GE Power Systems

Combined-Cycle Development Evolution and Future

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Introduction

Combined-cycle systems utilizing the Brayton Cycle gas turbine and the Rankine Cycle steam system with air and water as working fluids achieve efficient, reliable, and economic power generation. Flexibility provided by these systems satisfies both utility-power generation and industrial-cogeneration applications.

Current commercially available power-generation combined-cycle plants achieve net plant thermal efficiency typically in the 50–55% LHV range. Further development of gas turbine, high-temperature materials and hot gas path, metal surface cooling technology show promise for near-term future power generation combined-cycle systems capable of reaching 60% or greater plant thermal efficiency. Additional gas turbine technological development, as well as increases in steam-cycle pressure and temperature and steam-turbine stage-design enhancement, is expected to achieve further STAG™ combined-cycle efficiency improvement.

Current General Electric STAG™ (trade name designation for the GE product line of combined-cycle systems) product line offerings, combined-cycle experience, and advanced system development are used to demonstrate the evolution of combined-cycle system technology.

Gas Turbine Combined-Cycle Features

The combination of the gas turbine Brayton Cycle and the steam power system Rankine Cycle complement each other to form efficient combined-cycles. The Brayton Cycle has high source temperature and rejects heat at a temperature that is conveniently used as the energy source for the Rankine Cycle. The most commonly used working fluids for combined cycles are air and steam. Other working fluids (organic fluids, potassium vapor, mercury vapor, and others) have been applied on a limited scale. Combined-cycle systems that utilize steam and air-working fluids have achieved widespread commercial application due to:

1. High thermal efficiency through application of two complementary thermodynamic cycles.
2. Heat rejection from the Brayton Cycle (gas turbine) at a temperature that can be utilized in a simple and efficient manner.
3. Working fluids (water and air) that are readily available, inexpensive, and non-toxic.

These combined-cycle systems provide flexibility with features that include:

1. High Thermal Efficiency - Combined-cycle thermal efficiency is higher than that of other conventional power generation systems.

2. Low Installed Cost - Combined-cycle equipment is pre-engineered and factory-packaged to minimize installation time and cost. All major equipment (gas turbine generator, heat recovery steam generator [HRSG], and steam turbine generator) is shipped to the field as assembled and tested components. Auxiliary equipment, such as condensers, can be shipped factory-tubed and hydro-tested. This greatly reduces the inventory of parts that must be managed in the field and minimizes installation cost. Combined-cycle equipment cost is higher than that for conventional steam plants due to pre-engineering; however, combined-cycle plant installation costs are significantly lower, resulting from the reduced installation cycle.

3. Fuel Flexibility - Combined-cycle plants operate efficiently by burning a wide range of fuels, ranging from clean natural gas and distillate oil fuels to ash-bearing crude oil and residual oil fuels. Operation with coal-derived gas fuels has been applied in many commercial-size, combined-cycle systems.

4. Flexible Duty Cycle - Combined-cycle systems provide flexibility in operation for both baseload and mid-range duty with daily startup. Gas turbines in multi-shaft, combined-cycle configuration can be started quickly, bringing about two-thirds of plant power on-line, typically in less than 60 minutes. Combined-cycle plants also provide efficient operation at part load, particularly for multiple gas turbine combined-cycle systems. This is illustrated by the variation in plant output with variation in plant heat rate curve shown for a General Electric STAG 200 system (*See Figure 1*). Modulating compressor inlet guide vanes are standard features of many gas turbine models, enabling high efficiency operation at part load through reduction in turbine airflow. This is accomplished at nearly constant turbine exhaust temperature, so that design steam conditions and low stack loss can be maintained to provide excellent part-load efficiency.

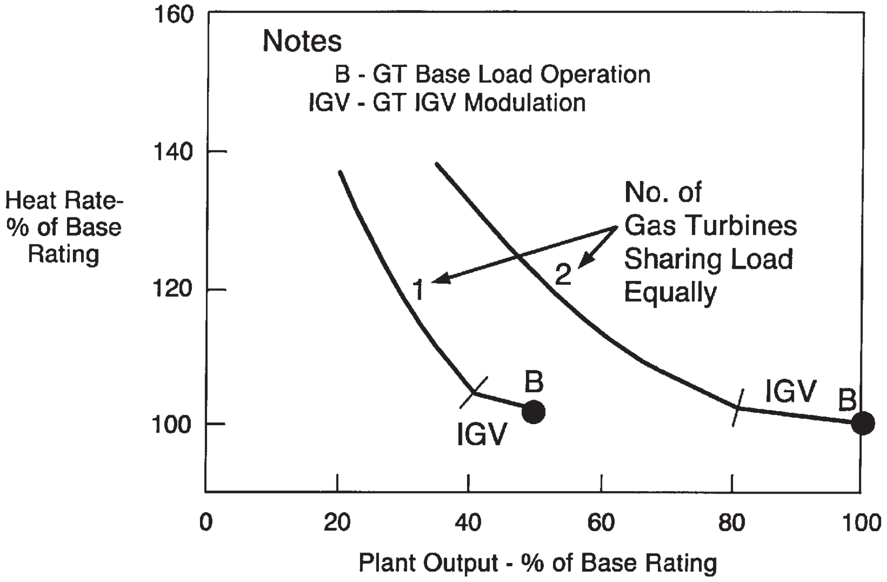

Figure 1. STAG 209E combined-cycle part load performance

5. Short-Installation Cycle - Combined-cycle plants can be installed and operated in less time than that required for conventional steam plants. Again, this is primarily due to the pre--engineering and packaging of major components in the factory. Phased installation of the plant, when gas turbines are installed and op-erated in the simple-cycle mode during the steam-cycle equipment installation, enables the user to generate power and revenue in as little as a year from order date (*See Figures 2–4*). A typical combined-cycle plant installation schedule is presented in *Figure 5*.

6. High Reliability/Availability - High reliability operation results from evolutionary design development that improves parts and components, and quality manufacturing programs that offer operational factory testing. High availability is achieved through development of sound operation and maintenance practices, which reside principally with the user. Manufacturer experi-ence and recommendations also contribute to this feature.

7. Low Operation and Maintenance Costs - Low operation and maintenance

Figure 2. Six MS7001B gas turbines

Figure 3. Two STAG 407B combined-cycle steam system installation

Figure 4. Two STAG 407B combined cycle

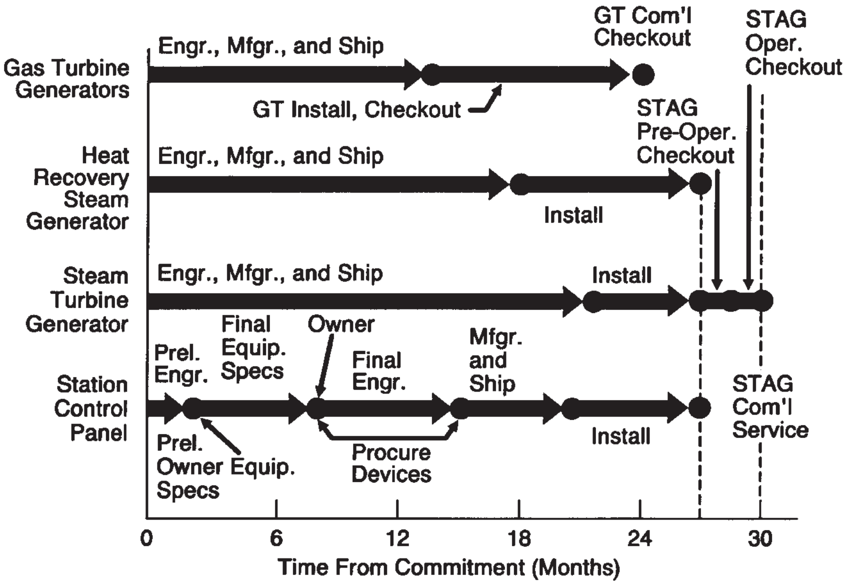

Figure 5. Typical project schedule

costs are achieved through quality design, prudent operation, and equipment design that allow convenient access for component inspection.

8. High Efficiency in Small Capacity Increments - Gas turbine generators are designed and manufactured in discrete frame sizes. For example, the General Electric heavy-duty, gas turbine-packaged power plant product line includes the MS6001B (50 Hz and 60 Hz), MS7001 FA (60 Hz), MS7001B (60 Hz) and the MS9001 FA (50 Hz) units, which cover an output range of approximately 37 MW to 250 MW. Application of these gas turbine models in combined-cycle systems as single or multiple gas turbine and HRSG installations can provide from about 50 MW to several thousand megawatts of power generation at essentially constant plant thermal efficiency.

Gas Turbine Combined-Cycle Development

The commercial development of combined-cycle systems has proceeded in parallel with gas turbine development. We are presently in the third generation technology of combined-cycle systems and are at the launch point of the fourth generation.

First Generation Combined-Cycle Plants

The first gas turbine installed in an electric utility in the United States was applied in a combined cycle. This was a 3.5 MW gas turbine that used the energy from the exhaust gas to heat feedwater for a 35 MW conventional steam unit. The gas turbine is shown in *Figure 6*. A schematic showing the combined-cycle system is shown in *Figure 7*. This system entered service in June 1949, and a similar system was added to this station in 1952. The heat recovery economizers applied in these systems used bare tubes, as was typical of heat exchangers in combined-cycle systems installed prior to 1959.

Most combined-cycle power generation systems installed during the 1950s and early 1960s included conventional-fired boilers. These systems were basically adaptations of conventional steam plants with the gas turbine exhaust gas serving as combustion air for the boiler. The efficiency of this type of combined cycle was approximately 5–6% higher than that of a similar conventional steam plant. These systems could economically utilize bare tubes in the boiler because of the high mean temperature difference between the combustion products and the water/steam.

The repowering of steam power plants with gas turbine generators and HRSGs is still attractive in many applications today as evidenced by the recent Colorado Public Service, Fort St. Vrain installation, which was placed in commercial operation in 1999.

The summary presented in *Table 1* characterizes the first generation combined-cyle systems.

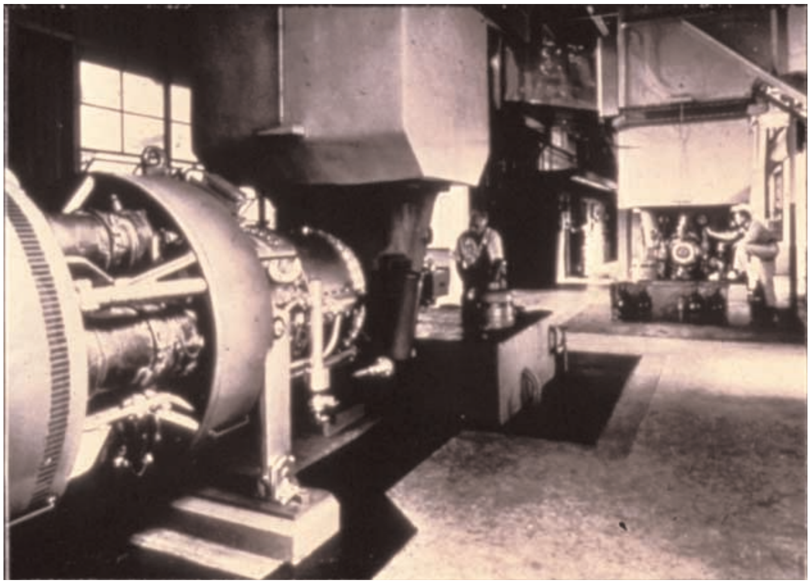

Figure 6. Gas turbine in first power generation combined cycle

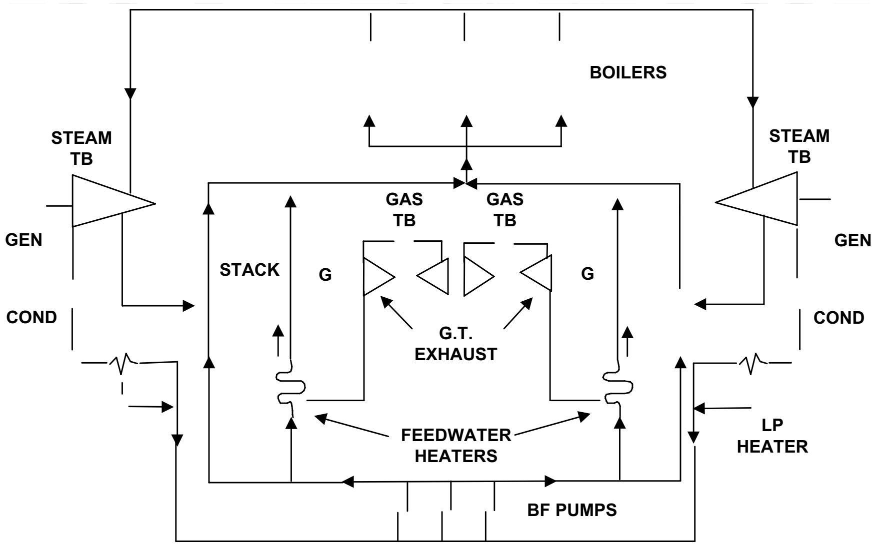

Figure 7. OG&E Belle Isle feedwater heating repowering system cycle diagram

Second Generation Combined-Cycle Plants

Equipment that made it economically feasible to weld continuous spiral fins to tubes was introduced to boiler manufacturers in 1958. Heat recovery combined cycles, using the sensible heat in the gas turbine exhaust gas, were made feasible by the enhanced gas-side heat transfer using finned tubes. Combined-cycle systems with finned tube boilers entered service in 1959.

During the 1960s the application of the heat recovery type of combined-cycle systems became more prevalent. Its initial application was in power and heat applications where its power-to-heat ratio was more favorable. Also, a small number of the heat recovery type combined cycles were installed in utility power generation applications during the 1960s. Application of these systems in the 1970s and 1980s established the heat recovery feedwater heating combined-cycle as a mature technology for baseload and mid-range service.

The summary presented in *Table 1* characterizes the first generation systems. *Table 2* and *Table 3* represent second generation characteristics and experience.

The requirements for stack gas NO_X emission control was initially legislated during the late 1970s. The first systems utilized gas turbine water or steam injection to meet new source performance standards of 75 ppmvd at 15% oxygen with efficiency and fuel-bound nitrogen adjustments. Combined-cycle plants utilized steam from the steam cycle for NO_X control because this had the least impact on plant efficiency. As emission requirements became more stringent, it was necessary to apply SCR to augment NO_X abatement (TEPCO Groups I and II). Application of SCR systems became common in Japan and in the USA in the mid-1980s.

Third Generation Combined Cycles

The first and second generation combined-cycles were configured using gas turbine designs that were optimized for simple-cycle output and efficiency. Gas turbine design optimization for simple-cycle and for combined-cycle output and thermal efficiency is illustrated

Gas Turbine	Small Size (Frame 3000 & 5000)
Application	Repowering & Cogeneration from 1949 - 1968
Steam Cycle	Non-reheat, Single or Two Pressure
Emission Control	None
Fuel	Distillate Oil / Natural Gas

Table 1. Gas turbine in first power generation combined cycle

Gas Turbine	50-90 MW Capacity (MS6000B, MS7000B/C/E and MS9000B/E
Application	Heat Recovery Feedwater Heating CC from 1968-1999
Steam Cycle	Non-reheat, Single, Two & Three Pressure
Emission Control	GT Water and Steam Injection plus Selective Catalytic Reduction System (SCR) Installed in the HRSG Gas Path for NOx Control
Fuel Heavy	Natural Gas / Distillate Oil / Low Btu Gas / Oils

Table 2. Second generation combined-cycle system characteristics

in *Figure 8* performance maps as a function of firing temperature and pressure ratio parameters.

Specific power (i.e., output per pound of airflow) is important since the higher the value, the smaller the gas turbine required for design power output. The importance of thermal efficiency is obvious since it directly impacts the operating fuel cost. *Figure 8* illustrates a number of significant points.

1. Where simple-cycle efficiency is the goal, high pressure ratio is desirable.
2. Where combined-cycle efficiency is the objective, more modest pressure ratios are selected.
3. Firing temperature has a greater impact on combined-cycle efficiency than simple-cycle efficiency.

Fuel price escalation in the 1970s and 1980s further increased the need for more efficient power plants for base- and mid-range service. This led to gas turbine designs in the late 1980s that were optimized specifically for combined-cycle efficiency.

Second Generation 60 Hz. STAG Combined Cycle Experience

Country	Installation	Configuration	COD	Total (MW)
USA	Wolverine Electric	S105 *	1968	21
USA	City of Ottawa	S103 *	1969	11
USA	City of Clarksdale	S105 *	1972	21
USA	City of Hutchinson	S103 *	1972	11
USA	Duquesne Power & Light	S307B	1974	330
USA	Houston Power & Light	2 x S407B	1994	574
USA	Salt River Project	4 x S107B *	1974	290
USA	Ohio Edison	S207B	1974	225
USA	Jersey Central	S407B	1974	340
USA	Arizona Public Service	3 x S107C *	1976	250
USA	Iowa Illinois G&E Co.	S405LA *	1977	105
USA	Puerto Rico WRA	2 x S407B *	1977	606
USA	Western Farmers	3 x S107E	1977	278
USA	Portland GE	S607B	1977	550
Korea	Korea Electric	2 x S407B	1979	640
USA	MMWEC	S307E	1983	360
Taiwan	Taiwan Power Co.	2 x S307E	1983	570
USA	SCE Cool Water IGCC	S107E	1984	120
Mexico	CFE Mexico	S407E	1984	375
Trinidad	Trinidad and Tobago	S207E	1995	198
USA	City of Fayetteville	S605P	1988	189
Japan	Chubu Electric Power Co.	5 x S107E *	1988	577
USA	Ocean States Power	2 x S207EA	1990	480
USA	TECO Power Services	S207EA	1992	250
Korea	Pyong Taek	S407EA	1994	531
USA	Mission Gordonsville	2 x S107EA	1995	240
Saudi Arabia	PP9	4 x S407EA	1999	1284
Saudi Arabia	Rabigh	S407EA	2000	383

Number of gas turbines = 115 Units
Installed Capacity = 9,809 MW

Second Generation 50 Hz. STAG Combined Cycle Experience

Country	Installation	Configuration	COD	Total (MW)
Argentina	EMSA	S205P	1984	65
Japan	TEPCO, Futtsu #1	7 x S109E *	1986	1155
China	MPI Lama Dien II	S106B *	1986	50
Pakistan	WAPDA	2 x S209E	1986	623
Japan	TEPCO, Futtsu #2	7 x S109E *	1988	1155
Egypt	Egyptian Electric Authority	2 x S 405P	1988	300
Austria	ESG Linz	S206B	1993	77
Indonesia	PLN-Maura Karang	S309E	1995	500
Egypt	EEA – Cairo South	S109E	1994	180
Indonesia	PLN-Tambrok Lorok	2 x S309E	1996	1000
Turkey	Colakoglu	S209E	1996	370
Malaysia	TNB/Melaka	S209E	1998	340
China	Wenzhou	S209E	1999	313
Pakistan	Uch	S309E	2000	560
Ghana	Vra/Takaradi	S209E	2000	337

Number of gas turbines = 52 units
Installed Capacity = 7,052 MW

Table 3. Second generation combined-cycle experience

The GE "F" Technology gas turbine designed in the 1980s, with pressure ratio of about 14:1 and 2400°F firing temperature was the result of a design effort aimed at optimization for combined-cycle peak efficiency rather than simple-cycle peak efficiency.

The fleet leader "F" Technology gas turbine entered commercial operation in 1990 in a combined-cycle installation at the Virginia Power Chesterfield site and launched the third generation of combined-cycle systems.

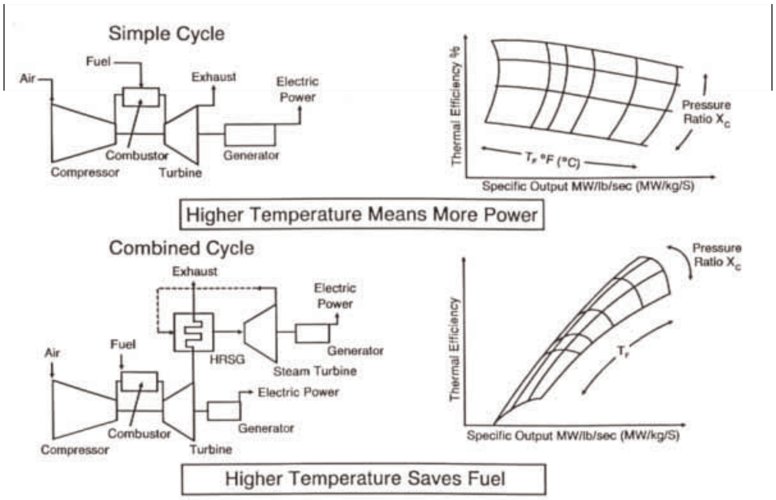

Figure 8. Gas turbine performance thermodynamics

The third generation "F" Technology combined-cycle experience is summarized in *Table 4* and system characteristics are defined in *Table 5*.

The trend of combined-cycle plant efficiency improvement is illustrated by *Figure 9*, which shows the performance of selected STAG plant installations as a function of commercial operating date. Gas turbine development has had the greatest impact on improved combined-cycle efficiency due primarily to the increase in firing temperature made possible through the development of high-temperature oxidation/corrosion-resistant metals and coatings, and advanced metal surface cooling techniques. Another important factor is that the gas turbine contributes about two-thirds of the combined-cycle plant's power.

Advances in steam system technology have also contributed to improved combined-cycle efficiency. The significant steam-cycle developments include:

1. Technology to weld continuous spiral fins on HRSG heat transfer tubes (1959).
2. Application of larger annulus area steam turbine designs for low exhaust pressure applications.
3. Application of reheat steam cycle with "F" Technology gas turbines.

The current STAG product line ratings, which represent third generation combined-cycle capability, is summarized in *Figure 10*.

Fourth Generation Combined-Cycle Plants

Further gas turbine materials development and hot gas path cooling technology advances, as well as higher temperature and pressure steam cycles, will continue the trend for more efficient combined-cycle systems in the future.

Gas turbines installed in the first, second and third generation combined-cycle plants are configured with open-loop cooling of the turbine hot gas path and cooling air supplied from the compressor. Hot gas path components are in large part cooled by film cooling. As a result, there is significant exhaust gas temperature drop across the first stage nozzle, and significant "chargeable air" required to cool down the steam turbine stages. The drop in exhaust gas temperature across the first stage nozzle and the increase in chargeable cooling loss due to increases in turbine firing temperature may diminish efficiency gains to the point of being uneconomical. For this reason, the GE fourth

60 Hz. STAG Combined Cycle Experience with "F" Technology Gas Turbine

Country	Installation	Configuration	COD	Output (MW)
USA	Virginia Power #7	S107F	1990	214
USA	Virginia Power #8	S107F	1992	218
Korea	KEPCO Seo-Inchon #1 & #2	8 x S107F	1992	1887
USA	Sithe Independence	2 x S207FA	1995	1062
USA	Tampa Electric, Polk Co.	S107FA	1996	313
Korea	KEPCO Seo-Inchon #3 & #4	2 x S207FA	1996	1004
USA	US Gen. Co., Hermiston	2 x S107FA	1996	425
USA	Crockett Cogen	S107FA *	1996	202/248
Mexico	CFE Samalayuca	3 x S107FA *	1998	506
USA	Cogentrix, Clark Co.	S107FA *	1998	254
USA	Ft. St. Vrain	S207FA	1999	487
Korea	KEPCO, POSCO	S207FA	1999	498
Columbia	EPM LaSierra	S207FA	2001	478
USA	Bucksport Energy	S107FA	2001	176
USA	Westbrook	S207FA	2001	528
USA	Santee Cooper	S207FA	2001	600
Korea	Pusan	4 x S207FA	2003/4	2000

Number of gas turbines = 2 Units
Installed Capacity = 12,411 MW

50 Hz. STAG Combined Cycle Experience with "F" Technology Gas Turbine

Country	Installation	Configuration	COD	Output (MW)
Japan	TEPCO, Yokahama	8 x S109FA *	1996/7	2800
China	China Power & Light	8 x S109FA *	1996/72	2731
Japan	TEPCO, Chiba	4 x S109FA *	1998	1440
India	Enron, Dabhol I	S209FA	1998	698
Chile	Renca	S109FA	1998	370
Netherlands	AKZO, Delesto	S109FA *	1999	364
U.K.	Sutton Bridge	S209FA	1999	800
Thailand	Ratchaburi	3 x S209FA	2000	2130
Argentina	Central Puerto	S209FA	2000	769
Japan	Hitachi Zosen	S106FA	1999	106
U.K.	Tri-Energy	S209FA	2000	700
U.K.	Great Yarmouth	S109FA *	2001	407
India	Enron, Dabhol II	2 x S209FA	2001	1600
Japan	TEPCO, Futtsu 3	4 x S109FA *	2002	1590
Spain	Castellon	S209FA	2002	285

*** Single-shaft Combined Cycle**

Number of gas turbines = 50 units
Stalled capacity = 17,795 MW

Table 4. Third generation combined-cycle experience

Gas Turbines	**70-250 MW (MS6001FA, MS7001FA, MS9001EC and MS9001FA)**
Application	**Heat Recovery Feedwater Heating CC in the 1990s**
Steam Cycle	**Reheat, Three Pressure**
Emission Control	**DLN Combustion with Natural Gas and Water / Steam Injection with Oil Fuels plus SCR Installed in the HRSG**
Fuel	**Natural Gas / Distillate Oil / Low Btu Gas**

Table 5. Third generation combined-cycle system characteristics

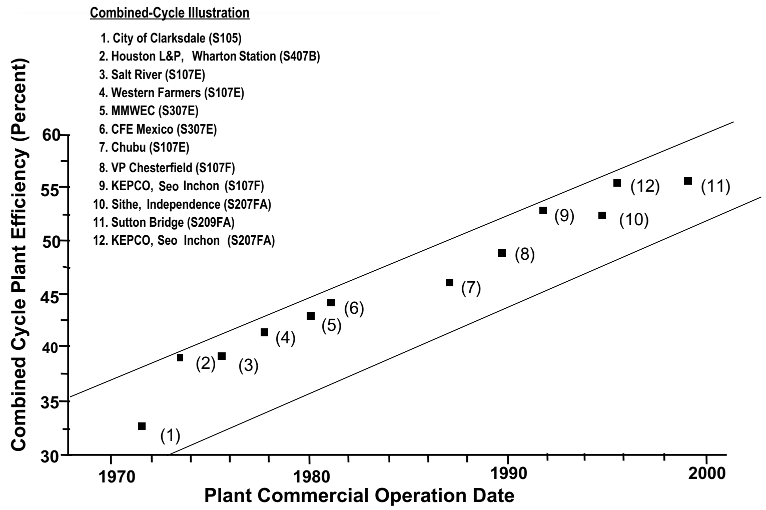

Figure 9. Combined-cycle system efficiency trend

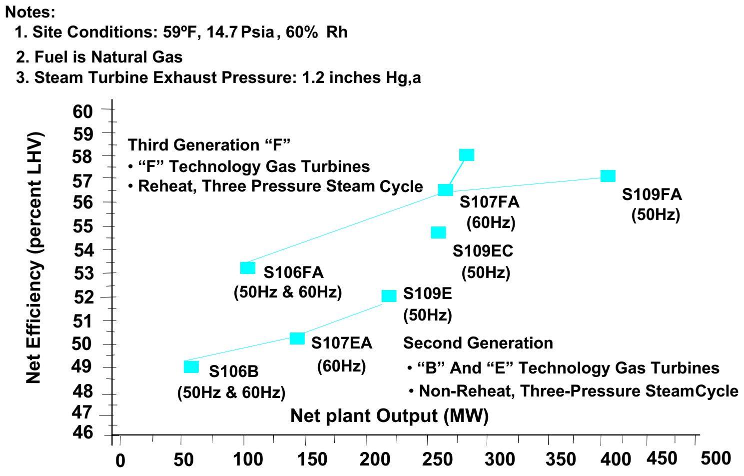

Figure 10. Current STAG product line ratings

generation plants with "H" Technology gas turbines will be configured with an integrated closed-loop steam cooling system (*See Figure 11*). This system allows higher turbine firing temperature to be achieved without increasing combustion temperature. This is because exhaust gas temperature drop across the first stage nozzle is significantly reduced as outlined in *Figure 12*. Another important benefit of the integrated closed-loop steam cooling system is the elimination of "chargeable cooling air" for the first and second stage rotating and stationary airfoils. This technology is expected to provide two percentage points thermal efficiency improvement.

The "H" platform gas turbine combined-cycle plants are expected to achieve 60% LHV thermal efficiency in the first half of this decade. The application of ceramic hot gas path parts and coatings show promise for further future performance gains.

Steam cycle improvements that include increased steam pressure and temperature with supercritical steam cycles have near-term applica-

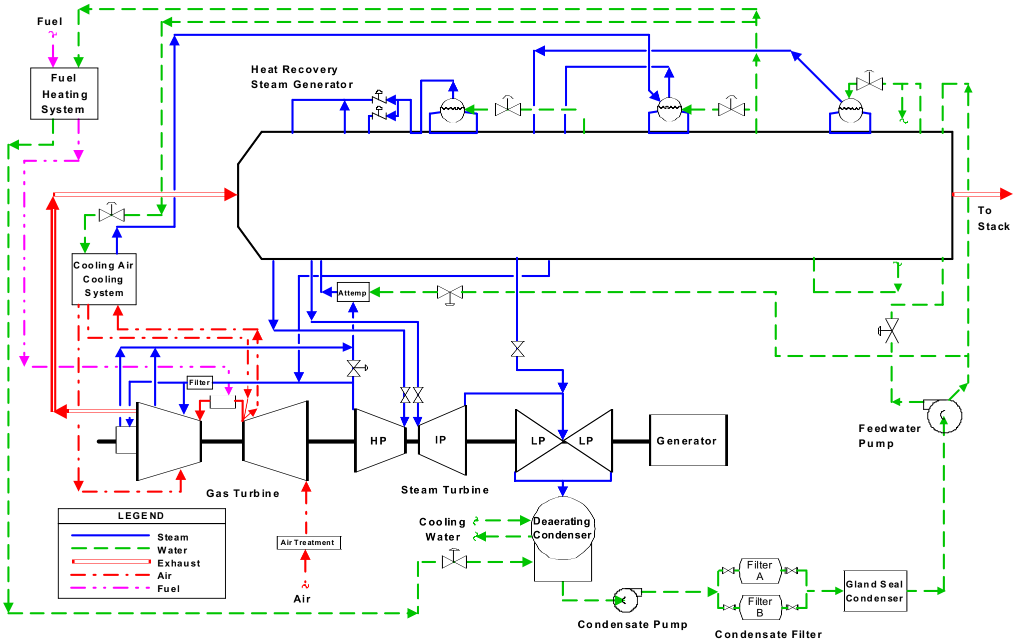

Figure 11. S107H/S109H cycle diagram

tion. Current economic analysis indicates, however, that the thermodynamic gain associated with steam cycles that have steam temperatures and pressures above the current levels (1050°F and 1400 PSIG to 1800 PSIG) cannot be justified in most cases because of the added costs.

As in the past, operating cost (fuel price) and the cost of new technology development will dictate the trend for increased combined-cycle efficiency.

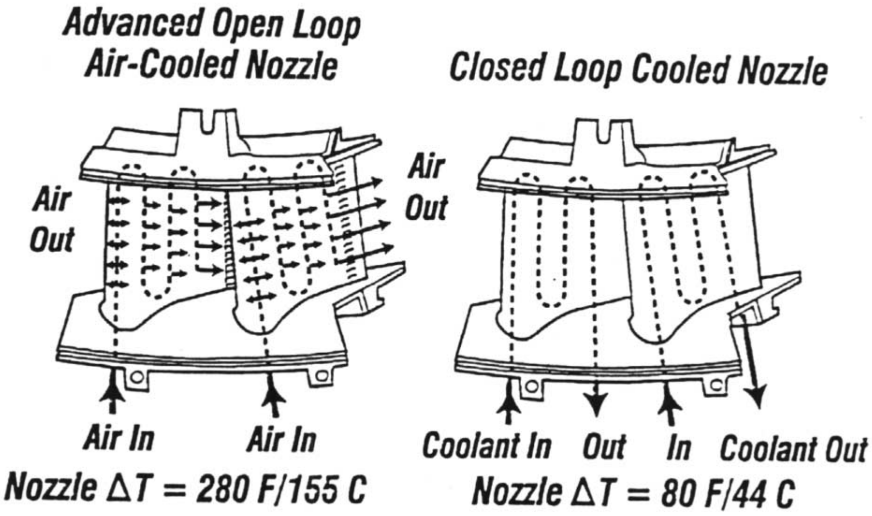

Figure 12. Impact of stage one nozzle cooling method

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