plant.

Thermodynamic evaluations were conducted by means of the GateCycle power-plant analysis software (version 4.34). GateCycle is a commercially available PC-based program for the steady-state analysis of thermal power plants. It is sponsored by the Electric Power Research Institute (EPRI) and features a model library of actual gas-turbine engines. GateCycle can analyze a power plant at both design and off-design operating conditions. For instance, if the thermalhydraulic conditions (such as mass flow rate and steam quality) within a steam turbine are different than in the reference design case, GateCycle can predict the off-design performance of the steam turbine through the Spencer-Cotton-Cannon method [3].

Prior to the evaluation of the various CANDU combined cycles, it was necessary to develop a GateCycle model of the conventional CANDU 6 BOP. In this prerequisite step, the simplified Wolsong 3&4 BOP flowsheet was adopted as the reference BOP design. The reference GateCycle model of the CANDU 6 BOP is shown in Figure 2.

Figure 2 includes customary symbols for the following major equipment: heat exchangers (for the reheaters, condenser, and feedwater preheaters), steam turbines, deaerator, moisture separator, and pumps. The steam-generator symbol in Figure 2 represents a boundary-condition component for the specification of the total heat input and exit steam-generator conditions. It should be noted that a steam generator is not physically modelled. It should also be noted that the rectangular arrows in Figure 2 represent sources and sinks used to transport leakage flows within the BOP. Overall, the computed results from the GateCycle analysis of the reference model agree very well with the flowsheet data. The reference GateCycle model represents the foundation of the various CANDU combined-cycle models.

3.2 Assumptions

As mentioned previously, four 50 MWe gas-turbine engines were deemed allowable for utilization in the proposed CANDU combined-cycle concept. From the GateCycle model library of gas-turbine engines, the Westinghouse Trent gas turbine was selected for the present study. This particular gas-turbine engine has a rated net power output of 48.6 MWe, which closely matches the above power limit; in the CANDU combined cycles, the net power output of each engine is actually 49.7 MWe. The temperature and flow rate of the exhaust gases are 425.7°C and 567,570 kg/hr (per engine) respectively.

In addition to the selection of the Westinghouse gas-turbine engines, the main assumptions in the present study are as follows, for full-power operating conditions.

(a) The rate of heat transfer through the steam generator is fixed at 2064 MW, as in the conventional CANDU 6 plant.

(b) The mass flow rate (3.7189×10^6 kg/hr), quality (0.997), and pressure (45.088 bar) of the steam at the outlet of the steam generator are the same as in the conventional CANDU 6 BOP.

(c) The feedwater temperature (186.7°C) at the inlet of the steam generator is the same as in the conventional CANDU 6 BOP.

(d) The fractional (11.3%) moisture separation is the same as in the reference CANDU 6 moisture separator.

(e) The steam temperature (243.6°C) at the end of the reheating process is the same as in the reference CANDU 6 reheater.

(f) The temperature of the gas-turbine exhaust gases is limited to 93°C (about 200°F).

(g) There is no injection of water into the gas-turbine combustion chambers.

When the combined-cycle plant is at *full power*, it is to be understood that all four gas turbines operate at maximum power output and the reactor produces 2064 MWth. From assumptions (a) to (c) inclusive, it follows that the NSSS operating conditions (such as the primary-coolant flow and reactor-header temperatures) in the CANDU combined-cycle plant are the same as in the conventional CANDU 6 plant, at full power. This minimizes the impact of the combined cycle on the design of the NSSS.

Assumptions (d) and (e) are somewhat arbitrary, but nonetheless reasonable. Assumption (f) addresses the practical requirement to reduce corrosion in the gas-turbine exhaust systems. When the exhaust gases are cooled below a certain temperature, the combustion products can become highly corrosive and can damage heat exchangers as well as pipe material.

Regarding assumption (g), water injection is a common practice to increase the power output of industrial gas turbines. It should be noted that this may significantly improve the overall thermodynamic performance of a CANDU gas-turbine combined cycle.

3.3 Combined-Cycle Configurations

With the four Westinghouse gas-turbine engines, numerous CANDU combined-cycle configurations are conceivable. The GateCycle models of the various CANDU combined cycles that were investigated in the present study are displayed in Figures 3 to 7. The corresponding results from the GateCycle analyses are discussed in the next section.

Figure 3 shows the trivial case in which the reference CANDU 6 plant is electrically coupled to the stand-alone gas-turbine engines; there is no thermal coupling. This case is similar to the existing coupling between the Gentilly-2 plant and the Bécancour gas-turbine station. With respect to overall thermodynamic performance, the configuration in Figure 3 represents the lower bounding case for the CANDU combined cycles.

In Figure 4, the gas-turbine exhaust gases are employed to carry out the entire low-pressure feedwater preheating process. In the reference CANDU 6 BOP (Figure 2), this process is accomplished using steam extractions from the low-pressure steam turbine. For the combined cycle in Figure 4, these steam extractions are eliminated; hence, the low-pressure steam turbine yields more power as a result of the steam conservation.

In Figure 5, the gas-turbine exhaust gases are employed to carry out high-pressure feedwater preheating and then low-pressure feedwater preheating. In the reference CANDU 6 BOP (Figure 2), the former process is mostly accomplished using one steam extraction and a fraction of the exhaust flow from the high-pressure steam turbine. For the combined cycle in Figure 5, the steam extraction is eliminated and the fraction of diverted exhaust steam from the high-pressure turbine is significantly reduced. Furthermore, the amount of steam extracted from the low-pressure turbine is also significantly reduced. Hence, as a result of steam conservation, both the high-pressure and low-pressure steam turbines generate more power than in the reference CANDU 6 BOP.

In Figure 6, the gas-turbine exhaust gases are employed to carry out the entire reheating process and then part of the high-pressure and low-pressure feedwater preheating processes. In the reference CANDU 6 BOP (Figure 2), the reheating process is accomplished using one steam extraction from the high-pressure turbine and a fraction of the saturated steam from the steam generator. For the combined cycle in Figure 6, both the steam extraction and the diversion of saturated steam are eliminated. Furthermore, less steam is needed for high-pressure and low-pressure feedwater preheating. Hence, as a result of steam conservation, both the high-pressure and low-pressure steam turbines produce more power than in the reference CANDU 6 BOP.

In Figure 7, the gas-turbine exhaust gases are employed to superheat the steam from the steam generator, reheat steam from the high-pressure turbine, and then carry out high-pressure and low-pressure feedwater preheating. The steam at the inlet of the high-pressure turbine is superheated by 30°C. This is beneficial from the standpoint of thermal efficiency. Moreover, the inherent efficiency of the high-pressure steam turbine is increased as a consequence of the higher-quality steam distribution within the turbine, relative to the reference design case. Furthermore, in comparison with the reference CANDU 6 BOP (Figure 2), the combined cycle in Figure 7 requires less steam for reheating and feedwater preheating. Hence, the high-pressure and low-pressure steam turbines generate more power in this combined cycle than in the reference CANDU 6 BOP.

It is important to note that, in practice, the transfer of heat from the gas-turbine exhaust gases to the water in the CANDU steam cycle would be performed in a HRSG, as in a conventional gas-turbine combined-cycle plant (see Figure 1). The gas-to-water heat exchangers represented in Figures 4 to 7 would constitute different sections of the heat recovery steam generator.

3.4 GateCycle Analysis Results

Table 2 summarizes the key findings from the GateCycle analyses of the CANDU gas-turbine combined cycles described in the preceding section. The net power output for Case 2 (Figure 3), which is the lower-bounding CANDU combined-cycle case, is greater than that of the reference CANDU 6 plant (Case 1 and Figure 2). Obviously, this is a direct consequence of the addition of the continuously operating gas-turbine engines, which contribute about 200 MWe. The significantly higher overall thermal efficiency of Case 2 is due to the fact that the inherent thermal efficiency of the Westinghouse Trent gas-turbine engine is greater than the overall thermal efficiency of the conventional CANDU 6 BOP. The former is about 40%, while the latter is approximately 33%.

The GateCycle results for Cases 3, 4, and 5 indicate that both the net power output and overall thermal efficiency of the CANDU combined cycle increase as more steam is conserved earlier (at the high-pressure end) rather than later (at the low-pressure end) of the steam cycle. Of these three combined-cycle configurations, Case 5 yields the highest net power output and overall thermal efficiency, primarily because most of the steam conservation takes place at relatively high pressures in the steam cycle.

The overall thermodynamic performance of Case 6 is only slightly better than that of Case 5, despite the substantial degree of superheating in the former case. This is attributed to a fundamental difference between these two cases, as explained below. In Case 5, all of the heat transferred by the gas-turbine exhaust gases is dedicated to the reduction in the amount of steam extracted from the steam turbines. Saving a steam extraction directly increases the power output from the associated steam turbine since that steam is then allowed to expand in the turbine. In Case 6, roughly half of the gas-turbine exhaust heat is used to reduce steam extractions; the other half is employed to superheat the high-pressure steam. However, in accordance with the laws of thermodynamics, a considerable percentage of the heat transferred for steam superheating is not converted to mechanical power in the high-pressure turbine. This undermines the benefits of superheating in the CANDU combined cycle (refer to Section 3.3).

Table 2 also includes the results from a hand-calculation for a hypothetical case (namely, Case 7) in which the reference CANDU 6 plant is electrically coupled to a stand-alone gas-turbine combined-cycle plant. This particular case was considered as an alternative option for Class IV power restoration. For the conventional combined-cycle plant in Case 7, the amount of gas-turbine power is scaled to 199 MWe; this value is identical to the gas-turbine power in Cases 2 to 6. Hence, in terms of overall thermodynamic performance, Case 7 can be fairly compared with Cases 2 to 6. From Table 2, such a comparison suggests that Case 7 represents the upper-bounding CANDU combined-cycle case with about 200 MWe gas-turbine power.

4. CONCLUSIONS

The main conclusion from the present study is that, with a minimal number and size of gas-turbine engines (4×50 MWe) for reliable Class IV power restoration, the overall thermodynamic performance of a CANDU 6 plant can potentially be significantly improved via combined-cycle configurations. Based on the GateCycle power-plant analysis software, certain

CANDU gas-turbine combined cycles can generate well over 900 MWe (net) with an overall thermal efficiency of up to 37%.

Further study is in progress to address the practical feasibility of the proposed concept. For example, future work includes an economic assessment as well as an investigation of the possible hazardous effects on the nuclear safety of the CANDU plant due to the proximity of the gas-turbine engines.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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Table 1
Performance Specifications of Conventional Gas-Turbine Combined-Cycle Plants
(base load rating, gas fuel, and lower heating value of fuel) [1]

Manufacturer	CC-model designation	Output (MW)	Therm. Efficy. (%)	GT Number & Model	GT (MW)	ST (MW)	Freq. (Hz)
ABB Power	KA26-1	387.0	58.5	1x GT26	232.6	133.4	50
Generation	KA24-1	267.3	57.3	1x GT24	159.5	88.8	60
GE	S107FA	259.7	55.9	1xMS7001FA	164.3	92.9	60
Power	S109FA	376.2	56.3	1xMS9001FA	221.2	131.6	50
Systems	S 109G	420.0	58.0	1xMS9001G	282.0	138.0	50
	S 109H	480.0	60.0	1xMS9001H	mono-block		50
Siemens AG	GUD2.64.3A	205.0	54.4	2x V64.3A	135	73.0	50/60
Power	GUD2.84.3A	499.0	56.9	2x V84.3A	330	176.0	60
Generation	GUD2.94.3A	705.0	57.2	2x V94.3A	466	249.0	50
Westinghouse	1x1501F	256.4	56.2	1x 501F	163	96.7	60
Electric	1x1501G	349.1	58.3	1x 501G	229	124.0	60
Corporation	1x1701F	356.1	55.1	1x 701F	239	121.4	50

Table 2
Summary of Results From GateCycle Analyses of CANDU Gas-Turbine Combined Cycles

Case	Description	Net Power Output[†] From CANDU Steam Cycle (MWe)	Thermal Efficiency[‡] of CANDU Steam Cycle	Net Power Output From Gas-Turbine Plant[§] (MWe)	Thermal Efficiency of Gas-Turbine Plant	Net Power Output From CANDU Steam Cycle Plus Gas-Turbine Plant (MWe)	Overall Thermal Efficiency
1	Reference C6 BOP	685	33.2%	—	—	685	33.2%
2	Reference C6 BOP and stand-alone GTs	685	33.2%	199	40.5%	884	34.6%
3	C6 BOP with LP feedwater preheating via GT exhaust gases	705	31.0%	199	40.5%	904	35.4%
4	C6 BOP with HP and LP feedwater preheating via GT exhaust gases	724	31.8%	199	40.5%	923	36.1%
5	C6 BOP with MP reheating and HP and LP feedwater preheating via GT exhaust gases	742	32.6%	199	40.5%	941	36.8%
6	C6 BOP with HP superheating, MP reheating, and HP and LP feedwater preheating via GT exhaust gases	748	32.9%	199	40.5%	947	37.0%
7	Reference C6 BOP and stand-alone GTCC plant[**] (with GT power = 199 MWe)	685	33.2%	303	58.3%	988	38.2%

List of Acronyms:

BOP	Balance Of Plant	HP	High Pressure
C6	CANDU 6	LP	Low Pressure
GT	Gas Turbine	MP	Medium Pressure
GTCC	Gas Turbine Combined Cycle	NSSS	Nuclear Steam Supply System

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† Includes CANDU BOP losses, but not NSSS power requirements

‡ Based on UEEP (Used-Energy End Point) for low-pressure steam turbine and includes heat input from gas-turbine exhaust gases (211 MW)

§ Total of 4 Westinghouse Trent gas turbines

** Based on Westinghouse 1501G gas-turbine combined-cycle plant

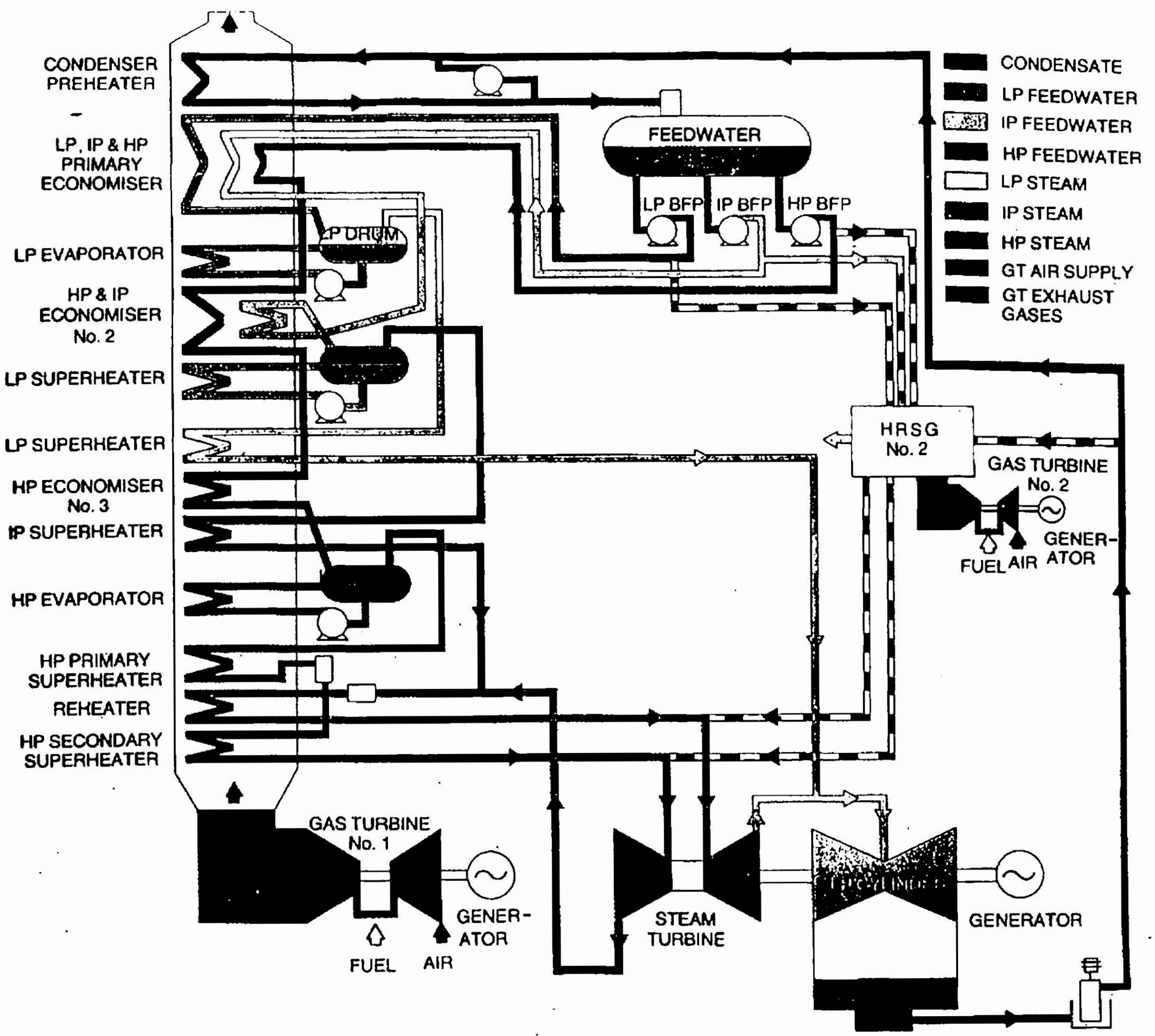

Figure 1 Schematic Diagram of a 690 MW Combined-Cycle Power Station

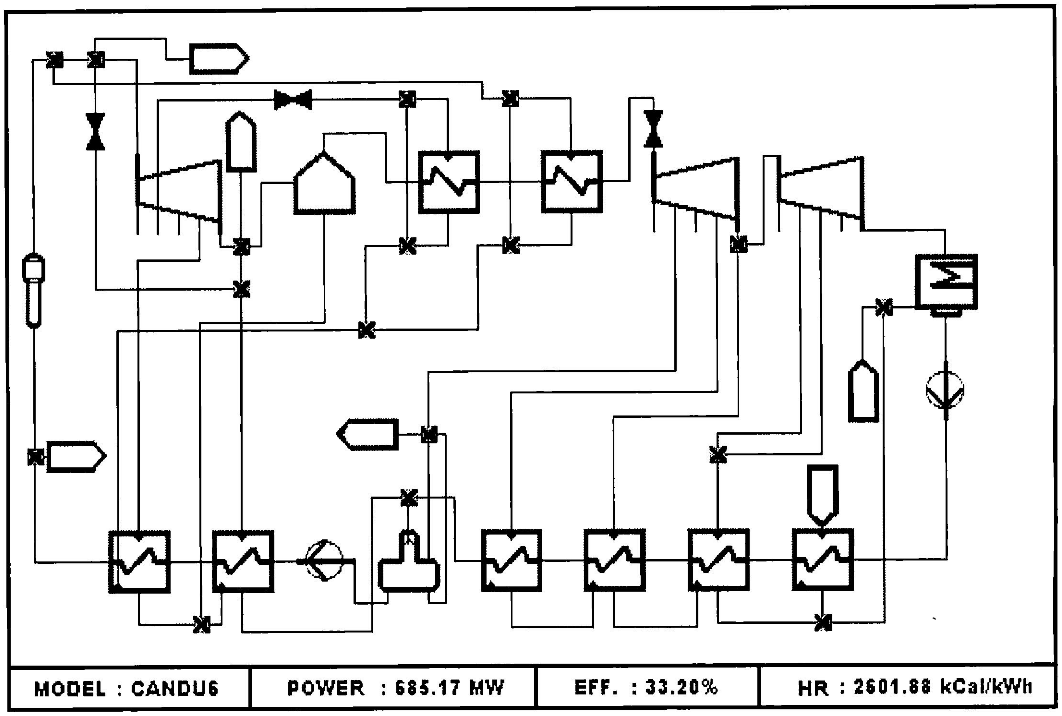

Figure 2 GateCycle Model of Conventional CANDU 6 BOP (Case 1)

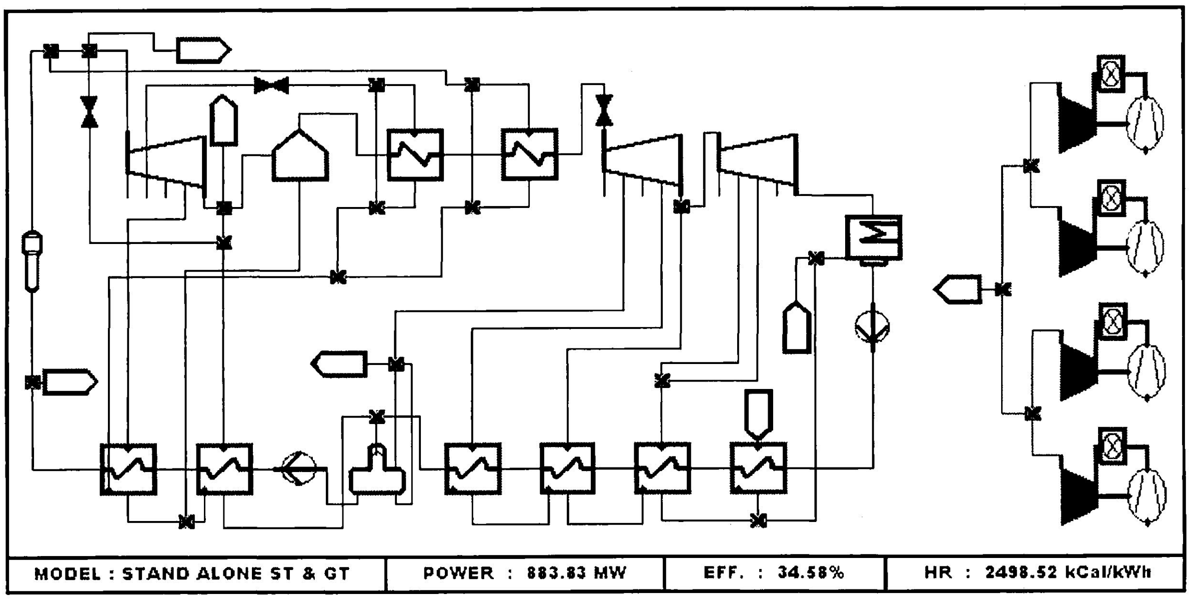

Figure 3 GateCycle Model of Conventional CANDU 6 BOP and Stand-Alone Gas-Turbine Engines (Case 2)

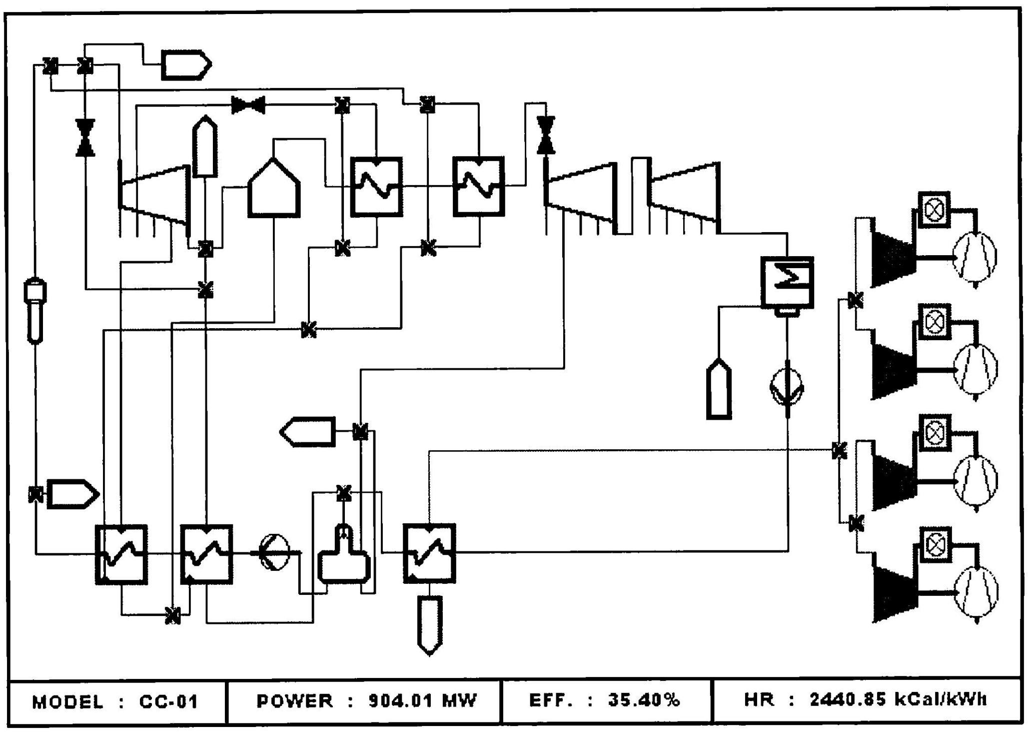

Figure 4 GateCycle Model of CANDU Gas-Turbine Combined Cycle (Case 3)

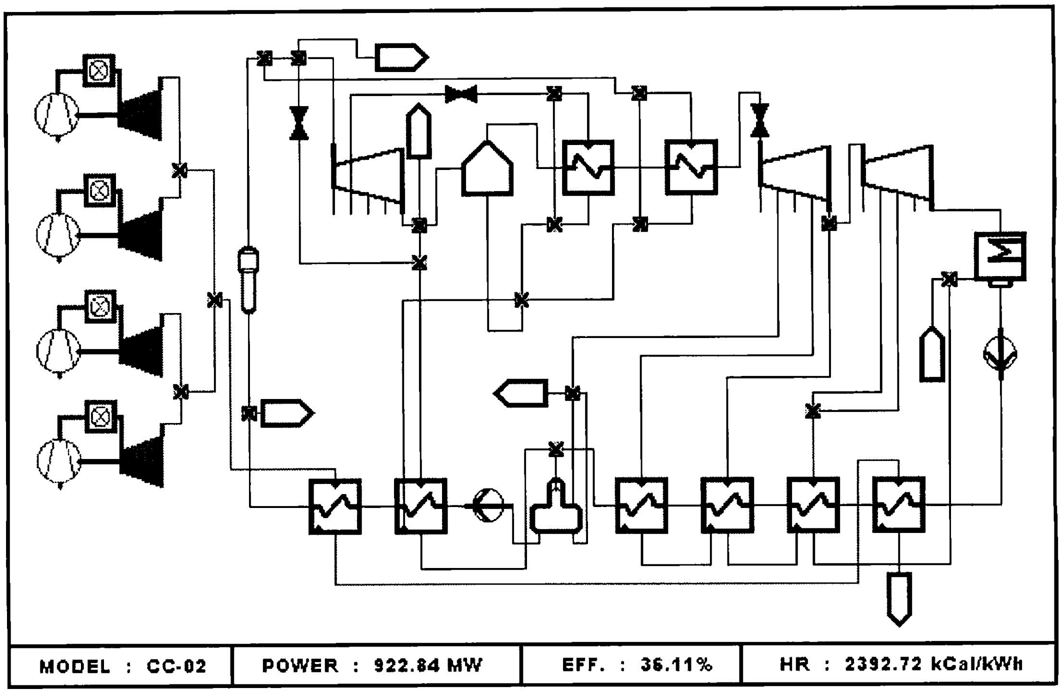

Figure 5 GateCycle Model of CANDU Gas-Turbine Combined Cycle (Case 4)

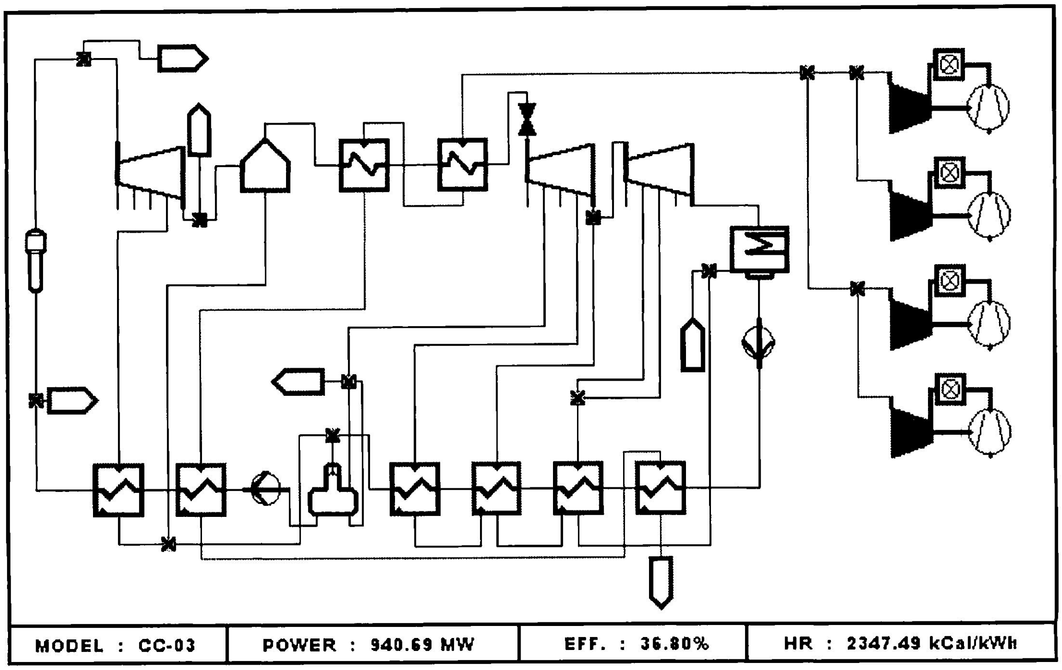

Figure 6 GateCycle Model of CANDU Gas-Turbine Combined Cycle (Case 5)

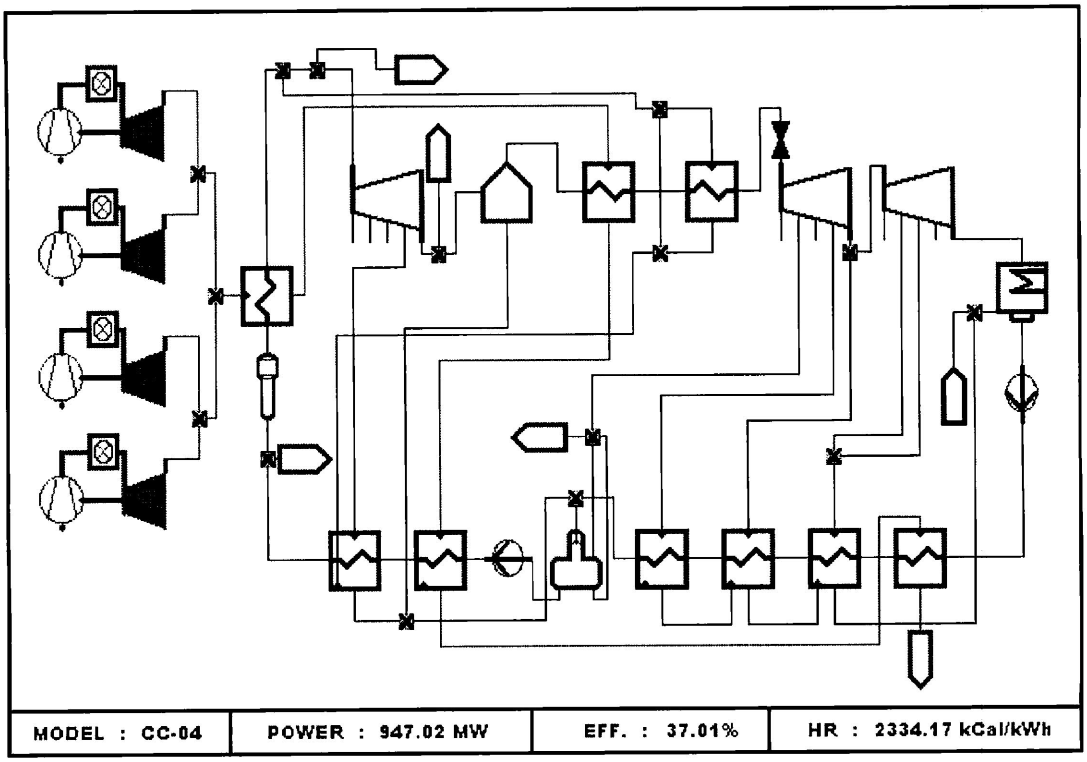

Figure 7 GateCycle Model of CANDU Gas-Turbine Combined Cycle (Case 6)