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GE Power Systems

Advanced Technology Combined Cycles

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Contents

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Introduction

The General Electric H technology combined cycles represent the most advanced power generation systems available today. These combined-cycle power generation systems can achieve 60% net thermal efficiency burning natural gas. Their environmental impact per kilowatt-hour is the lowest of all fossil-fired generation equipment. These highly efficient combined cycles integrate the advanced technology, closed-circuit steam-cooled 60 Hz MS7001H and 50 Hz MS9001H gas turbines with reliable steam cycles using state-of-the-art steam turbines and unfired, multi-pressure, reheat heat recovery steam generators (HRSGs).

System Integration Overview

The STAG 107H and STAG 109H are offered in a single-shaft combined-cycle configuration. *Figure 1* is a conceptual presentation of an outdoor power plant with this equipment. This configuration complements the cycle integration between the steam-cooled gas turbine and the steam bottoming cycle.

A diagram of the cycle (*Figure 2*) shows an overview of the three-pressure, reheat steam cycle and its integration with the gas turbine cooling system. Gas turbine cooling steam is supplied from the intermediate pressure (IP) superheater and the high pressure (HP) steam turbine exhaust to the closed circuit system that cools the gas turbine stage 1 and 2 nozzles and buckets. The cooling system operates in series with the reheater, with gas turbine cooling steam returned to the steam cycle cold reheat line.

Air extracted from the compressor discharge is cooled using water from the IP economizer. The cooled air is readmitted to the gas turbine and compressor to cool compressor wheels and selected turbine gas path components. The energy extracted from the compressor discharge air is returned to the steam cycle by generating IP steam. A fuel gas heating system utilizes low grade energy from the HRSG to improve combined-cycle thermal efficiency. Water extracted from the discharge of the HRSG IP economizer is supplied to the fuel gas

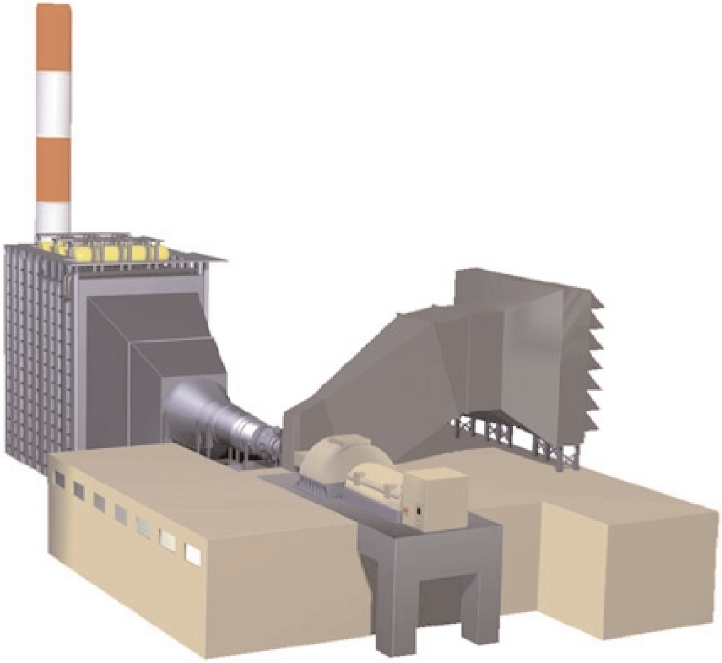


Figure 1. Advanced technology combined-cycle unit

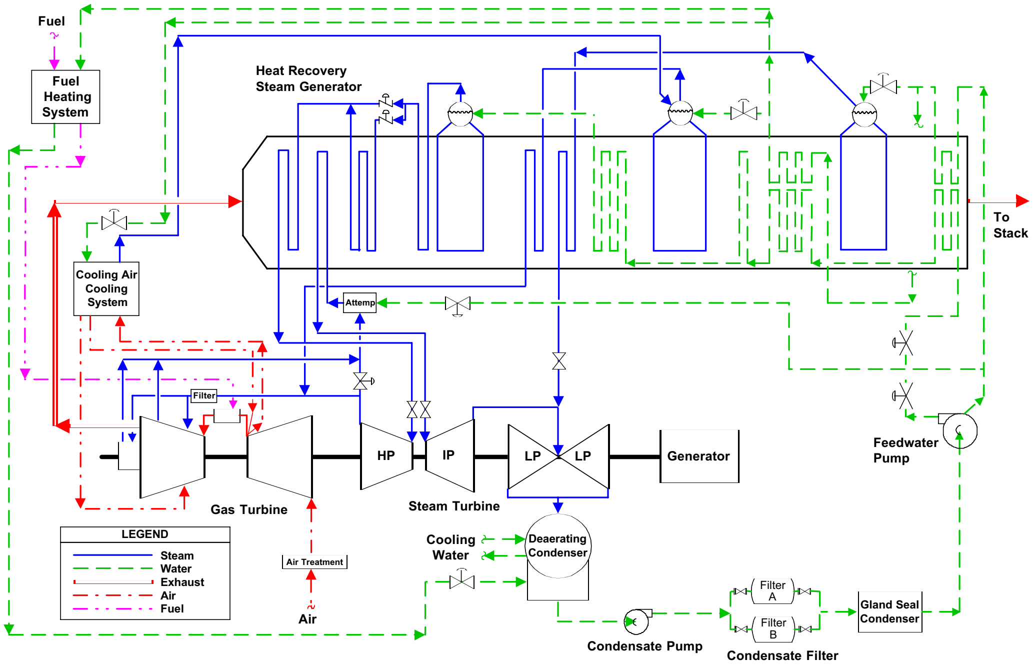


Figure 2. STAG 107H/109H cycle diagram

heater to pre-heat the fuel gas supplied to the combustion system. The water leaving the fuel heater is returned to the cycle through the condensate receiver to the condenser.

Performance

The rating point thermal and environmental performance is summarized in *Table 1* for the advanced technology single-shaft combined-cycle units burning natural gas fuel. The graphs in *Figure 3* show the ambient temperature effect on performance for the STAG 107H as well as the part load performance. The graphs in *Figure 4* show the ambient temperature effect on performance for the STAG 109H as well as the part load performance.

The low NO_x emissions are achieved by a Dry Low NO_x (DLN) combustion system. The closed circuit steam-cooling system also contributes to the low NO_x emissions because a minimum of air bypasses the combustors for cooling the gas turbine hot gas path parts.

Combined-Cycle Unit	Net Power, MW	Net Heat Rate (LHV) BTU/kWh	kJ/kWh	Thermal Efficiency (LHV), %	NO_x Emissions ppmvd at 15% O_2	Thermal Discharge to Cooling Water BTU/kWh	kJ/kWh
STAG 107H	400	5,687	6,000	60	< 9	1,790	1,888
STAG 109H	480	5,687	6,000	60	< 25	1,790	1,888

Notes:

1. Ambient Air Conditions = 15°C (59°F), 1.0133 barA (14.7 psia), 60% RH
2. Steam Turbine Exhaust Pressure = 0.04064 barA, (1.2 In HgA)
3. Performance is net plant with allowances for equipment and plant auxiliaries with a once-through cooling water system
4. Three-Pressure, Reheat, Heat Recovery Feedwater Heating Steam Cycle

Table 1. Advanced technology combined cycle – thermal and environmental performance

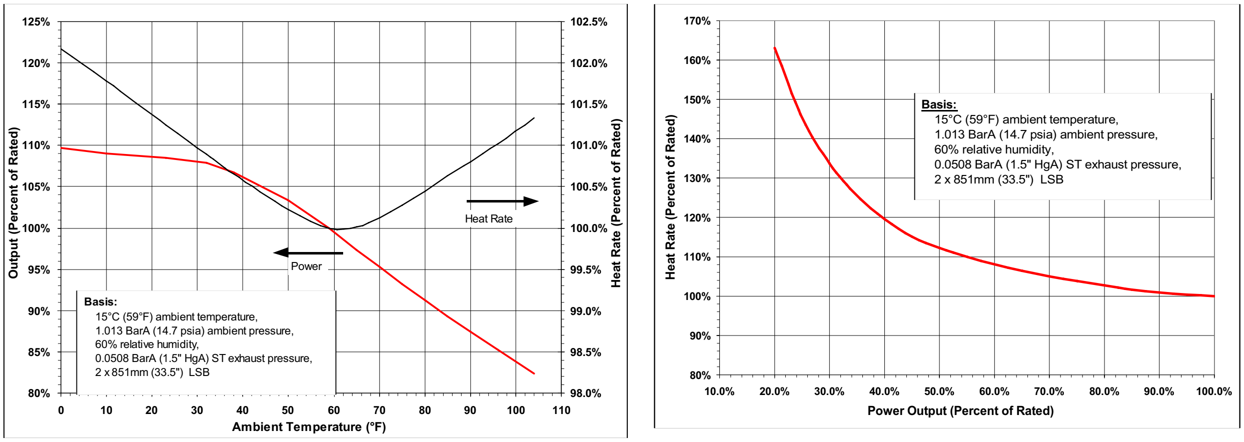


Figure 3. S107H ambient temperature effect on performance and part load performance

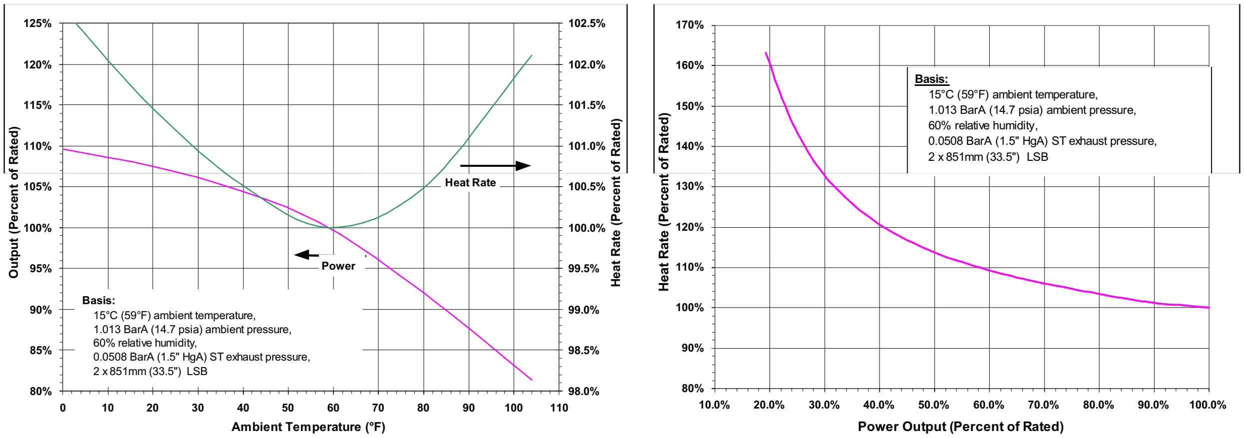


Figure 4. S109H ambient temperature effect on performance and part load performance

HP Throttle	
Pressure (psig/Barg)	2400/165
Temperature (°F/°C)	1050/565
Hot Reheat	
Pressure (psig/Barg)	345/23.8
Temperature (°F/°C)	1050/565
LP Admission	
Pressure (psig/Barg)	31/2.2
Temperature (°F/°C)	530/277
Exhaust Pressure	
Pressure (in. HgA/barA)	1.2/0.04064

Table 2. Advanced technology combined-cycle steam conditions

The low thermal discharge to cooling water results from the high efficiency and the general characteristic of combined-cycle systems in which approximately 30% of the unit power output is produced by the steam cycle.

Bottoming cycle steam conditions are tabulated in *Table 2* for systems that produce the performance shown in *Table 1*. The combined-cycle systems are also available with 124 barA / (1800 Psig) throttle pressure which may more optimally suit systems with lower cost fuel or a mid-range duty cycle.

Steam Turbine

A wide range of steam turbines are available to suit specific site, duty and economic requirements for both 50 Hz and 60 Hz applications while satisfying all of the combined-cycle integration requirements. Since there are no extractions for feedwater heating and since steam is generated and admitted to the turbine at three pressures, the flow at the exhaust is approximately 30% greater than the throttle flow. The last stage generates up to 15% of the steam turbine output, so the efficiency of the turbine's last stage and the sizing of the exhaust annulus area are particularly important for all combined-cycle applications. The range of site-specific back pressure conditions expected requires low-pressure section designs with a broad range of exhaust annulus areas. This is achieved by selection of the last stage bucket length and the use of both single-flow and double-flow exhausts. *Table 3* summarizes the last-stage buckets that are applicable for the advanced technology combined cycle units.

Applications with low condenser pressure require a steam turbine with a double-flow exhaust. This two-casing design is similar in configuration and construction to that applied by GE in single-shaft combined-cycle applications with F technology gas turbines. The high and intermediate pressure sections are combined in one casing connected by a single crossover to the center of the double-flow low-pressure section.

Operation is with sliding pressure with the control valves wide open. A control stage at the inlet is therefore not required.

Shaft Train Configuration

The single-shaft power train is configured with the gas turbine on one end, the steam turbine in the middle and the generator on the other end, as shown in *Figure 5*. This close coupling of the steam and gas turbines permits full mechan-

Frequency	**Length**		**Pitch Diameter**		**Exhaust annulus Area for Number of Parallel Flows**			
					1	1	2	2
Hz/RPM	mm	inches	mm	inches	Sq M	Sq Ft	Sq M	Sq Ft
60/3600	851	33.5	2300	95.5			12.28	132.2
	1016	40.0	2540	100.0	8.11	87.3	16.22	174.6
50/3000	851	33.5	2530	99.5			13.51	145.4
	1067	42.0	2804	110.4	9.4	101.2	18.80	202.4

Table 3. Last-stage buckets for advanced technology combined-cycle applications

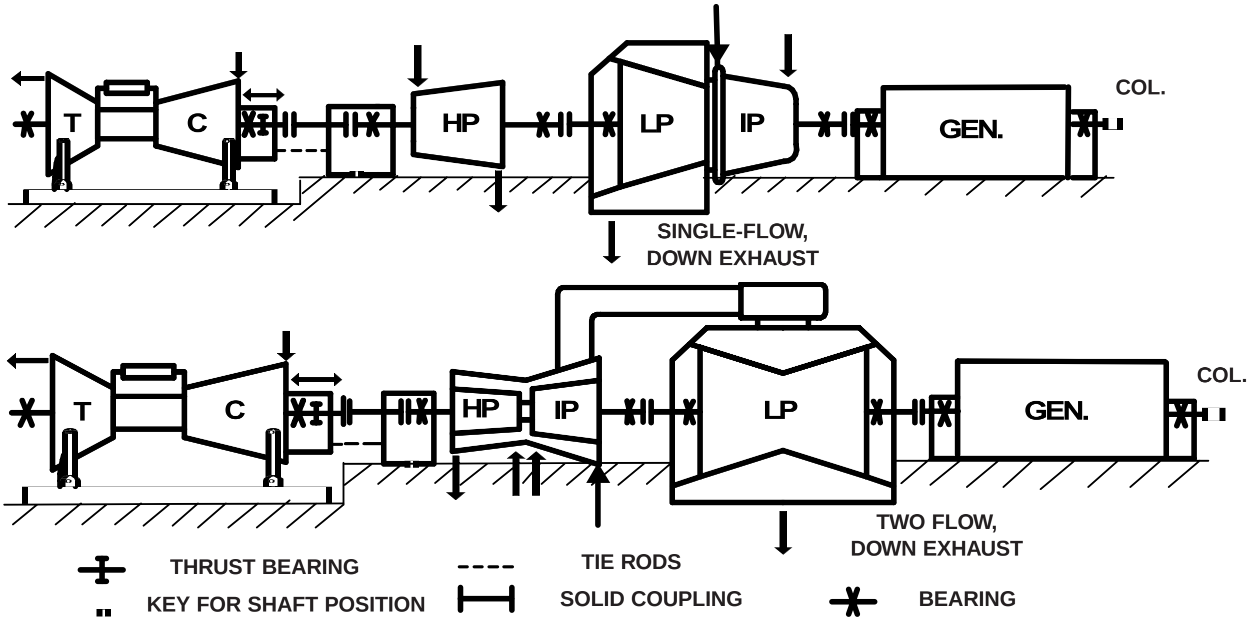


Figure 5. S107H and S109H single-shaft STAG equipment configuration

ical integration as a single prime mover with a single thrust bearing, thus minimizing the overall machine length. Use of all solid rotor couplings provides maximum reliability and simplifies the control, overspeed protection, and auxiliary systems.

The thrust bearing is located in the gas turbine inlet end bearing housing, which permits independent operation of the gas turbine for testing in the factory. This location is at the high pressure end of the steam turbine, which minimizes differential expansion and permits use of small axial clearances throughout the HP and IP sections. The steam turbine contribution to the shaft thrust load is low and in the opposite direction to that of the gas turbine, so that the thrust bearing is lightly loaded under all operating conditions.

A single lubricating oil system with AC- and DC-powered pumps provides oil to all shaft bearings and to the generator hydrogen seals. Similarly, a single high-pressure hydraulic fluid system is used for all control and protective devices.

Features:

1. Steam turbine installed between the gas turbine and the “field assembled” hydrogen-cooled generator.
2. Solid coupling between gas turbine and steam turbine. Direct coupled steam turbine shafts and direct coupled steam turbine to generator.
3. Single thrust bearing in the gas turbine compressor to fix shaft position in conjunction with tie rod installation between the steam turbine front standard and the gas turbine compressor inlet casing.
4. Steam turbine front standard keyed to foundation.
5. Common lube oil system with hydrogen seal oil system. Common fire-resistant hydraulic oil system.
6. Static start (LCI).
7. Turning gear mounted between steam turbine and generator

8. Lift oil for gas turbine only.
9. Gas turbine, steam turbine, generator, and gas skid installed on a pedestal foundation. All other modules (lube oil, hydraulic, fuel oil/atomizing air, etc.) are installed at lower level. Shaft center line height (approximately 10.2M [33.5 feet] above grade) determined by gas turbine inlet duct location and/or steam turbine condenser.
10. Single-flow or two-flow down exhaust steam turbine with sliding shell support on the fixed/keyed front standard.
11. Integrated unit control system (GT, ST, Gen, HRSG & Mechanical Auxiliaries).
12. Integrated overspeed protection.
13. Down generator terminals.
14. Reheat, three-pressure steam cycle.
15. Integrated drawings - Shaft Mechanical Outline, One-Line Diagram, Device Summary, Piping Schematics (Lube Oil, Hydraulic).

The selection of the single shaft as the preferred configuration for the advanced technology combined cycles is based on the extensive experience since its introduction by GE in 1968. *Table 4* presents the operating experience on 86 GE single-shaft combined-cycle units with nearly 18,000 MW of installed capacity.

Steam-Cooling System

The gas turbine steam cooling system is integrated with the steam bottoming cycle to reliably provide cooling steam at all operating conditions. The normal supply of cooling steam is from the outlet of the HRSG IP superheater, supported as necessary with HP steam turbine exhaust. The steam is delivered to the gas turbine stationary parts through casing connections and to the rotor through a conventional gland connection. The cooling steam is returned to the steam cycle at the cold reheat

Utility	Site	No. Units	Rating (MW)		Gas Turbine	Commercial Operation
			Unit	Plant		
Wolverine Electric	Michigan, USA	1	21	21	MS5001	1968
City of Ottawa	Ottawa, KS, USA	1	11	11	MS3002	1969
City of Clarksdale	Clarksdale, MS, USA	1	21	21	MS5001	1972
City of Hutchinson	Hutchinson, MN, USA	1	11	11	MS3002	1972
Salt River Projects	Santan, AZ, USA	4	72	290	MS7001B	1974
Arizona Public Ser.	Phoenix, AZ, USA	3	83	250	MS7001C	1976
Western Farmers	Anadarko, OK, USA	3	93	278	MS7001E	1977
Tokyo Electric	Futtsu, Japan	14	165	2310	MS9001E	1986
Chubu Electric	Yokkiachi, Japan	5	112	560	MS7001E	1988
Chugoku Electric	Yanai, Japan	6	125	750	MS7001E	1990
Ministry of Pet.	Lama Dien, China	1	50	50	MS6001B	1990
Kyushu Electric	Shin-Oita, Japan	5	138	690	MS7001EA	1992
Power Gen	Connah's Quay, UK	4	350	1400	MS9001F	1995
EPON	Netherlands	5	350	1400	MS9001FA	1995
Tokyo Electric	Yokohama, Japan	8	343	2742	MS9001FA	1997
Chubu Electric	Kawagowe, Japan	7	235	1645	MS7001FA	1998
China Light & Power	Black Point, Hong Kong	8	340	2720	MS9001FA	1996
Crocket Cogen	Calif, USA	1	248	248	MS7001FA	1996
Cogentrix	Clark County, WA	1	253	253	MS7001FA	1997
Tokyo Electric	Chiba, Japan	4	360	1440	MS9001FA	1999
Boffolora	Italy	1	110	110	MS6001FA	1998
Akzo	Delesto II, Netherlands	1	360	360	MS9001FA	1999
Great Yarmouth	Great Yarmouth, UK	1	407	407	MS9001FA	2001
Total		86		17,967		

Table 4. Single-shaft combined-cycle experience

line. The gas turbine cooling steam return and any HP steam turbine exhaust steam not used for gas turbine cooling are reheated in the HRSG and admitted to the IP steam turbine.

During unit acceleration to rated speed and operation at low load, the gas turbine is cooled by air extracted from the compressor discharge. The air is filtered prior to supply to the cooling system. The cooling air from the gas turbine cooling circuit is discharged to the gas turbine exhaust. During air-cooled gas turbine operation steam flow is established through the steam supply system to warm the steam lines and stabilize the steam supply conditions prior to admission of steam to the gas turbine cooling system. This steam is discharged via the reheater to the condenser through the IP bypass valve, which is modulated to maintain the pressure of the cooling steam above the gas turbine compressor discharge pressure to preclude gas leakage into the steam cycle. Appropriate shutoff valves isolate the gas turbine cooling circuit from the steam cycle while it is operating with air cooling. These cooling steam shutoff valves are included in the trip circuit such that the system is transferred to air cooling immediately upon an emergency shutdown to purge steam from the cooling system.

Initial cooling steam supply and line warming steam is supplied from the HRSG. Steam is extracted from the HP superheater after the first pass and mixed with steam from the HP superheater discharge to supply steam to the cooling steam system at the required temperature. The cooling steam temperature control will match gas turbine cooling steam supply to the gas turbine compressor discharge temperature during transfer from gas turbine air cooling to gas turbine steam cooling, which occurs prior to steam turbine loading. In addition to providing start-up cooling steam supply to the gas turbine cooling steam circuit, the HP steam extraction after the first superheater pass is used to cool the LP steam turbine from ~70% speed until steam turbine loading is underway.

Figure 2 includes a diagram of the three-pressure, reheat HRSG. While the system can be configured with either forced or natural circulation evaporators, *Figure 2* shows a system with natural circulation evaporators. The HRSG is a typical three-pressure, reheat HRSG that is commonly applied in combined cycles. It includes the following features to accommodate the steam cooling system:

- The reheater size is reduced since part of the reheating is performed by the gas turbine cooling steam system.
- The reheater is located in the gas path downstream of the high temperature section of the HP superheater. The reheater receives steam during all operating modes except at very low loads during startup, prior to availability of IP steam.
- HP steam is extracted after the first pass of the HP superheater during low load operation to establish gas turbine steam cooled operation before the steam turbine is loaded and provide cooling steam to the LP steam turbine above ~70% speed.
- Control of the HP steam temperature is accomplished by a steam attemperation system which bypasses a section of the HP superheater. This system eliminates the potential for dissolved contaminants to enter the steam as can occur with attemperation with feedwater. Attemperation steam is extracted after it passes through one pass in the superheater to assure that it will be dry after the small pressure drop across the steam control valve.

Supply of high purity steam to the gas turbine cooling system is an essential requirement of the system for efficient long-term plant operation with high availability. Features included in the system to accomplish this requirement are:

- Reliable condenser leakage detection system with redundant condensate conductivity sensors and automated protection logic.
- Full flow feedwater filtration.
- All cooling steam is purified by evaporation in a steam drum with continuous monitoring of drum water purity.
- HP steam temperature control by steam attemperation.
- Full flow steam filtration.
- Application of non-corrosive materials in piping, filters and equipment downstream of the cooling steam shut-off valves.

The steam filter is the final line of defense against particulate contaminants in the cooling steam supply to the gas turbine. This device will operate at least 24,000 hours without maintenance when provided with steam meeting the system purity requirements. The upstream system design features and associated protective strategies provide a means of assuring the design life of the steam filter.

Figure 6 presents the location of the steam and water sampling points within the S107H and S109H combined-cycle systems. All sampling probes and instrumentation (including a sampling panel) are of high sensitivity and reliable design. Steam and water conductivity, pH, and sodium measurements are continuously sampled and monitored. Other measurements not required for plant protection are monitored intermittently.

Integrated Control System

The single-shaft combined-cycle unit is controlled by an integrated, computer control system that coordinates the gas turbine, steam turbine, generator, HRSG and unit auxiliaries to start, stop and operate the unit to meet system

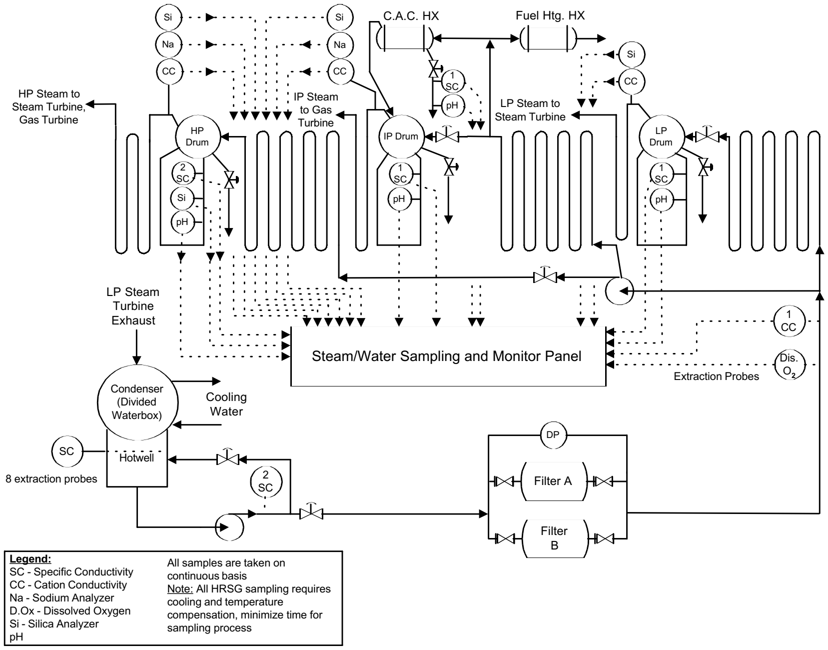
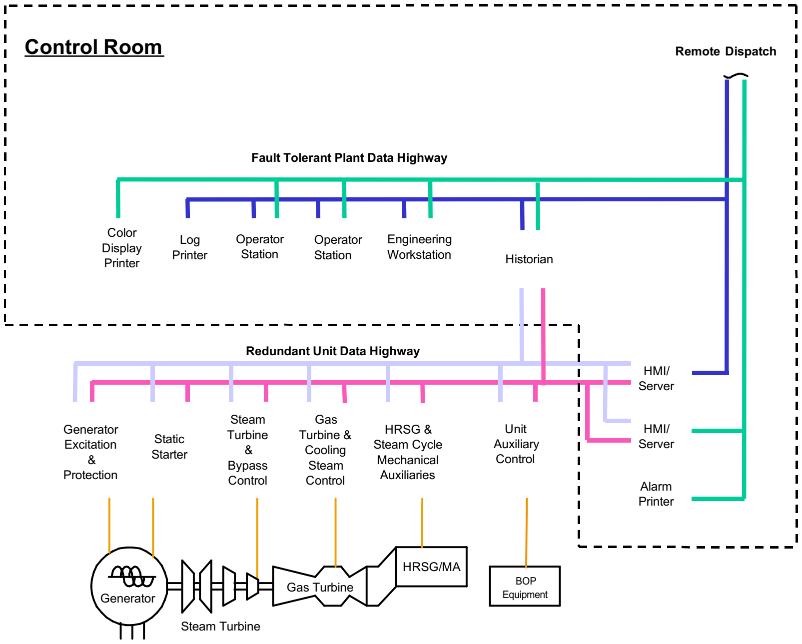


Figure 6. Steam and water sampling schematic

power requirements with input from a control room operator or from a remote dispatch area. The architecture for the single-shaft integrated control system (ICS) for a single unit is shown on *Figure 7*. *Figure 8* shows the architecture for a multiple-unit plant.



- All New Microprocessor Design
- Triple Modular Redundant
- Remotable I/O
- Capability for I/O Expansion
- Redundant Control and Plant Data Highways
- Peer-to-Peer Communications
- Time Synchronized Unit Controls
- Time Coherent System Data

Figure 7. Single-shaft combined-cycle unit integrated control architecture

A redundant data highway connects all control components with the central control room consoles. Historical archival and retrieval of plant data assists performance optimization and equipment maintenance. Time synchronization of all control components provides time coherent, time tagged data for process monitoring, historical archival, sequence of events logging, real time trending and comprehensive alarm management. High speed communication interfaces link the plant control to external dispatch and control systems.

The control and protection strategies are integrated between all components of the system. High levels of fault tolerance maximize unit starting and running reliability for both base load and daily start service. The high degree of control integration maximizes automation of startup, shutdown and normal operations, which reduces plant operating costs.

Easy to configure color graphic displays provide a common look and feel to both the unit and plant level control. Windowed displays enable the operator to constantly monitor the desired process and simultaneously view detailed popup windows to trend equipment operating data or diagnose process problems. An engineering workstation enables the operator to configure and tune control loops, perform detailed control and process diagnostics, maintain software, manage the system configuration and generate operation reports.

The ICS is designed with dedicated I/O (inputs/outputs) to control the engineered equipment packages. In addition, it has the flexibility and expandability needed to address additional I/O requirements to satisfy individual owner requirements. This includes both

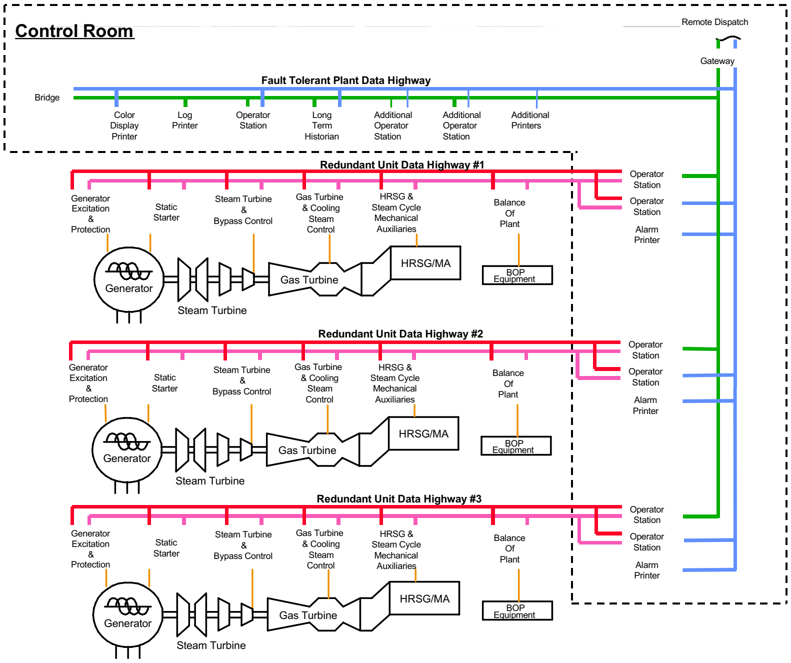


Figure 8. Multiple-unit station control architecture

redundant and non-redundant I/O which is integrated with serial remote I/O (e.g. GENIUS, Fieldbus) and connections to programmable logic control systems. All I/O points are available to the controls database for the integrated system.

The speed and load control for the unit operates through control of the gas turbine fuel valves. The steam turbine control valves are closely coordinated, being closed at startup until steam at sufficient pressure and temperature for admission is available from the HRSG. They are then ramped open and held in fixed position as load is changed with sliding pressure. The steam turbine control valves do not participate in normal frequency control. The HP and LP control valves begin to close when speed rises to 103% of rated speed and are fully closed at 105%.

The intercept valves operate in a pressure control mode at low load to maintain proper steam pressure in the gas turbine steam cooling system. With increasing speed the intercept valves lag the control valves by 2% speed, beginning to close at 105% rated speed and reaching the fully closed position at 107% of rated speed. This normal governing characteristic is overridden by a power/load unbalance-sensing feature upon the sudden loss of significant electrical load. Pressure in a steam turbine stage, representative of steam turbine output, is summed with a gas turbine fuel flow signal and continuously compared with the generator electrical output. When a significant imbalance of power generated over electrical output is detected the control and intercept valves are closed as rapidly as possible, limiting the speed rise to less than the 110% setting of the emergency overspeed trip. Ultimate protection against excessive overspeed is provided by the emergency governor that trips the unit by simultaneously closing all gas turbine fuel and steam turbine control and stop valves.

The sequencing system automatically starts the unit from a ready-to-start condition and loads it to gas turbine base load or a preset load. *Table 5* shows starting time from initiation to full load.

Figure 9 presents an overview of the starting and loading sequence for a hot start. *Figure 10* is a similar presentation of the cold start sequence of a single unit. Note the speed hold shown for developing steam for steam turbine cooling, which is not required in multi-unit installations where running units can be used to support steam turbine cooling needs of the starting unit.

Start Designation	Standby Period (hrs)	Time to Full Load (min)
Hot	0-12	60
Warm	12-48	120
Cold	>48	180

Table 5. Starting time from initiation to full load

Plant Arrangement

The high power density of the advanced technology combined-cycle systems enables a compact plant arrangement. Typical plan and elevation arrangements are shown in *Figure 11* with overall dimensions for outdoor STAG 107H and STAG 109H plants. In this arrangement, the steam turbine has a single-casing and single-flow exhaust as would be applied at a site with steam turbine condenser cooling that accommodates the higher range of exhaust pressures. Plants using steam turbines with double-flow exhausts are approximately 10 feet (3m) longer. The plan area for the 60 Hz advanced technology combined cycle is approximately 10% larger than that for current technology combined cycles, while the power is increased approximately 60% so that the plot space per unit of installed capacity is reduced approximately 45%.

Plant related considerations that influence the selection of the single-shaft configuration for the advanced technology combined cycle are tabulated in *Table 6*. The gas turbine cannot operate independently of the steam cycle so there is no operating flexibility advantage for the multi-shaft system. The single-shaft system is lower in installation cost because of the single generator, main electrical connections, transformer and switchgear as compared to two for the multi-shaft system.

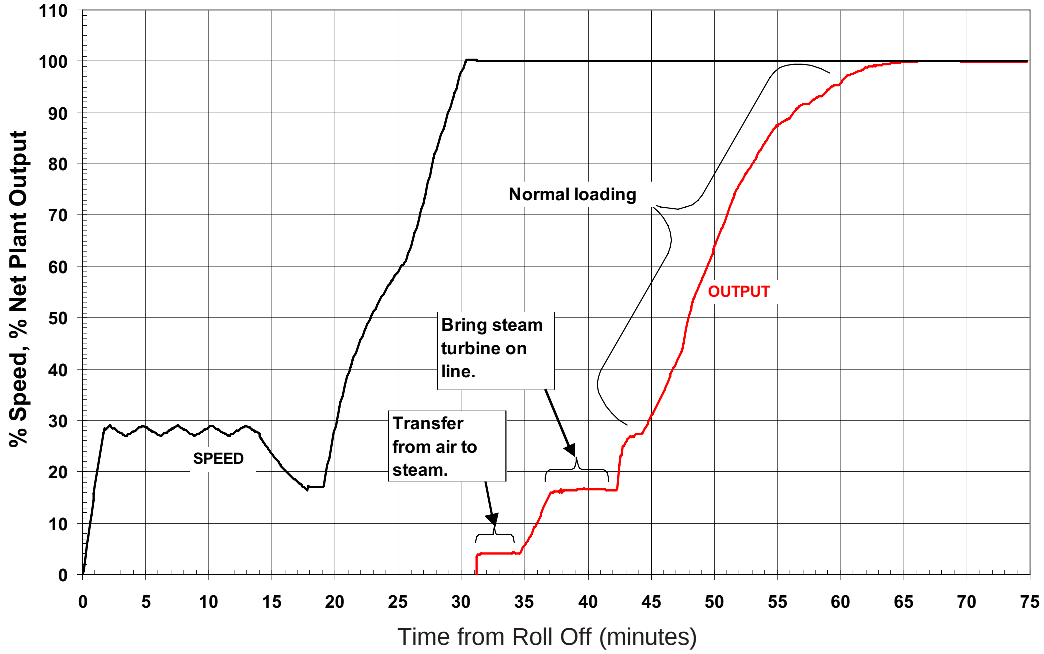


Figure 9. Typical S107H/S109H hot start loading profile

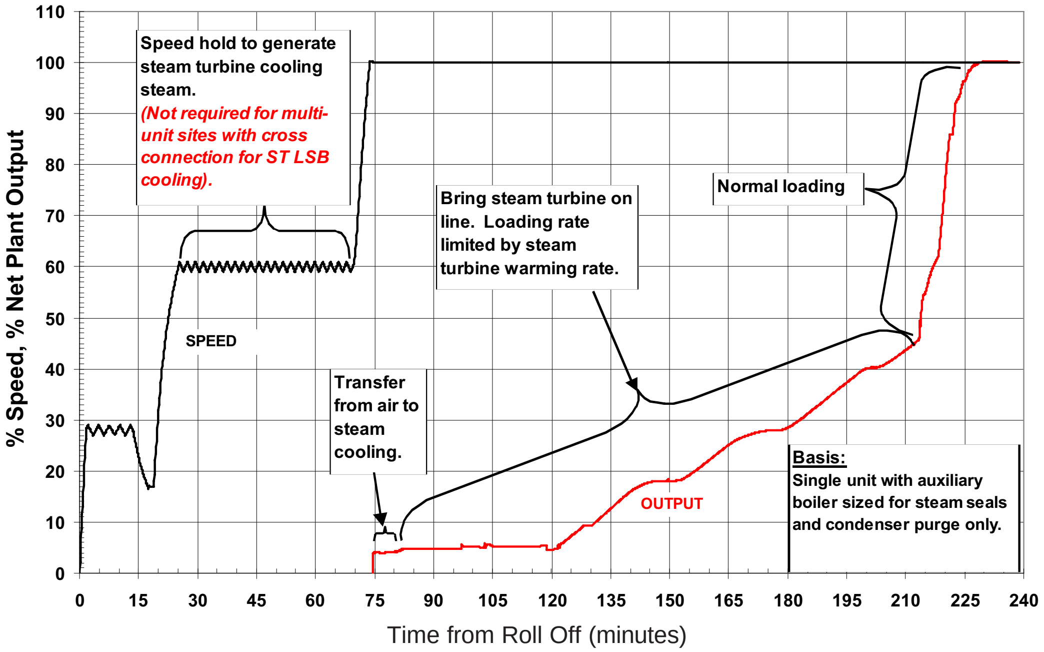


Figure 10. Typical S107H/S109H cold start loading profile, single unit

	STAG 107H Single Shaft	Multi-Shaft STAG 107H (One GT/ST)
Equipment (Quantity)		
– Gas Turbine	1	1
– Steam Turbine	1	1
– Condenser	1	1
– Cooling Water Trains	1	1
– Generators	1	2
– Main Electrical Connections	1	2
– Generator Transformers	1	2
Steam Valves (Quantity)		
– Main Steam Non-Return	0	0
– Reheat Isolation	0	1
– Reheat Relief	2	2
– Reheat Stop/Control	1	1
– Low Pressure Non-Return	0	0
Foundations	High	High/Low
Installed Cost	Low	High
Operation		
– Combined-Cycle	Simple	Simple
– Start/Stop	Simple	Simple
– Load Following	Good	Good
– Contingency Management	Simple	Complex
– Islanding	Good	—
– Simple Cycle	No	Yes
Staged Construction	No	Yes

Table 6. Combined-cycle configuration comparison summary

Integrated Gasification Combined Cycle (IGCC)

The IGCC is broadly recognized as the coal-fired generation plant with the best environmental performance. Integration with the advanced technology combined cycle also will enable it to be the most economical power generation system firing coal, petroleum coke, heavy residual oil and other solid or low grade liquid fuels. *Figure 12* shows a diagram of a typical unitized advanced technology IGCC system with an oxygen blown gasifier and integration of the air separation unit with the gas turbine.

The range of ratings for the advanced technology IGCC plants are shown in *Table 7*:

IGCC UNIT	Frequency Hz	Capacity Range (MW)	Thermal Net LHV Eff. Range (%)
STAG 107H	60	400-425	45-49
STAG 109H	50	500-530	45-49

Table 7. Ratings for advanced technology IGCC plants

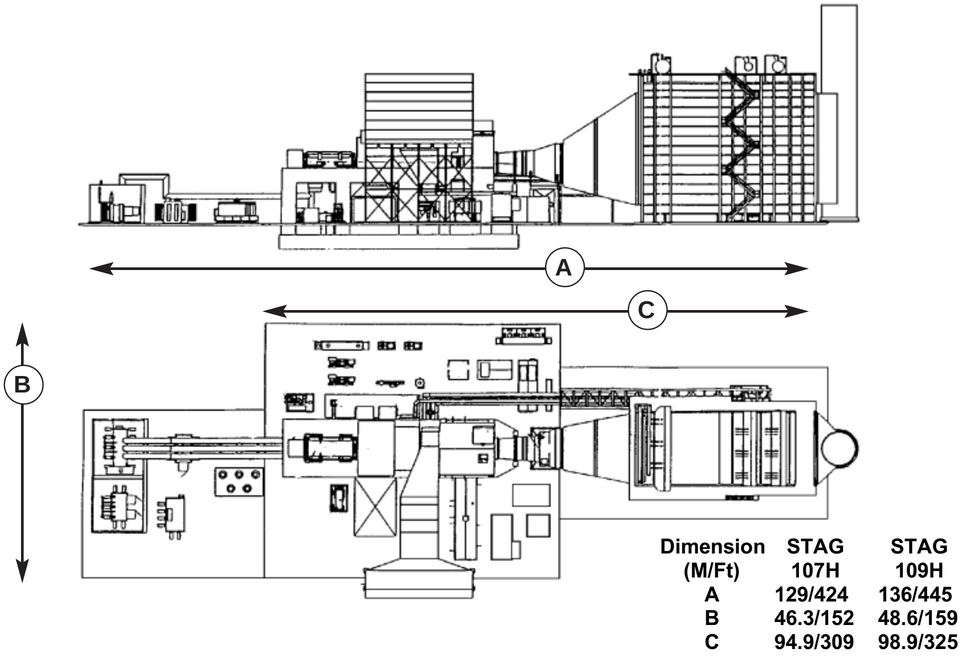
The capacities and efficiencies are shown as ranges because they vary with plant economic considerations and the type of gasifier, gas cleanup system, air and steam cycle integration and the coal or other solid fuel analysis and moisture content.

Key features of an advanced technology IGCC plant that enable economical power generation are:

- Low installed cost resulting from the capacity of the unit which enables it to be matched with a single large gasifier.
- High efficiency which reduces fuel consumption and further reduces plant cost by reducing the capacity of the gasification and cleanup system per unit of installed generation capacity.

Repowering

The advanced technology combined-cycle system is readily adaptable to the repowering of existing steam turbine generator units. The



Dimension (M/Ft)	STAG 107H	STAG 109H
A	129/424	136/445
B	46.3/152	48.6/159
C	94.9/309	98.9/325

Figure 11. Single-shaft unit plan and elevation

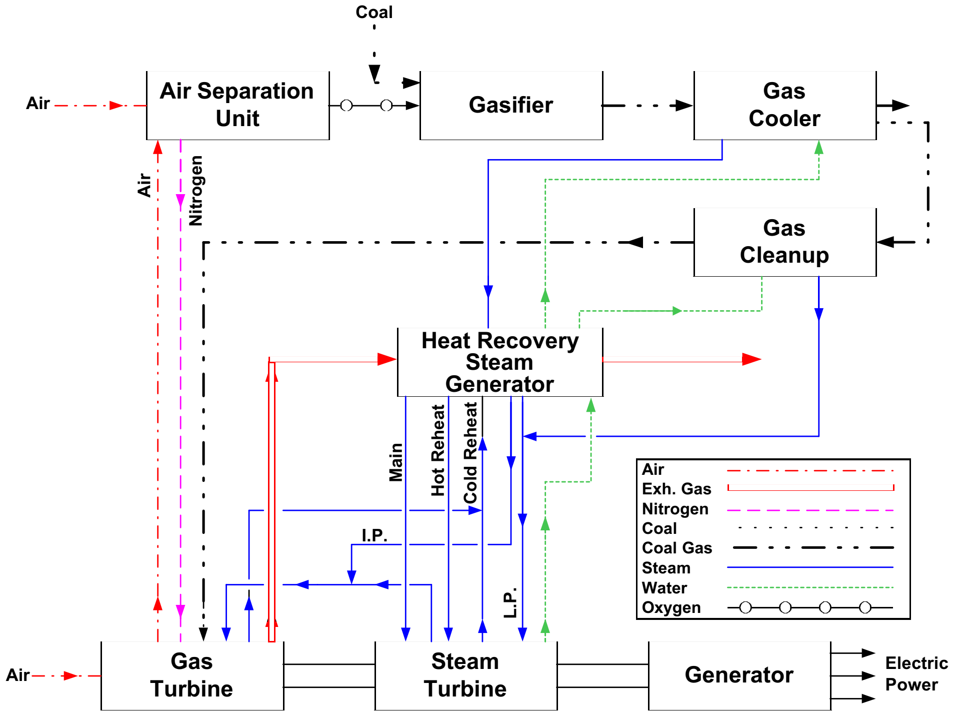


Figure 12. Unitized advanced technology IGCC system

integration of the steam cycle with the gas turbine cooling system requires appropriate consideration, but several methods for matching the cooling requirements to the existing steam cycle are available and include the following:

- The cooling steam temperature and pressure for the MS7001H and MS9001H gas turbines are in the same range as those of the cold reheat steam in many conventional steam units with 2400 psig (165 bar) throttle pressure.
- Apply cooling water and existing support facilities and replace the existing steam turbine with a modern, high efficiency steam turbine that is specifically matched to the combined-cycle requirements. This option is attractive when the use of existing water permits can minimize site permitting work.

A wide range of steam turbine ratings can be matched to the MS7001H and MS9001H gas turbines by retaining existing feedwater heaters as may be necessary to meet exhaust flow limitations.

Conclusion

The GE advanced technology combined cycles promise improved economics of electric power generation with outstanding environmental performance in natural gas and coal-fired applications. These characteristics are enhanced by the evolutionary development from a technology base with extensive experience, which assures low maintenance and reliable, convenient operation.

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