



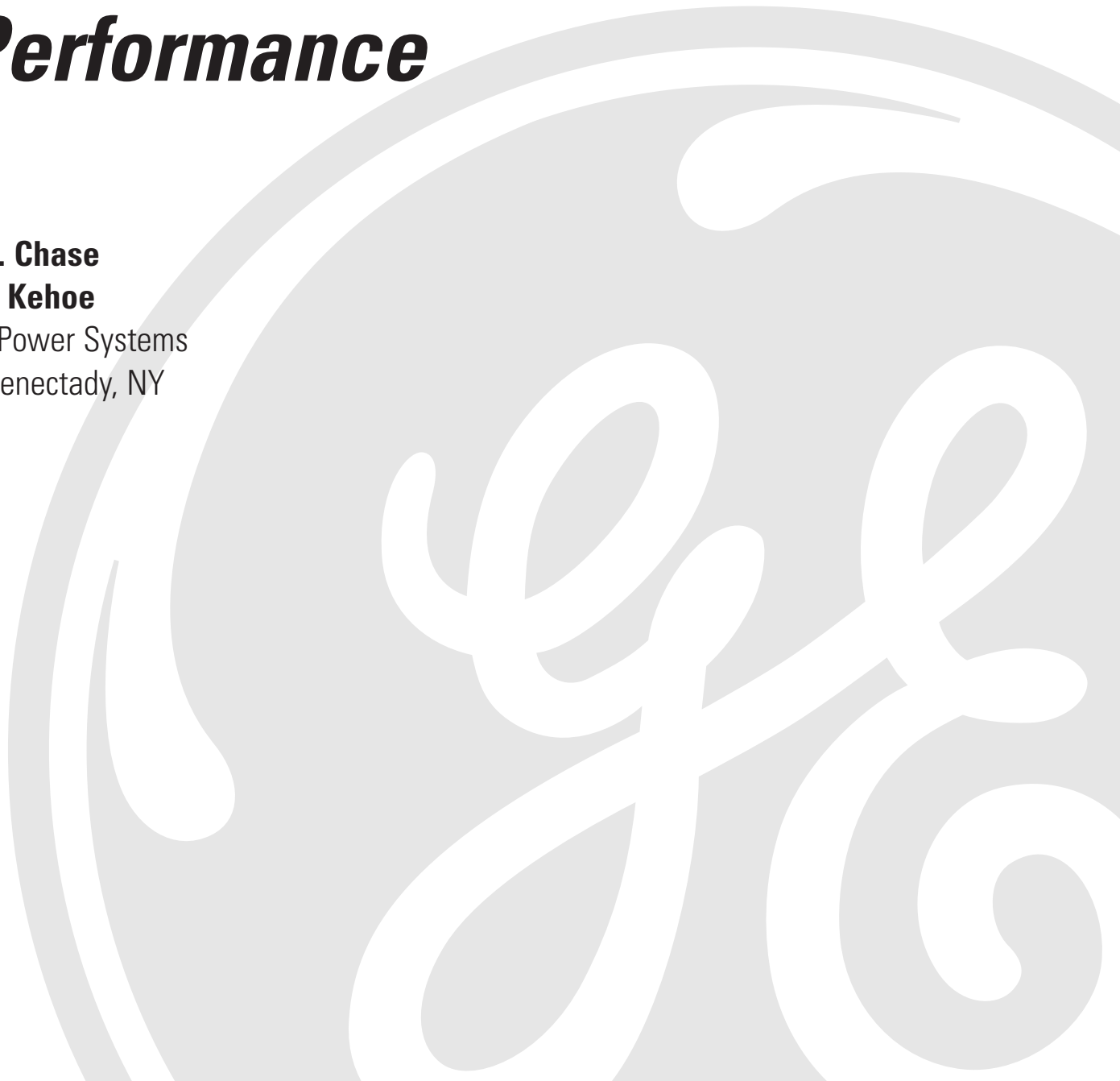
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***GE Power Systems***

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# ***GE Combined-Cycle Product Line and Performance***

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# **GE Combined-Cycle Product Line and Performance**

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# *GE Combined-Cycle Product Line and Performance*

# GE Combined-Cycle Product Line and Performance

## Introduction

The development during the past four decades of larger capacity gas turbine designs (50 MW to 380 MW) with increased specific power has led to the parallel development of highly-efficient and economical combined-cycle systems. The GE pre-engineered, combined cycle product line is designated STAG™, which is an acronym for Steam And Gas. Each STAG combined cycle system is an Engineered Equipment Package (EEP) consisting of GE gas turbines, steam turbines, generators, Heat Recovery Steam Generators (HRSGs) and controls. The most efficient of these STAG systems is configured with the GE "H" model gas turbine and is scheduled for commercial operation by the year 2003. The "H" combined cycle will achieve 60 percent (LHV) thermal efficiency.

The STAG EEP is an optimized and matched system of high technology power generation equipment, software, and services configured for convenient integration with the owner's auxiliaries and balance of plant equipment to form an economical power plant. This single source supply of the EEP enables GE to provide guarantees of plant thermal and emission performance as well as warrant system operation.

The product line spans a wide range of capabilities for both 50 and 60 Hz applications. A wide range of configurations is available with standard options that enable the systems to be adapted to suit the economic requirements of each application. The STAG combined-cycle product line includes two major categories:

- Pre-engineered oil- or natural gas-fired systems for electric power generation
- Pre-engineered building blocks for combined-cycle cogeneration systems and coal- or oil-fired integrated gasification combined-cycle (IGCC) power generation systems.

Economical performance of function is the outstanding characteristic of STAG combined-cycle systems. The features that contribute to economical power generation by STAG combined-cycle power generation systems are shown in *Table 1* and those for thermal and power systems are presented in *Table 2*.

<ul style="list-style-type: none"><li>• High Thermal Efficiency</li><li>• Low Installed Cost</li><li>• Fuel Flexibility – Wide Range of Gas and Liquid Fuels</li><li>• Low Operation and Maintenance Cost</li><li>• Operating Flexibility – Base, Mid-range, Daily Start</li><li>• High Reliability</li><li>• High Availability</li><li>• Short Installation Time</li><li>• High Efficiency in Small Capacity Increments</li></ul>
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**Table 1.** STAG combined-cycle power generation system features

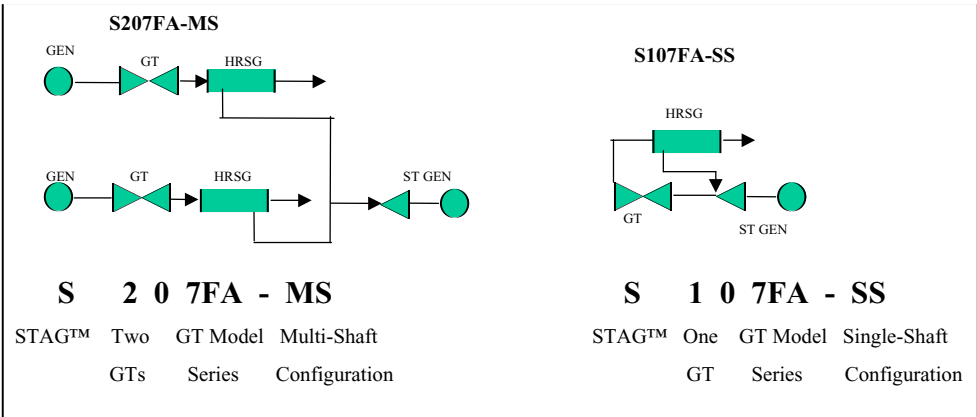
<ul style="list-style-type: none"><li>• High Thermal Efficiency</li><li>• Low Installed Cost</li><li>• Low Operation and Maintenance Costs<ul style="list-style-type: none"><li>- Steam Generation at Process Conditions</li><li>- Extraction/Condensing Steam Turbine</li><li>- Non-Condensing Turbine Exhausting to Process</li><li>- Unfired/Fired HRSGs</li><li>- Gas Turbine DLN/Steam Injection</li></ul></li><li>• High Power to Thermal Energy Ratio</li><li>• High Reliability/Availability</li><li>• Short Installation Time</li></ul>
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**Table 2.** STAG combined-cycle thermal energy and power system features

## STAG Product Line Designations

System designations that identify STAG combined-cycle product line configurations are defined in *Table 3*. This example defines the designation for the single-shaft and multi-shaft combined-cycle configurations.

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STAG IS A REGISTERED TRADEMARK OF GENERAL ELECTRIC(USA)  
AND IS AN ACRONYM FOR STeam And Gas

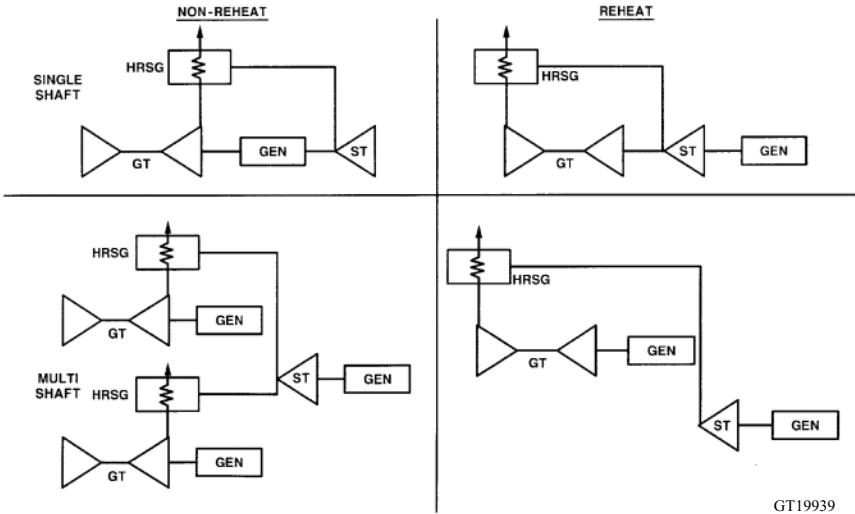
**Table 3.** STAG combined-cycle system designations

### STAG Product Line Configurations

The product line includes single-shaft and multi-shaft configurations. Simplified block diagrams of these configurations are presented in *Figure 1*. The single-shaft STAG system consists of one gas turbine, one steam turbine, one generator, and one HRSG with the gas turbine and steam turbine coupled to the single generator in a tandem arrangement on a single shaft. Multi-shaft STAG systems have one or more gas

turbine generators and HRSGs that supply steam through a common header to a separate, single steam turbine generator.

Single- and multiple-pressure non-reheat steam cycles are applied to STAG systems equipped with GE gas turbines that have rating point exhaust gas temperatures of approximately 1000°F / 538°C or less. Selection of a single- or multiple-pressure steam cycle for a specific application is determined by economic evalua-



**Figure 1.** STAG system configurations

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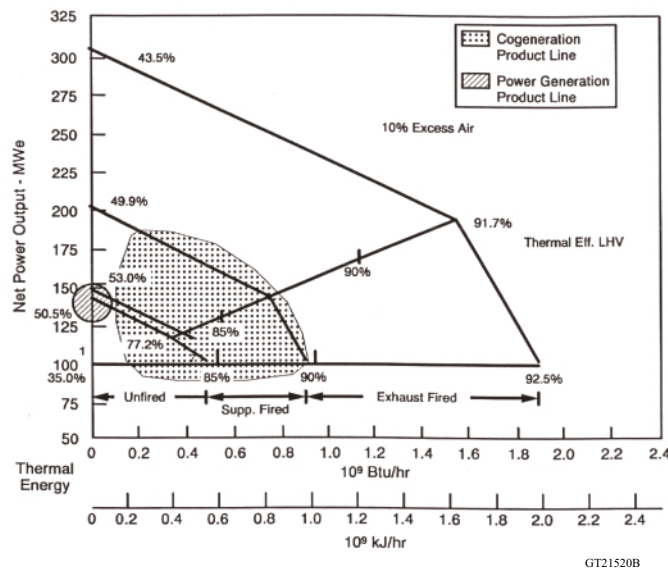
tion, which considers plant-installed cost, fuel cost and quality, plant-duty cycle, and operating and maintenance cost.

Multiple-pressure reheat steam cycles are applied to STAG systems with GE gas turbines that have rating point exhaust gas temperatures of approximately 1100°F / 593°C or greater.

A generalized combined-cycle, electric power generation and thermal energy capability map is presented in *Figure 2*. This map is typical of a system supplying process steam at 150 psig/11.4 bars and utilizing a gas turbine with 100 MW rated output.

customer specific applications in which the need for increased power offsets the corresponding reduction in thermal efficiency.

The most efficient cycles for cogeneration applications are those with fully-fired HRSGs, as indicated by *Figure 2*, at maximum thermal energy output. The fully-fired HRSGs are high in cost because of their water wall construction and need for field erection. Also, fully-fired HRSGs may add to emission considerations as plant siting requirements are evaluated. The primary regions of interest for cogeneration, combined-cycle systems are those with unfired



**Figure 2.** Generalized combined-cycle performance capability

The vertical axis of *Figure 2* with zero thermal energy shows the power and thermal efficiency of combined cycles with unfired, supplementary-fired, and fully-fired steam cycles. The most efficient power generation cycles are those with unfired HRSGs having modular pre-engineered components. These unfired steam cycles are also the lowest in cost and are, therefore, applied in the STAG combined-cycle power generation product line. Supplementary-fired combined-cycle systems are provided for cus-

and supplementary-fired steam cycles. These systems provide a wide range of thermal energy to electric power ratio, 0–12,000 Btu thermal energy per kW (0–12,660 kJ per kW), and represent the range of thermal energy capability and power generation covered by the product line for cogeneration capability.

## **STAG Power Generation Product Line**

The STAG power generation product line includes an array of steam cycle options, which

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satisfies a wide range of fuels, fuel cost, duty cycle, and other economic considerations. This enables selection of a steam cycle for each application that suits specific economic and operational requirements. Steam cycles utilized in the STAG product line include:

- Single-Pressure, Non-Reheat Heat Recovery Feedwater Heating.** This steam cycle, shown in *Figure 3*, has an unfired HRSG with finned tube superheater, evaporator, and

economizer sections. Energy is recovered from the exhaust gas by convective heat transfer. The HRSG schematic diagram is shown in *Figure 4*. This is the simplest steam cycle that can be applied in a combined cycle and it has been used extensively. It results in a low installed cost. Although it does not produce the highest combined-cycle thermal efficiency, it is a sound economic

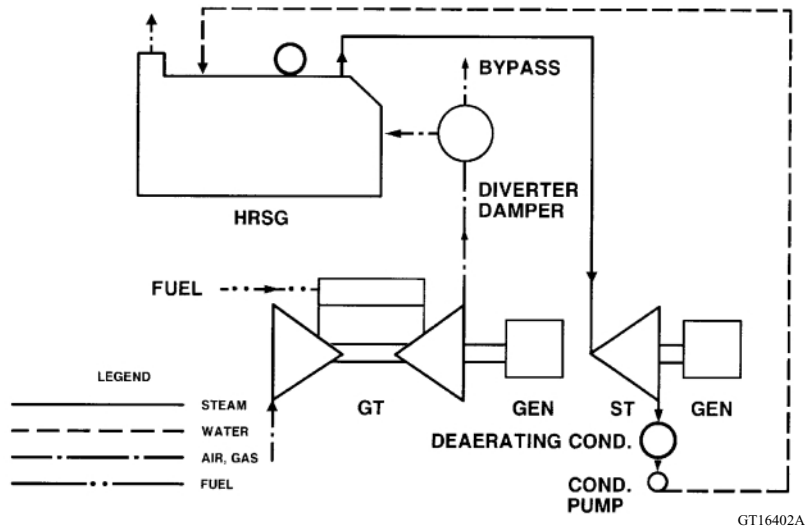


Figure 3. Single-pressure non-reheat cycle diagram

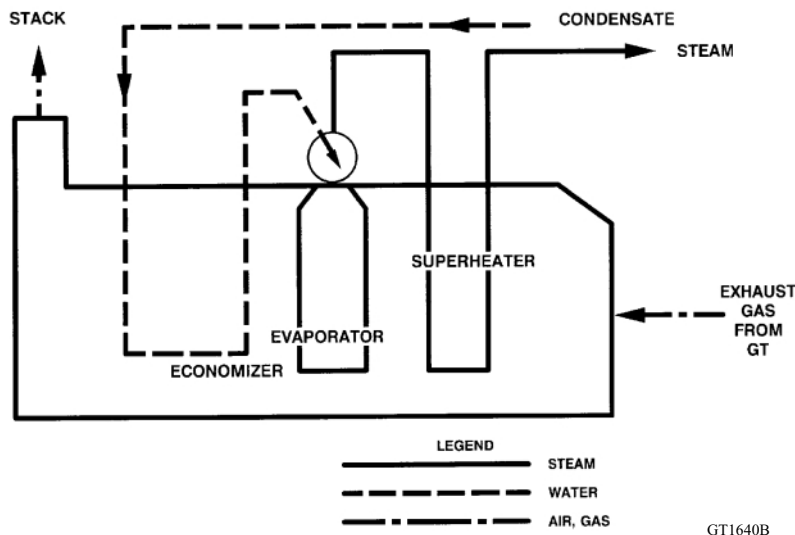


Figure 4. Single-pressure non-reheat HRSG diagram

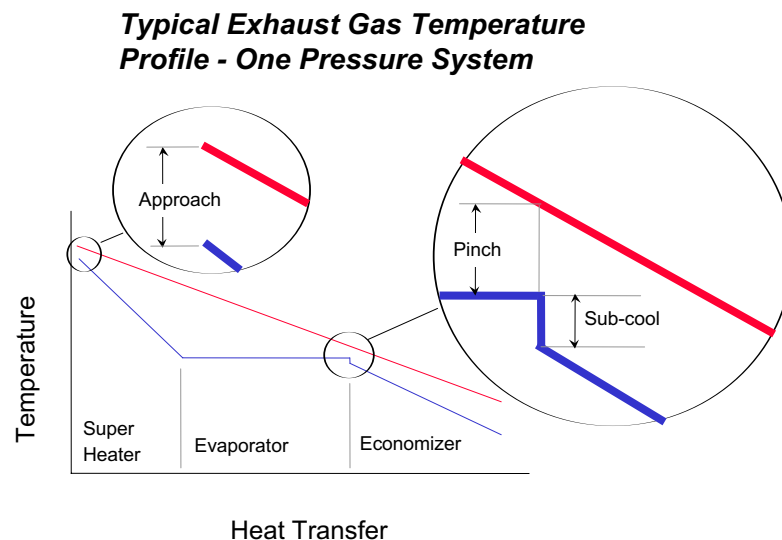


selection when fuel is inexpensive, when applied in peaking type service, or when burning ash-bearing fuel with high sulfur content. This steam cycle is utilized in the STAG product line primarily with GE gas turbines having a baseload exhaust gas temperature of approximately 1000°F / 538°C or less. The HRSG stack gas temperature with this steam cycle is approximately 340°F / 171°C.

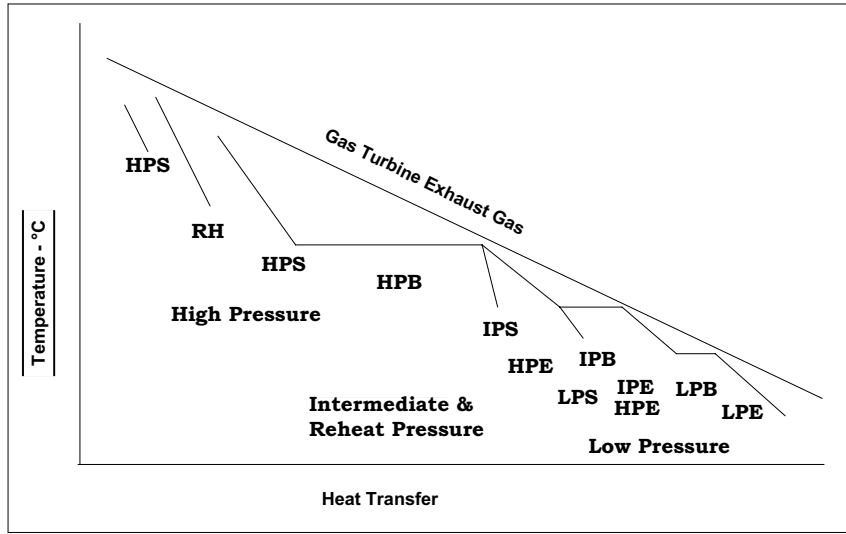
■ **Multiple-Pressure, Non-Reheat Heat Recovery / Feedwater Heating.** Multi-pressure steam generation is used to maximize energy recovery from gas turbine exhaust. HRSG gas-side and steam-side temperature profiles for single- and multiple-pressure steam cycles are presented in *Figures 5 and 6*. This illustrates that increasing the number of steam pressure levels reduces the exhaust gas and steam/water energy difference. Two- or three-pressure steam cycles achieve better efficiency than the single-pressure systems, but their installed

cost is higher. They are the economic choice when fuel is expensive or if the duty cycle requires a high load factor. The three-pressure steam cycle is shown in *Figure 7* and the HRSG schematic diagram is shown in *Figure 8*. This cycle is similar to the single-pressure cycle with the addition of the low-pressure and intermediate-pressure sections. Improved plant performance with multiple-pressure steam cycles results from additional heat transfer surface installed in the HRSG. The HRSG stack gas temperature is in the range of 200°F / 93°C to 260°F / 127°C.

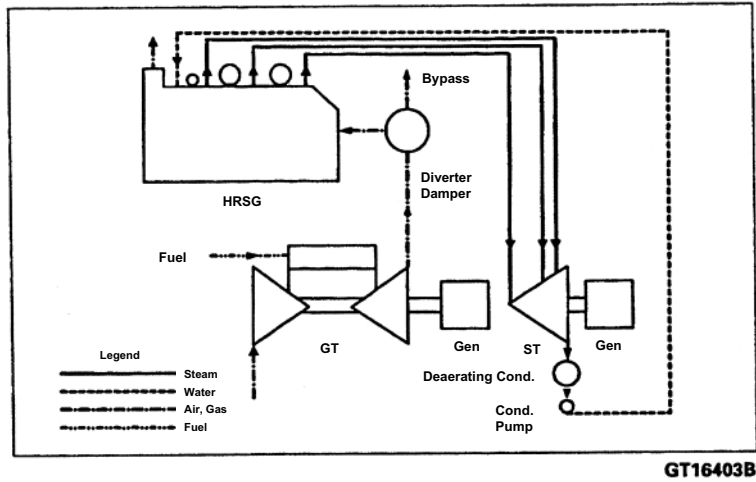
■ **Three-Pressure, Reheat Heat Recovery Feedwater Heating.** The reheat steam cycle matches the characteristics of the “EC,” “F,” and “H” technology gas turbines. The higher exhaust gas temperature of 1100°F / 593°C or greater provides sufficient high temperature energy to the HRSG to make the reheat steam cycle practical. Fuel gas heating to approximately



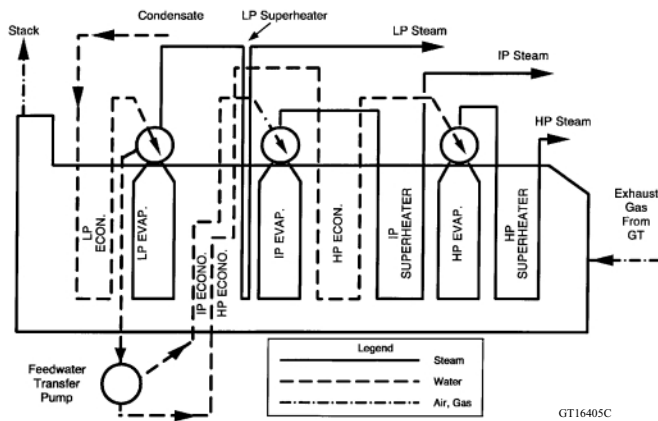
**Figure 5.** Typical exhaust gas/steam cycle temperature profile for single-pressure system



**Figure 6.** Typical exhaust gas/steam cycle temperature profile for three-pressure system



**Figure 7.** Three-pressure non-reheat cycle diagram

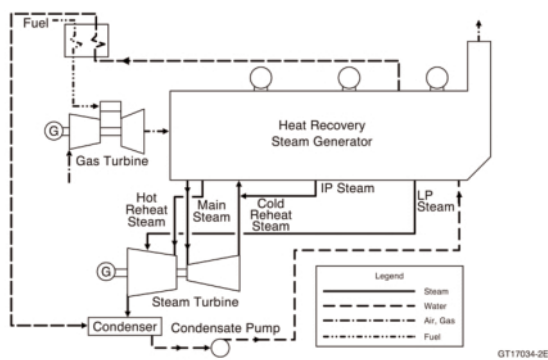


**Figure 8.** Three-pressure non-reheat HRSG diagram

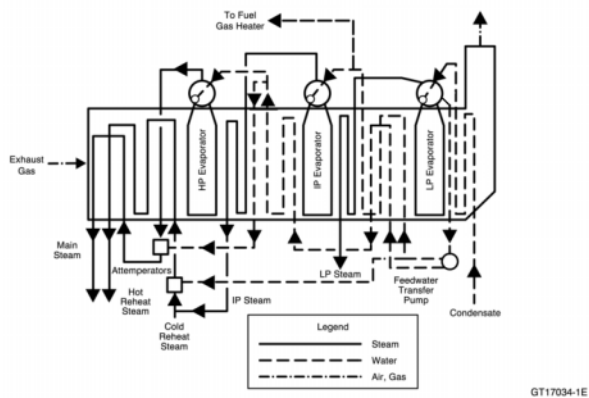
# GE Combined-Cycle Product Line and Performance

365°F / 185°C, using water supplied from the HRSG IP economizer discharge, is also included with the “EC” and “F” technology gas turbines. This steam cycle is shown in *Figure 9*. The HRSG schematic is presented in *Figure 10*.

The “H” platform gas turbines, configured with hot gas path components cooled with both a



**Figure 9.** Three-pressure reheat cycle diagram



**Figure 10.** Three-pressure reheat HRSG diagram

closed-loop, steam-cooling system and an open-loop, air-cooling system design, are designated as MS7001H and MS9001H. The reheat steam cycle utilized with these gas turbines is closely integrated with the gas turbine steam-cooling

system. This integration provides additional incentive to select single-shaft STAG configuration for these gas turbines. The steam cycle used with the S107H and S109H is shown in *Figure 11*. The HRSG schematic is shown in *Figure 12*.

These STAG combined-cycle systems are the most efficient power generation systems currently available. The base configuration for the

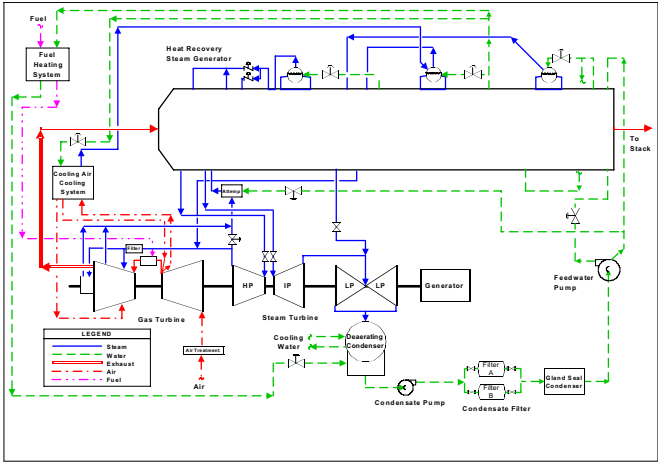
- Unfired, three-pressure steam cycle
  - Non-reheat for rated exhaust gas temperature less than 1000°F/538°C
  - Reheat for rated exhaust gas temperature higher than 1050°F/566°C and fuel heating
  - Heat recovery feedwater heating
  - Feedwater deaeration in condenser
  - Natural circulation HRSG evaporators
- Gas turbine with Dry Low NO<sub>x</sub> combustors
- Once-through condenser cooling water system
- Multi-shaft systems
- Single-shaft systems
  - Integrated equipment and control system

**Table 4.** STAG power generation combined-cycle base configuration

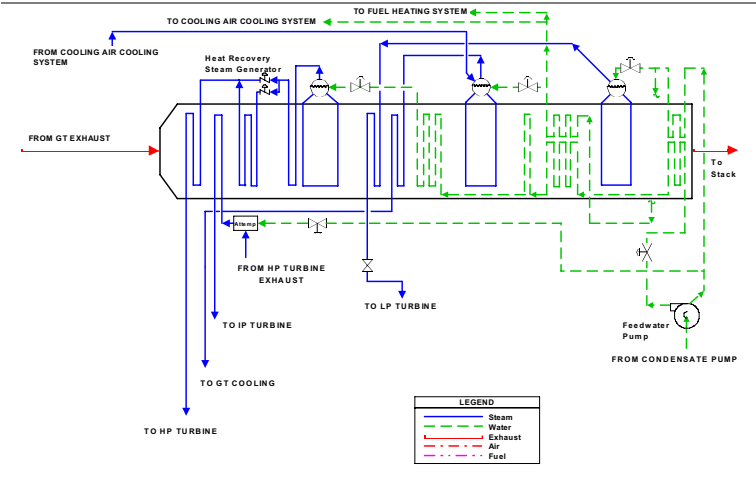
STAG power generation combined-cycle product line is designed for high efficiency when firing natural gas or distillate fuel. A summary of the equipment and system configuration is presented in *Table 4*.

The 60 Hz STAG power generation product line ratings are presented in *Table 5*. *Table 6* shows the major equipment in each standard STAG system. The 50 Hz product line ratings are presented in *Table 7*, and *Table 8* shows the major equipment in each of these standard STAG systems. These ratings are presented for gas turbine base load operation with natural gas fuel. Nominal throttle and reheat steam conditions for the non-reheat and reheat STAG product lines are defined in *Table 9*.

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**Figure 11.** STAG 107H/S109H cycle diagram



**Figure 12.** HRSG schematic for S107H/S109H

The STAG product line equipment and plant natural gas fuel ratings defined in *Tables 5 and 7* represent thermodynamic optimum performance that is expected to be the economic optimum configuration for baseload and mid-range dispatch using clean fuels costing about \$2.50 per 10<sup>6</sup> Btu, HHV (\$2.64 per 10<sup>6</sup> KJ, HHV). A wide array of options is available for the STAG power generation product line to suit specific economic criteria as well as the operating and installation preferences of the owner. *Table 10* lists the most commonly-applied options in addition to the base configuration.

Non-reheat steam cycles with one or two pres-

ures and reheat steam cycles with two pressures are also available for the STAG product-line systems. Typical performance variation for these optional steam cycles is presented in *Table 11*. HRSGs with forced circulation evaporators are available to suit specific installation situations and owner preferences. *Figure 13* shows a two-pressure, non-reheat steam cycle with forced circulation HRSG.

Systems can be provided with a deaerator integral to the HRSG that utilizes low-pressure evaporator energy to perform the feedwater deaeration at positive pressure at a small reduction in thermal efficiency. Those systems that include a

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Combined cycle Designation	Net Plant Power (MW)	Net Plant Heat Rate(LHV)		Thermal Efficiency (% LHV)
		Btu/kWhr	kJ/kWhr	
S106B (4)	64.3	6960	7340	49.0
S206B (4)	130.7	6850	7230	49.8
S406B (4)	261.3	6850	7230	49.8
S106FA (5)	107.1	6440	6795	53.0
S206FA (5)	217.0	6355	6705	53.7
S107EA (4)	130.2	6800	7175	50.2
S207EA (4)	263.6	6700	7070	50.9
S107FA (5)	262.6	6090	6425	56.0
S207FA (5)	529.9	6040	6375	56.5
S107FB (5)	280.3	5950	6280	57.3
S207FB (5)	562.5	5940	6260	57.5
S107H (6)	400.0	5690	6000	60.0

Notes: 1. Site conditions =59 F, 14.7 psia, 60% RH (15 C, 1.013 bar)  
2. Steam turbine exhaust pressure = 1.2 inches Hg,A (30.48 mm Hg,A)  
3. Performance is net plant with allowance for equipment and plant auxiliaries including those associated with a once-through cooling water system  
4. Three-pressure, non-reheat, heat-recovery feedwater heating steam cycle  
5. Three-pressure, reheat, heat-recovery feedwater heating steam cycle with integrated fuel, gas-heating system  
6. Three-pressure, reheat, heat-recovery feedwater heating steam cycle with integrated turbine steam- and air-cooling and fuel-heating systems

**Table 5.** 60 Hz STAG product line performance

Designation	Gas Turbine		No.	HRSG Type	Exhaust No.	Steam Turbine LSB		Exhaust Config.
	No.	Frame				Inches	mm	
• Heavy Duty GT								
S106B	1	PG6581 B	1	Non-Reheat, Unfired	1	23	584	Axial
S206B	2	PG6581 B	1	Non-Reheat, Unfired	1	33.5	851	Axial
S406B	4	PG6581 B	2	Non-Reheat, Unfired	2	33.5	851	Down
S106FA	1	PG6101 FA	1	Reheat, Unfired	1	30	762	Axial
S206FA	2	PG6101 FA	1	Reheat, Unfired	2	30	762	Down
S107EA	1	PG7121 EA	1	Non-Reheat, Unfired	1	33.5	851	Axial
S207EA	2	PG7121 EA	2	Non-Reheat, Unfired	2	33.5	851	Down
S107FA	1	PG7241 FA	1	Reheat, Unfired	2	30	762	Down
S207FA	2	PG7241 FA	2	Reheat, Unfired	4	30	762	Down
S107FB	1	PG7251 FB	1	Reheat, Unfired	2	30	762	Down
S207FB	2	PG7251 FB	2	Reheat, Unfired	4	30	762	Down
S107H	1	PG7001 H	1	Reheat, Unfired	2	40	1016	Down

**Table 6.** 60 Hz STAG product line equipment

low-pressure economizer for high thermal efficiency will require material that resists corrosion because feedwater passing through this section may have a high oxygen concentration, and the external tube surface temperature may be below the exhaust gas dew point temperature. *Figure 14* shows a three-pressure non-reheat HRSG with integral deaerator.

Fuel characteristics affect combined-cycle performance in a variety of ways. High hydrogen content in fuels such as natural gas results in

high water content in the combustion products. Water has a higher heat content than air or other combustion products, so fuels with high hydrogen content increase output and efficiency. Ash-bearing fuels foul the gas turbine and HRSG; therefore, equipment and system design considerations that accept fouling reduce plant output and efficiency. Sulfur content in the fuel may require adjustment in the temperature of the stack gas and the water entering the HRSG economizer to prevent condensation of corrosive sul-

# GE Combined-Cycle Product Line and Performance

Combined cycle Designation	Net Plant Power (MW)	Net Plant Heat Rate (LHV)		Thermal Efficiency (% LHV)	
		Btu/kWhr	kJ/kWhr		
S106B	(4)	64.3	6950	7340	49.0
S206B	(4)	130.7	6850	7230	49.8
S406B	(5)	261.3	6850	7230	49.8
S106FA	(5)	107.4	6420	6775	53.2
S206FA	(4)	218.7	6305	6650	54.1
S109E	(4)	189.2	6570	6935	52.0
S209E	(4)	383.7	6480	6840	52.7
S109EC	(5)	259.3	6315	6660	54.0
S209EC	(5)	522.6	6270	6615	54.4
S109FA	(5)	390.8	6020	6350	56.7
S209FA	(5)	786.9	5980	6305	57.1
S109H	(6)	480.0	5690	6000	60.0

Notes: 1. Site conditions = 59 F, 14.7 psia, 60% RH (15 C), 1.013 bar  
2. Steam turbine exhaust pressure = 1.2 Inches HgA (30.48 mm HgA)  
3. Performance is net plant with allowance for equipment and plant auxiliaries including those associated with a once-through cooling water system  
4. Three-pressure, non-reheat, heat recovery feedwater heating steam cycle  
5. Three-pressure, reheat, heat-recovery feedwater heating steam cycle with integrated fuel gas heating system  
6. Three-pressure, reheat, heat-recovery feedwater heating steam cycle with integrated turbine steam and air cooling and fuel heating systems.

**Table 7.** 50 Hz STAG product line performance

Designation	Gas Turbine		HRSG		Exhaust No.	Steam Turbine LSB		Exhaust Config.
	No.	Frame	No.	Type		Inches	mm	
• <i>Heavy Duty GT</i>								
S106B	1	PG6581 B	1	Non-Reheat, Unfired	1	17	432	Axial
S206B	2	PG6581 B	1	Non-Reheat, Unfired	1	33.5	851	Axial
S406B	4	PG6581 B	2	Non-Reheat, Unfired	2	33.5	851	Down
S106FA	1	PG6101 FA	1	Reheat, Unfired	1	26	660	Axial
S206FA	2	PG6101 FA	2	Reheat, Unfired	1	42	1066	Axial
S109E	1	PG9171 E	1	Non-Reheat, Unfired	1	42	1066	Down
S209E	2	PG9171 E	2	Non-Reheat, Unfired	2	42	1066	Down
S109EC	1	PG9231 EC	1	Reheat, Unfired	1	42	1066	Down
S209EC	2	PG9231 EC	2	Reheat, Unfired	2	42	1066	Down
S109FA	1	PG9351 FA	1	Reheat, Unfired	2	33.5	851	Down
S209FA	2	PG9351 FA	2	Reheat, Unfired	4	33.5	851	Down
S109H	1	PG9001 H	1	Reheat, Unfired	2	42	1066	Down

**Table 8.** 50 Hz STAG product line equipment

furic acid. The increased stack gas temperature required by higher sulfur content decreases output and efficiency. Performance variation with fuel type (hydrogen, ash and sulfur content typical of each) is presented in *Table 12*.

The STAG product line includes gas turbines with Dry Low NO<sub>x</sub> (DLN) combustors that can operate with stack gas NO<sub>x</sub> emission concentration as low as 9 ppmvd at 15% oxygen (15.5 g/GJ) without water or steam injection, when operating on natural gas fuel. Water or steam injection may be required to meet NO<sub>x</sub> emission requirements when operating on distillate oil fuel. Also, gas turbines are available with

conventional, diffusion flame combustors operating with water or steam injection to meet NO<sub>x</sub> emission limits. *Table 13* presents stack gas NO<sub>x</sub> emissions from gas turbines in typical STAG combined cycle systems for operation with DLN or diffusion flame combustors with natural gas fuel. The effect of water- or steam-injection on NO<sub>x</sub> abatement and thermal performance is also presented.

Selective catalytic reduction (SCR) is a stack gas NO<sub>x</sub> reduction system that uses ammonia to react with NO<sub>x</sub> over a catalyst that reduces NO<sub>x</sub> to nitrogen and water. These systems increase the plant installation and operating cost, but

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Heat Recovery Feedwater Heater Steam Cycle Steam Turbine Size (MW)	Non-Reheat Three-Pressure			Reheat Three-Pressure
	≤ 40	>40 <60	≥ 60	> 60
Throttle Pressure (psig) (Kg/cm <sup>2</sup> .g)	820 (58)	960 (68)	1200 (84)	1400-1800 (98)
Throttle Temperature (°F) (°C)	40 Approach to Gas Turbine (22) Exhaust Gas Temperature			1000-1050 (538-566)
Reheat Pressure (psig) (Kg/cm <sup>2</sup> .g)	--	--	--	300-400 (21-28)
Reheat Temperature (°F) (°C)	--	--	--	1000-1050 (538-566)
IP Admission Pressure (psig) (Kg/cm <sup>2</sup> .g)	100 (7)	120 (8)	155 (11)	300-400 (21-28)
IP Admission Temperature (°F) (°C)	20 Approach to Exhaust Gas Temperature (11) Upstream of Superheater			
LP Admission Pressure (psig) (Kg/cm <sup>2</sup> .g)	25 (1.8)	25 (1.8)	25 (1.8)	40 (2.8)
LP Admission Temperature (°F) (°C)	20 Approach to Exhaust Gas Temperature (11) Upstream of Superheater			

**Table 9.** STAG product line steam turbine throttle and admission steam conditions

they can reduce NO<sub>x</sub> to less than 9 ppmvd at 15% oxygen (15.5 g/GJ) for all combined-cycle systems in the product line. The SCR catalyst typically operates in the 570°F/300°C to 750°F/400°C temperature range, so the catalyst is typically installed within the high-pressure evaporator as shown in *Figure 15*. The ammonia injection grid is installed upstream of the evaporator where the gas temperature is below the temperature at which ammonia oxidizes to form NO<sub>x</sub>. This provides intimate mixing of the ammonia and NO<sub>x</sub> as the gas passes through the pre-evaporator section.

Carbon monoxide (CO) emissions are low at gas turbine loads above 50%, typically less than

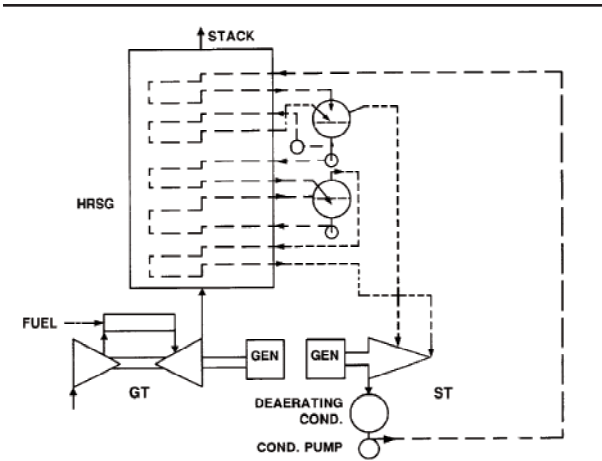
<b>STEAM CYCLE</b> <ul style="list-style-type: none"> <li>• Single pressure</li> <li>• Two pressure</li> <li>• <b>Three pressure*</b></li> <li>• Reheat</li> <li>• Non-reheat</li> </ul> <b>DEAERATION</b> <ul style="list-style-type: none"> <li>• <b>Deaerating condenser*</b></li> <li>• Deaerator/evaporator integral with HRSG</li> </ul> <b>HRSG DESIGN</b> <ul style="list-style-type: none"> <li>• <b>Natural circulation evaporators*</b></li> <li>• Forced circulation evaporators</li> <li>• <b>Unfired*</b></li> <li>• Supplementary fired</li> </ul>	<b>NO<sub>x</sub> CONTROL</b> <ul style="list-style-type: none"> <li>• Water injection</li> <li>• Steam injection</li> <li>• SCR (NO<sub>x</sub> and/or CO)</li> <li>• <b>Dry Low NO<sub>x</sub> combustion*</b></li> </ul> <b>CONDENSER</b> <ul style="list-style-type: none"> <li>• <b>Water cooled (once-through system)*</b></li> <li>• Water cooled (evaporative cooling tower)</li> <li>• Air-cooled condenser</li> </ul> <b>FUEL</b> <ul style="list-style-type: none"> <li>• <b>Natural gas*</b></li> <li>• Distillate oil</li> <li>• Ash bearing oil</li> <li>• Low BTU coal and oil-derived gas</li> <li>• Multiple fuel systems</li> </ul>
* Base configuration	

**Table 10.** Power generation combined-cycle product line system options

STAG 207EA		
<b>STEAM CYCLE</b>	<b>NET PLANT OUTPUT (%)</b>	<b>NET PLANT THERMAL EFFICIENCY (%)</b>
<b>THREE PRESSURE, REHEAT</b>	+0.7	+0.7
<b>THREE PRESSURE, NON-REHEAT</b>	BASE	BASE
<b>TWO PRESSURE, NON-REHEAT</b>	-1.0	-1.0
<b>SINGLE PRESSURE, NON-REHEAT</b>	-4.7	-4.7
STAG 107EA		
<b>STEAM CYCLE</b>	<b>NET PLANT OUTPUT (%)</b>	<b>NET PLANT THERMAL EFFICIENCY (%)</b>
<b>THREE PRESSURE, REHEAT</b>	BASE	BASE
<b>TWO PRESSURE, REHEAT</b>	-1.1	-1.1
<b>THREE PRESSURE, NON-REHEAT</b>	-1.2	-1.2
<b>TWO PRESSURE, NON-REHEAT</b>	-2.0	-2.0

**Table 11.** Performance variation with steam cycle

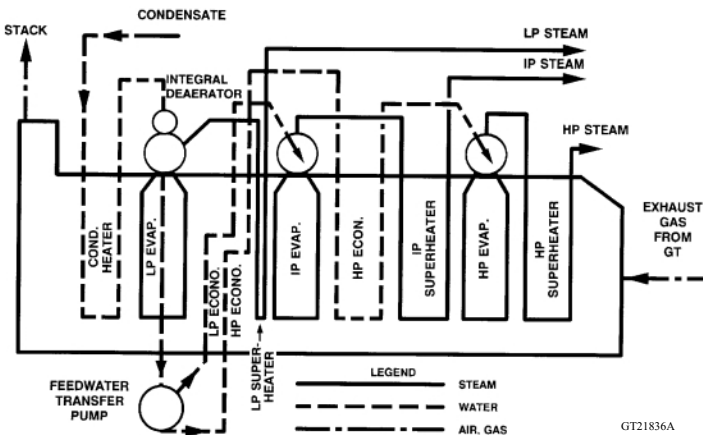
# GE Combined-Cycle Product Line and Performance



**Figure 13.** Two-pressure non-reheat steam cycle with forced circulation HRSG

5–25 ppmvd (9-43 g/GJ). Low CO emissions are the result of highly-efficient combustion. Catalytic CO emission abatement systems are also available, if required, for lower emission rates. The CO catalyst is installed in the exhaust gas path, typically upstream of the HRSG superheater.

Options such as compressor inlet cooling, steam or water injection for power augmentation, HRSG supplementary firing and gas turbine peak load capabilities are available for combined-cycle plant power enhancements. They are generally applied primarily for peak period capacity additions.



**Figure 14.** Three-pressure non-reheat HRSG with integral deaerator

**STAG 209E**

FUEL	NET PLANT OUTPUT (%)	NET PLANT THERMAL EFFICIENCY (%)
NATURAL GAS	BASE	BASE
DISTILLATE OIL	-3.0	-2.1
RESIDUAL OIL	-9.3	-7.6

- NOTES**
1. OPERATING POINT = BASE LOAD
  2. TWO PRESSURE, NON-REHEAT RECOVERY FEEDWATER HEATING SYSTEM CYCLE

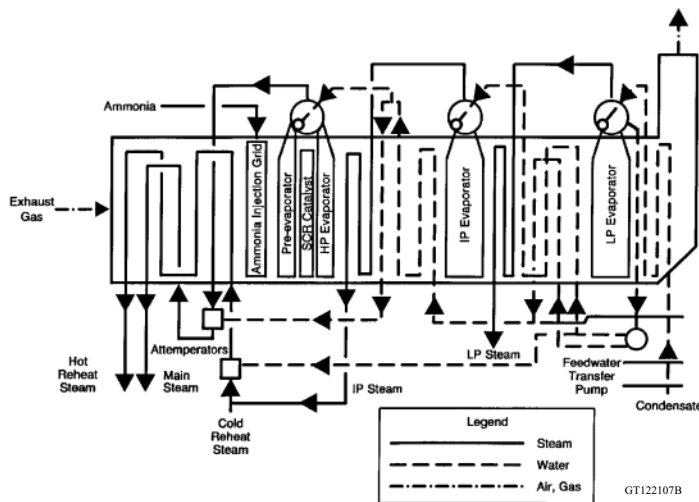
**Table 12.** STAG combined-cycle performance variation with fuel characteristics



# GE Combined-Cycle Product Line and Performance

Gas Turbine	MS7001EA						MS7001FA			
Combustion System	DLN	Diffusion Flame				DLN	Diffusion Flame			
NOx PMVD at 15% O2 (g/GJ)	9 (15.5)	160 (275)	42 (72)	25 (43)	25 (43)	9 (15.5)	212 (365)	42 (72)	42 (72)	
Diluent Injection Water/Fuel by Wt	0	0	0.81	-	1.04	-	0	0	0.89	-
Steam/Fuel by Wt	0	0	-	1.22	-	1.58	0	0	-	1.62
STAG Plant Performance										
Net Power ( $\Delta\%$ )	Base	Base	+3.5	+1.0	+5.0	+1.1	Base	Base	+5.4	+2.8
Net Heat Rate ( $\Delta\%$ )	Base	Base	+3.6	+2.1	+5.2	+3.4	Base	Base	+3.9	+3.1
Steam Cycle	Non-Reheat, Three Pressure						Reheat, Three Pressure			
Notes:	1. Site Conditions 59°F, 14.7 psia, 60% RH (15°C, 1.013 bars) 2. Fuel – Natural Gas									

**Table 13.** Effect of NO<sub>x</sub> control on combined-cycle performance



**Figure 15.** Three-pressure reheat HRSG with SCR

Compressor inlet cooling that uses evaporative cooling is an effective means of adding plant capacity for applications with high ambient air temperature and low relative humidity. An 85% effectiveness evaporative cooler is expected to increase plant output by about 5% during operation at 90°F / 32°C and 30% relative humidity site conditions.

Evaporative and mechanical chiller systems may be used to cool gas turbine inlet air to as low as 45°F / 7°C. These inlet cooling systems can

achieve up to 11% capacity increase during operation at site conditions of 90°F / 32°C and 30% relative humidity. Evaporative cooling and chilling systems do not improve combined-cycle plant efficiency; however, they may provide economic peak power addition during warm summer periods.

Supplementary firing of the HRSG can be utilized to increase steam turbine capability by as much as 100%. This will increase plant capacity by about 25%. Cogeneration of power and

# GE Combined-Cycle Product Line and Performance

process energy is usually the incentive for HRSG supplementary firing; however, peaking capacity credits, or leveling fuel consumption over the ambient temperature range to accommodate “take-or-pay” fuel contracts may also justify this option. The incremental efficiency for power produced by supplemental firing is in the 34–36% range based on the lower heating value of the fuel.

While gas turbine water or steam injection can be applied to enhance plant output as well as reduce NO<sub>x</sub> emissions, plant efficiency is degraded.

Gas turbine peak load capability is available with many gas turbine configurations and can add 3–10% combined-cycle plant capacity. This may be the most economic approach to small capacity additions for short periods of time because peak load operation significantly impacts gas turbine parts life and maintenance cost. *Table 14* summarizes the performance impact of these combined-cycle power enhancement options.

Combined-cycle systems can be integrated with gasification systems to form efficient coal- or oil-

fired power plants with outstanding environmental performance. The standard modules in the STAG combined-cycle product line can be readily adapted to integrated gasification combined cycles (IGCCs).

*Figure 16* shows a diagram of an advanced technology “H” platform combined-cycle IGCC system with oxygen-blown gasifier and integration of the air separation unit with the gas turbine. This advanced technology IGCC system promises to be an economical power generation system that can fire coal, petroleum coke, heavy residual oil and other solid or low-grade liquid fuels. The range of ratings for the advanced technology IGCC plants is as follows:

IGCC Unit	Frequency (Hz)	Capacity Range (MW)	Net LHV Thermal Eff. Range (LHV)
STAG 107H	60	400-460	49-51 %
STAG 109H	50	480-550	49-51 %

The capacities and efficiencies are shown as ranges because they vary with the type of gasifiers, gas clean-up systems, air and steam cycle integration, coal or other fuel analysis, and fuel moisture content.

Power Enhancement Option	Typical Performance Impact	
	Δ Output	Δ Heat Rate
Base Configuration	Base	Base
Evaporative Cooling GT Inlet Air (85% Effective Cooler)	+5.2%	-
Chill GT Inlet Air to 45°F	+10.7%	+1.6%
GT Peak Load	+5.2%	-1.0%
GT Steam Injection (5% of GT Air Flow)	+3.4%	+4.2%
GT Water Injection (2.9% of GT Air Flow)	+5.9%	+4.8%
HRSG Supplementary Firing	+28%	+9%

Notes: 1. Site Conditions = 90°F, 30% RH  
 2. Fuel = Natural Gas  
 3. Three Pressure, Reheat Steam Cycle

**Table 14.** STAG system power enhancement options

## STAG Combined-Cycle Major Equipment

The major equipment for STAG combined-cycle electric power generation systems includes the line of packaged gas turbine power generation units, unfired HRSGs, steam turbine-generators, and controls. This is a line of proven, reliable equipment with excellent performance characteristics for combined-cycle systems. This equipment includes gas turbine generators and steam turbine generators manufactured by GE as well as HRSGs and controls selected to form a coordinated combined-cycle system for each application. Features of the major equipment that are significant for efficient, reliable combined-cycle systems are presented in the following discussion.

FA gas turbine is shown in *Figure 18*, which is typical of the GE gas turbines with 2420°F / 1327°C firing temperature, including the PG7241FA.

The next generation “FB” and “H” platform gas turbines are expected to be in commercial service in the first half of this decade. The cross-section of the “H” gas turbine is shown in *Figure 19*. This new machine features closed-loop steam cooling for the first and second stages of its four-stage turbine. In order to optimize performance at the 2600°F / 1426°C firing temperature, a higher-pressure ratio compressor derived from the GE CF680C2 aircraft engine is utilized.

These gas turbines have the following features that uniquely suit them for combined-cycle applications:

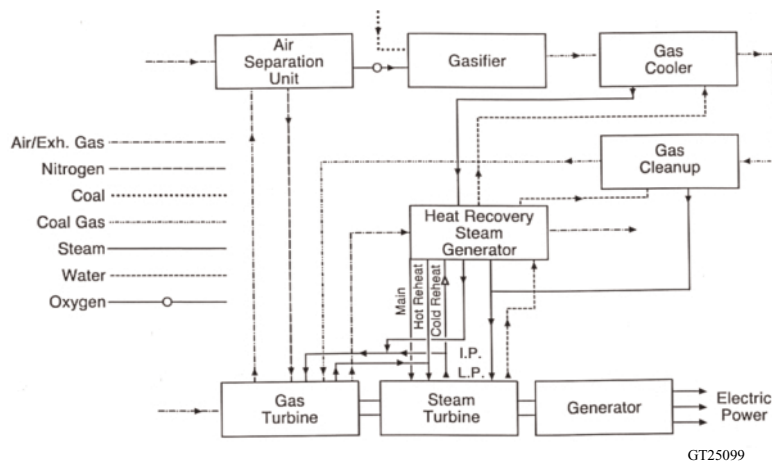


Figure 16. Advanced technology IGCC system

## Gas Turbines

The ratings of GE gas turbines applied in the STAG combined-cycle product line are presented in *Table 15*. *Figure 17* shows a cross-section of the PG7121EA gas turbine typical of GE gas turbines with 2035°F / 1113°C firing temperature. The PG9171E gas turbine firing temperature is 2055°F / 1124°C. A cross-section of the PG9351

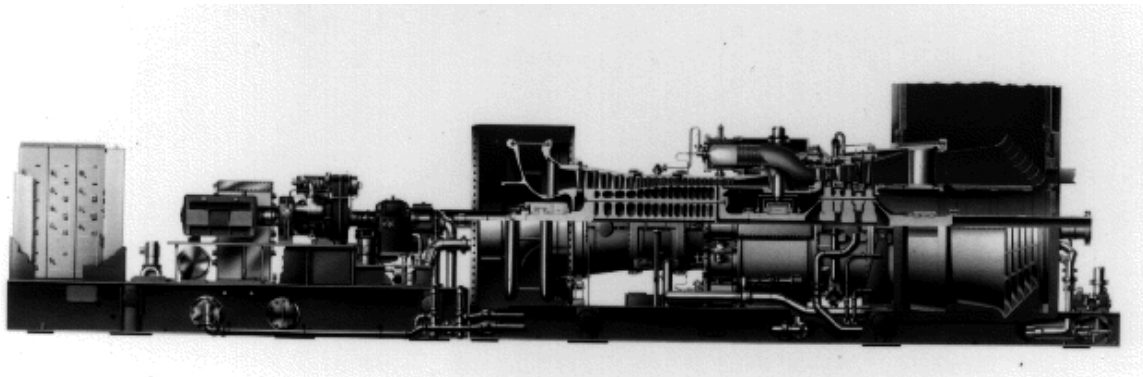
- The key performance characteristic of the gas turbine that influences combined-cycle performance is specific power. Specific power is the power produced by the gas turbine per unit of airflow (kW output per lb/sec of compressor airflow). Combined-cycle thermal efficiency

# GE Combined-Cycle Product Line and Performance

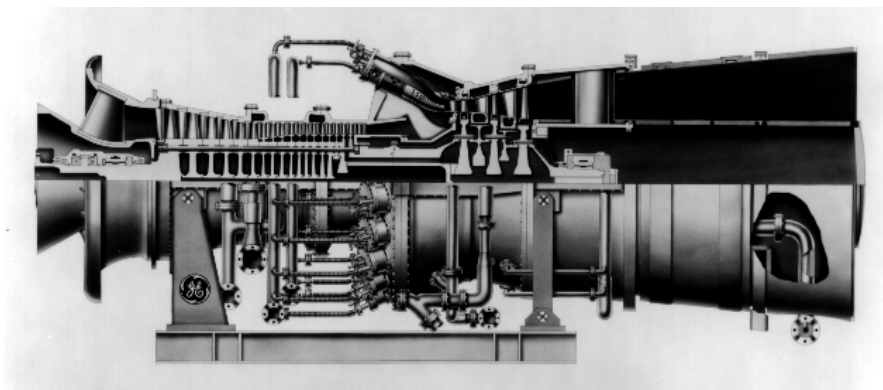
<u>Heavy-Duty</u>	<u>Output (kW)</u>	<u>Frequency (Hz)</u>
PG6581 B	42,100	50 and 60
PG6101 FA	70,140	50 and 60
PG7121 EA	85,400	60
PG7241 FA	171,700	60
PG9171 E	123,400	50
PG9231 EC	169,000	50
PG7251 FB	184,400	60
PG9351 FA	255,600	60
MS7001 H	*	60
MS9001 H	*	50

Notes: 1. Fuel = Natural Gas  
 2. Site Conditions = ISO Ambient  
 3. Operating Mode = Base Load, Simple Cycle  
 \*Single-Shaft STAG Combined Cycle Configuration Only

**Table 15.** GE gas turbines applied to STAG product line



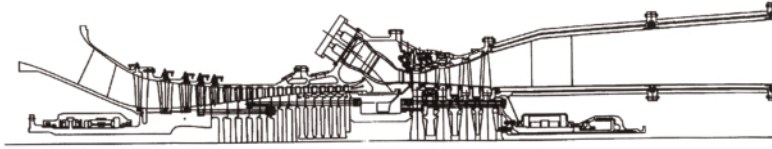
**Figure 17.** MS7001EA heavy-duty gas turbine



**Figure 18.** MS9001FA heavy-duty gas turbine

increases as gas turbine specific power increases, as shown in *Figure 20*. This figure shows that gas turbine firing temperature is the primary

determinant of specific power. Improvements in combined-cycle thermal efficiency have developed primarily through the increases in gas



## Features

- **Closed Loop Steam Cooling**
- **4-Stage Turbine**
- **Compressor Scaled From Proven Design**
- **Dry Low No<sub>x</sub> Combustor**

GT25129

**Figure 19.** “H” gas turbine cross-section

turbine firing temperature, which have resulted from the development of high-temperature / high strength materials, corrosion-resistant coatings, and improved cooling technology. Commercial development of combined cycles and improvements in combined-cycle efficiency have proceeded in parallel with advances in gas turbine technology.

- STAG systems that utilize the “F” technology gas turbines achieve net thermal efficiencies of 53% (LHV) or greater. STAG systems that utilize “H” technology gas turbines achieve net thermal efficiencies of 58–60% (LHV). These gas turbines have a rated firing temperature of 2420°F / 1327°C and 2600°F / 1426°C, respectively. The “FA” technology turbine has a 15.5 pressure ratio, whereas the “H” technology turbine has a 23.0 pressure ratio. These designs provide the highest gas turbine specific power for this firing temperature. High specific power provides the lowest simple-cycle installed cost in addition to high

combined-cycle efficiency.

- The exhaust gas temperature range of 1000–1100°F / 538–566°C is uniquely suited to efficient combined cycles because it enables the transfer of heat from exhaust gas to the steam cycle to take place over a minimal temperature difference. This temperature range results in the maximum in thermodynamic availability while operating with highest temperature and highest efficiency steam cycles.
- Multiple can-annular type combustors with film and impingement cooling meet the environmental requirements for applications throughout the world. They provide reliable operation at high firing temperatures while burning fuels that range from natural gas to residual oil.
- Turbine materials, coatings and cooling systems enable reliable operation at high firing temperatures. This achieves high gas turbine specific power and high efficiency for combined-cycle systems.

## GE Combined-Cycle Product Line and Performance

- Most GE current product line gas turbines are configured with open-loop cooling of the turbine hot gas path. Hot gas path components are in large part cooled by film cooling that uses air supplied from the compressor. This results in a significant exhaust gas steam temperature drop across the first stage nozzle, and requires significant “chargeable air” to cool the turbine stages. The temperature drop across the first stage nozzle and the chargeable cooling losses increase as turbine inlet temperature increases.
- The advanced “H” platform gas turbine is configured with an integrated closed-loop steam-cooling system. The change in strategy to the closed-loop, steam-cooled system without film cooling allows higher turbine inlet temperatures to be achieved without increasing combustion temperature. This is because the temperature drop across the first stage nozzle is significantly reduced, as shown in *Figure 21*. Gas turbine NO<sub>x</sub> emissions can then be maintained at low levels at increased turbine inlet temperature. 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 results in two percentage points improvement in combined cycle thermal efficiency.
- Factory packaging and containerized shipment of small parts achieve low installed cost and short installation time.
- Reliable operation results from evolutionary design development that improves parts and components, a high-quality manufacturing program that includes operational factory testing of the gas turbine and accessory systems, follow-up service support by experienced installation and service personnel, and effective spare parts support.
- Low maintenance costs are the result of the combination of the above features and a design to allow convenient access. These include borescope ports to permit inspection of key parts and components without dismantling the equipment.
- The heavy-duty gas turbine product line has fuel flexibility provided by accessory systems, combustion systems, and turbine components, which enable utilization of a wide range of liquid and gaseous fuels. These include 150-400 Btu/scf (6520-16,850 kJ/nm<sup>3</sup>) gaseous fuels, including those derived from coal, coke, or heavy petroleum products, and liquid fuels including naphtha, light distillates, heavy distillates, crude oil and residual oil.

### HRSG

HRSGs in the GE STAG product line are unfired and feature modular construction with finned-tube heat transfer surface and natural or forced-circulation evaporators. *Figure 22* illustrates a natural circulation HRSG with modular construction. An installation showing two of these HRSGs operating with MS7001EA gas turbines is shown in *Figure 23*. *Figure 24* illustrates the modular-construction, forced-circulation HRSG, and *Figure 25* shows an installation of

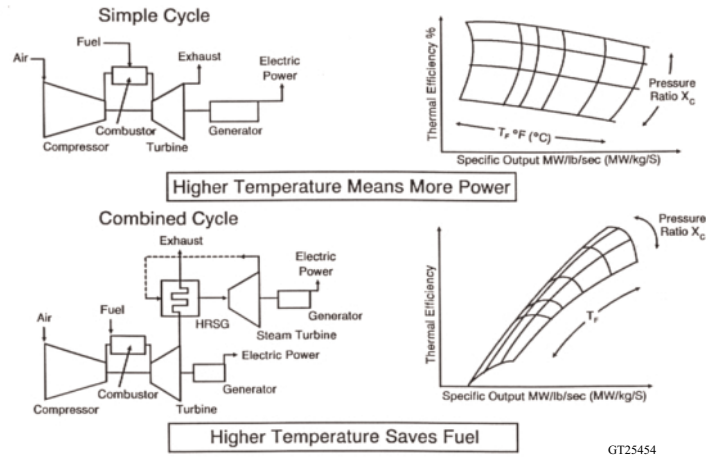
# GE Combined-Cycle Product Line and Performance

this type HRSG in a STAG 107EA system.

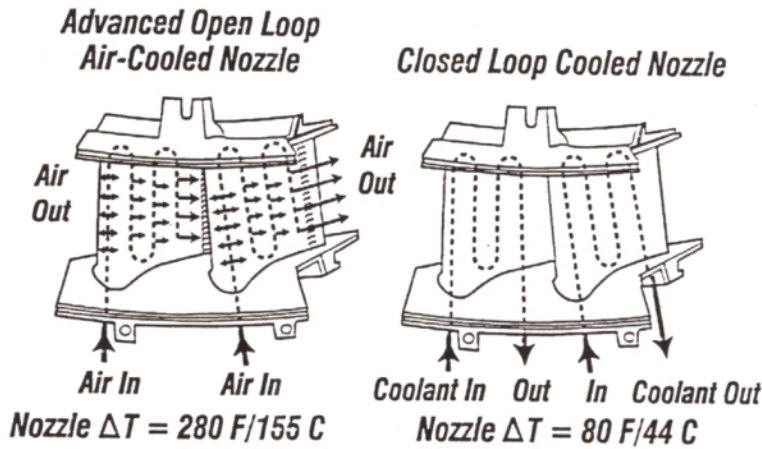
Each gas turbine exhausts to an individual HRSG. For STAG systems with a MS6001B gas turbine, the standard gas ducting is designed so that two gas turbines exhaust to a single HRSG. These STAG systems are also available with one HRSG per gas turbine. The HRSG and auxil-

fast startup and shutdown and flexibility of operation for multi-shaft STAG systems. Exhaust gas bypass systems are not used with single-shaft STAG units.

- Flexible tube support system to enable fast startup and load following



**Figure 20.** Gas turbine performance thermodynamics



**Figure 21.** Impact of stage-one nozzle cooling method

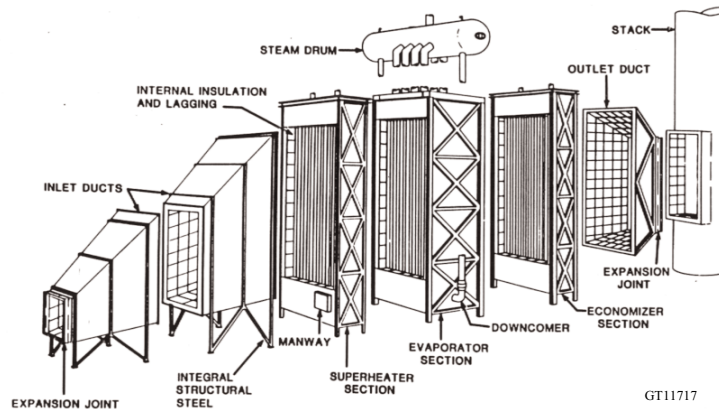
aries are designed for the specific operating requirements of the STAG combined cycle system. Design features include:

- Exhaust gas bypass system to provide

capability.

- Low gas side pressure drop for optimum gas turbine performance.
- Large, factory-tested modules that can be shipped to provide short

## HRSG MODULAR CONSTRUCTION



**Figure 22.** Natural-circulation HRSG modular construction



**Figure 23.** Two natural-circulation HRSGs operating with MS7001EA gas turbines

installation time and low construction cost.

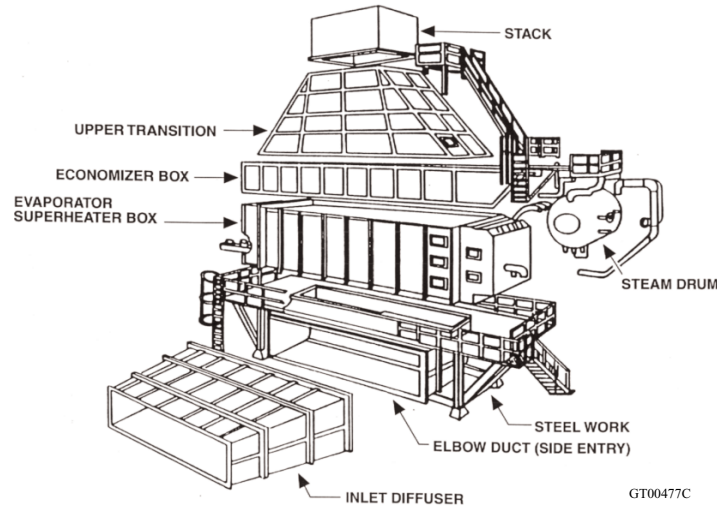
- Fuel flexibility provided by the ability to operate reliably and efficiently, using exhaust gas from gas turbines that burn fuels ranging from natural gas to residual oil.

### **Steam Turbine**

GE offers a complete line of steam turbines for combined-cycle applications. Two or more steam turbine selections are available for each

STAG product line offering. Steam turbines with different exhaust annulus areas are available to permit optimization to meet specific condenser cooling conditions. Steam turbines with large exhaust annulus areas are more expensive, but provide increased capability and may be the most economic selection for applications with low steam turbine exhaust pressure. For applications in which steam turbine exhaust pressures are high, small exhaust annulus-area steam turbines provide comparable or higher capability and low cost, and therefore are the economic choice. *Figure 26* illustrates





**Figure 24.** Forced-circulation HRSG modular construction



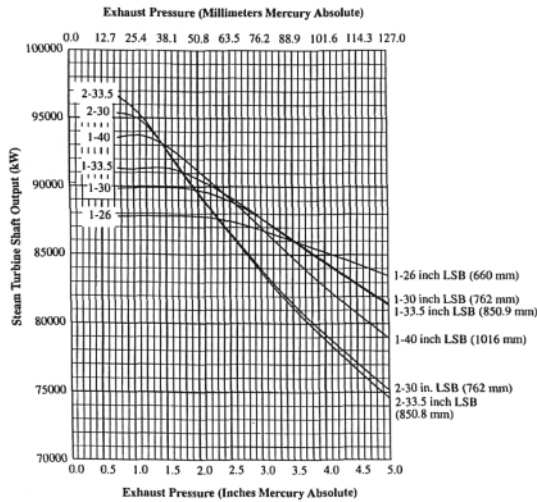
**Figure 25.** Forced-circulation HRSG with PG7111EA gas turbines

the performance difference for four last-stage buckets that are available for the STAG 107FA combined cycle. Steam turbine last-stage bucket lengths for the STAG product line steam turbines range from 14.3 inches / 363 mm to 42 inches / 1067 mm.

Because there are no extractions for feedwater heating, and 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 turbine's 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 combined-cycle applications.

As with all modern GE steam turbine last-stage buckets, the continuously-coupled design is used for high efficiency and reliability. Continuously-coupled designs permit the use of many relatively slender blades with narrow,



**Figure 26.** STAG steam turbine last-stage bucket selection

closely-controlled flow passages, particularly in the critical high-velocity tip region. Covers reduce tip leakage losses, provide damping, and help to maintain control of the flow passage.

Steam turbine designs for high exhaust pressure operation typical of those that are needed for air-cooled condenser operation at high ambient temperature are available. These steam turbine designs are capable of reliable and efficient operation at exhaust pressures up to 15 inches Hg,a/381mm Hg,a.

Advanced 3D aero packages incorporate advanced vortex design, contoured inlet section sidewalls, and additional radial tip spill strips for steam turbines larger than 80 MW, which contribute to maximum combined cycle thermodynamic efficiency.

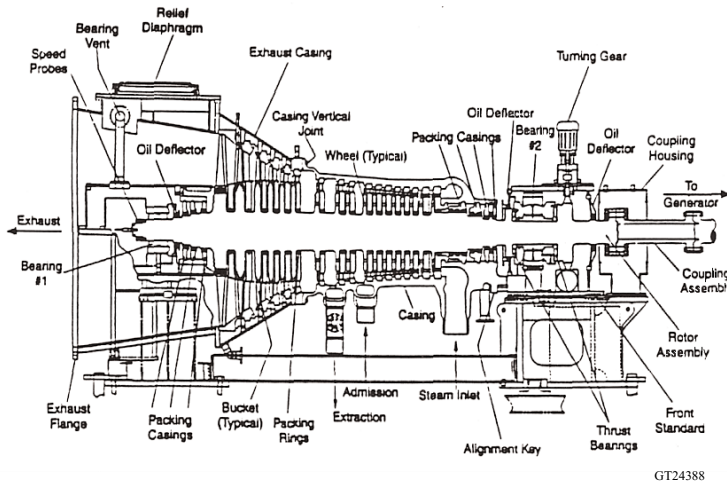
The STAG combined-cycle product line steam turbines include axial exhaust and down exhaust configurations. Axial exhaust is preferred for the single-flow steam turbines, typically applied in the small capacity STAG systems. *Figure 27* shows a single-flow axial exhaust steam turbine.

A line of reheat steam turbines designed specif-

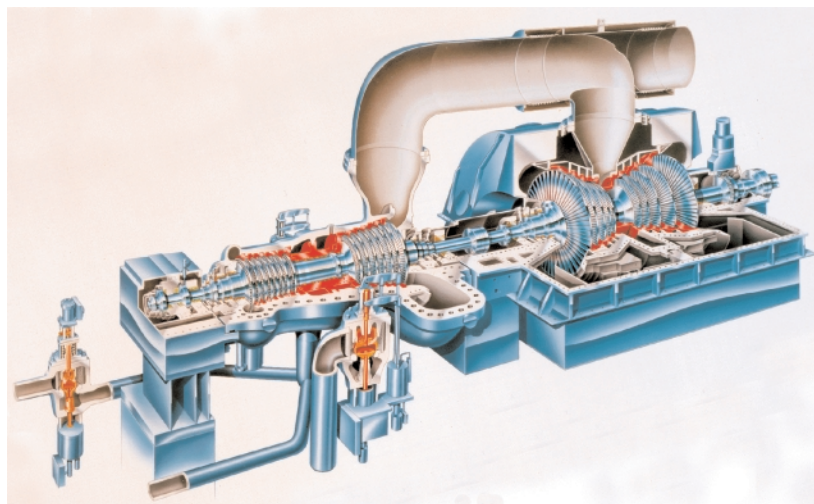
ically for combined-cycle service is available for STAG systems employing the “EC,” “F,” and “H” technology gas turbines. The single-shaft STAG 107FA, STAG 109FA and STAG 109H are designed as integrated machines with a solid turbine/generator coupling and a single-thrust bearing that includes common lubrication and hydraulic and control systems for both gas turbine and steam turbine. A two-flow reheat steam turbine is shown in *Figure 28*.

Steam turbines specially designed for combined-cycle service have features that include:

- Assembled modules that can be shipped and assembled with a low profile installation that reduces installation time and cost. (Building cost, for indoor installation, also is reduced with the low profile design.)
- Access for borescopic inspection of buckets and nozzles without removal of the turbine upper casing.
- Fast startup and load-following capability provided by minimum shaft diameter in the vicinity of the first stage, large fillets between wheels and rotor, long coupling spans, vertical flexible plate support near the centerline with keys for maintenance of alignment, and off-shell valves with full-arc steam admission.
- All main steam, cold reheat and hot reheat steam pipes connect to the lower half of the shell. This facilitates removal of the upper half shell for maintenance, and eliminates the need for bolted connections in a high temperature piping.
- Sliding pressure operation with the control valves wide open. A control stage at the inlet is, therefore, not



**Figure 27.** Non-reheat, single casing, axial exhaust steam turbine



**Figure 28.** Two-flow, reheat steam turbine

required.

- Applications at 1800 psig/124 bar,g use a single wall construction at the high-pressure stages as well as the reheat inlet. With 2400 psig/165 bar,g applications, a short inner shell encloses the early high-pressure stages. This reduces the load on the horizontal joint bolting and reduces the thickness of the shell flange.

## Generators

Generators for the STAG combined-cycle product line gas turbines and steam turbines are factory assembled and tested. Air-cooled generators are standard for the smaller STAG systems using PG6581B, PG6101FA and PG7121EA gas turbines. They may be open-ventilated or totally enclosed water-to-air cooled. If open-ventilated, they are equipped with self-cleaning air filters for desert or other dusty or dirty environments, as shown in *Figure 29*. Hydrogen-cooled generators are standard for the single-shaft and larger multi-shaft STAG systems. The hydrogen-cooled generators can be cooled by plant-cool-

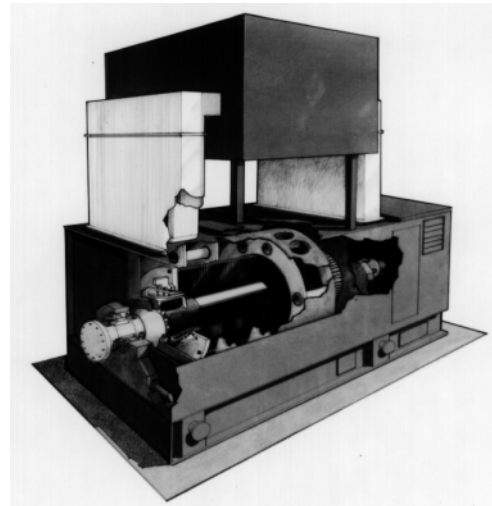
ing water or by ambient air with water-to-air heat exchangers. *Figure 30* shows a typical packaged hydrogen cooled generator for gas turbine application.

### Controls

The STAG combined-cycle plant has a distributed digital control system with a redundant data highway. The station operator consoles provide interactive color graphic displays of the overall STAG plant, with sufficient detail to enable the operator to conveniently operate the plant.

The control systems for multi-shaft and single-shaft STAG combined-cycle system fundamentally follow the same principle objectives of simplicity, easy starting, automated operation and superior load following ability. All main components of the combined-cycle plant have individual control panels and interfaces that relay information and instructions to and from the plant operator through data highways to the operator console. The operator console will have a detailed graphic display with a high level of detail that enables convenient and informative interaction with the plant as required.

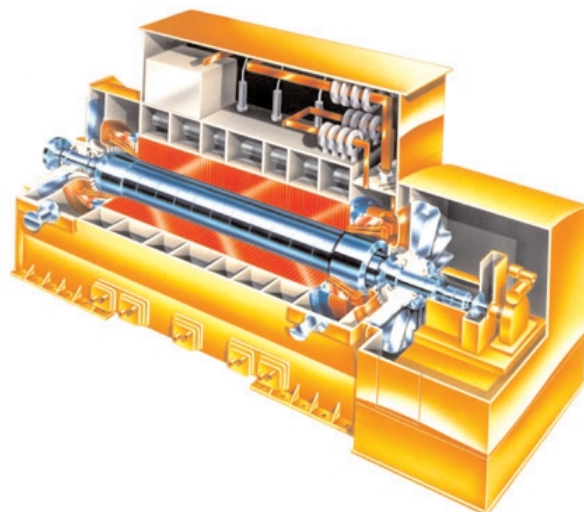
The single-shaft power train is a simple tandem arrangement that does not include an exhaust



**Figure 29.** Air-cooled generator with self-cleaning air filter

bypass system and is solidly coupled to one generator with a common overspeed protection device with less auxiliary equipment. *Figures 31 and 32* show block diagrams for multi-shaft and single-shaft arrangements.

The heat recovery combined cycle is a simple system with a minimum of control loops, as shown by the control diagram (*Figure 33*) for a single-pressure, multi-shaft STAG system. The simplicity of this system, coupled with well-established, automated operation of system components, enables effective automation of



**Figure 30.** Typical packaged hydrogen-cooled generator

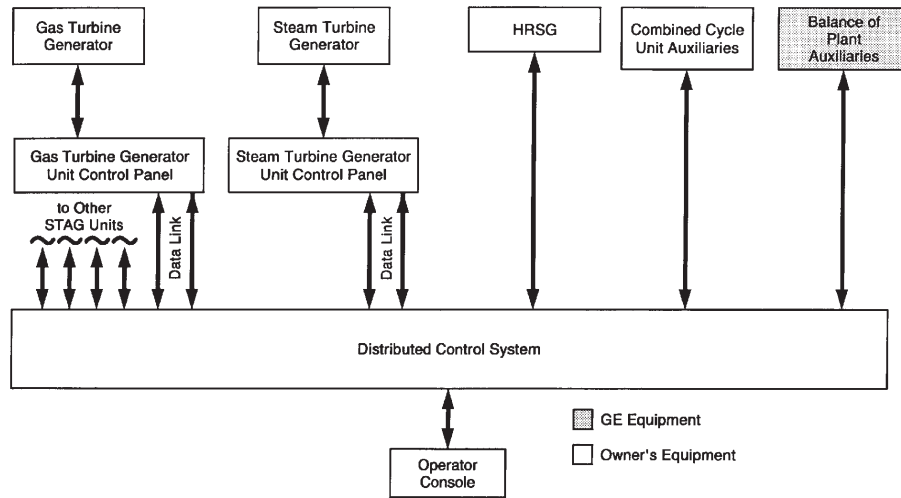
# GE Combined-Cycle Product Line and Performance

the complete power plant. This minimizes the number of control room operators. Most STAG systems operate with only one control room operator and one roving operator.

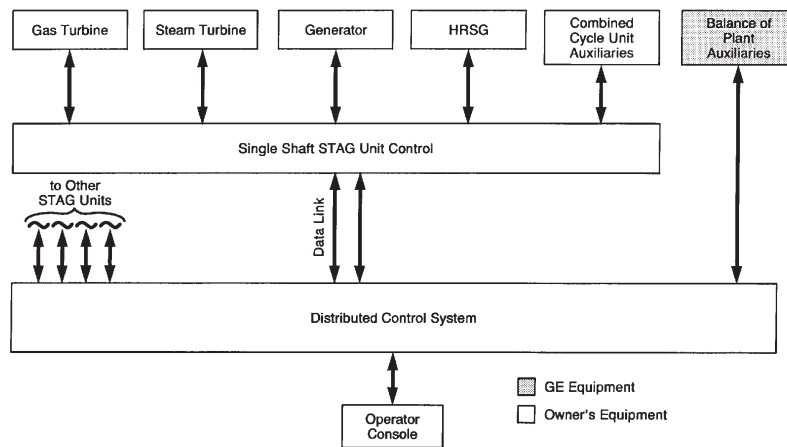
The multi-shaft STAG control is configured to enable automated startup and operation after remote manual starting of plant auxiliaries, remote manual operation of each major component, or operation of the gas turbine-generator units from local-control compartments. The control configuration enables maximum availability because the plant can be operated

remotely with no additional control room operators. The equipment protection system is provided within the unit controls, so normal protection is maintained during all modes of operation, including local or remote manual operation.

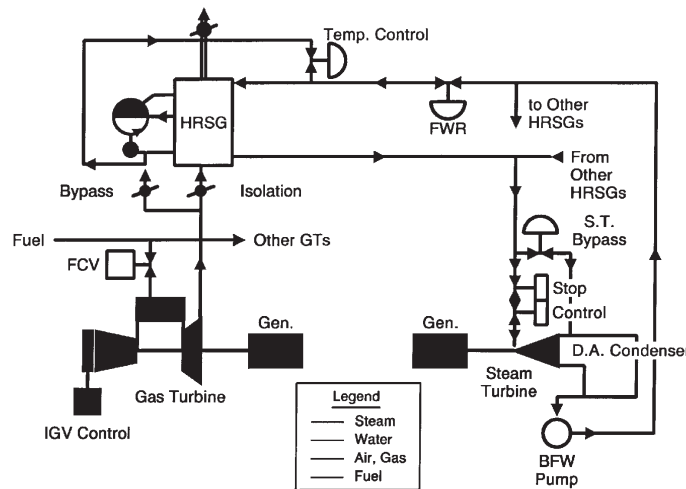
The single-shaft STAG unit control system is a microprocessor-based controller that coordinates the operation of the components in each integrated combined-cycle unit and communicates with the plant control. Because of the simple steam cycle, the tandem coupling of the gas



**Figure 31.** Distributed control system for plant with multi-shaft STAG combined cycle



**Figure 32.** Distributed control system for plant with single-shaft STAG combined cycle



**Figure 33.** Multi-shaft STAG control diagram

and steam turbines to a single generator, and the elimination of the HRSG exhaust-gas, bypass system, the single-shaft STAG combined-cycle control is very simple. Starting, operation, and shutdown of individual units are automatic. Single-shaft STAG units are controlled by a local unit control system that is coupled to the central control room operator's console by a data highway. One control room operator can operate one or more single-shaft STAG combined-cycle units with this type of control system and the aid of one local operator.

## Auxiliaries

The STAG product line ratings are based on plants with once-through systems (seawater or river water) for steam turbine condenser cooling. STAG combined-cycle configurations are also available for operation with a wide range of owner-specified auxiliaries, including evaporative cooling towers and air-cooled condensers. Plant capability and efficiency with these systems is expected to be lower because steam turbine exhaust pressure and cooling system auxiliary power consumption are increased.

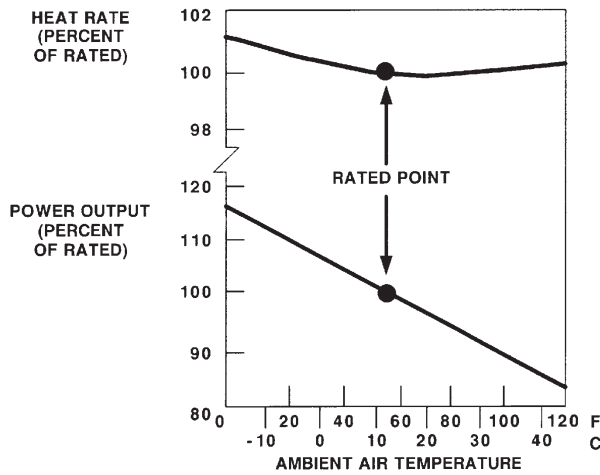
## Plant Operation

Typical STAG plant performance variation with ambient air temperature is illustrated by the heat rate and power-output capability ambient-temperature effect curves in *Figure 34*. Low heat rate throughout the ambient-air-temperature range is typical of these plants. The low heat rate and increase in output as ambient temperature decreases are achieved by the gas turbine characteristics and optimum equipment matching.

Gas turbine exhaust flow and temperature vary with ambient temperature and barometric pressure. Steam production and steam turbine output vary with the exhaust gas flow and temperature supply to the HRSG. Steam turbines are selected to suit specific application requirements. The steam turbines in the standard systems are sized so that their rated flow matches the steam production.

Excellent part-load heat rate is achieved on multi-shaft systems or multiple single-shaft units by sequentially loading gas turbines to meet system requirements (*Figure 35*). This curve also shows that the plant can operate efficiently following system load with all gas turbines operating. The heat rate increases only 1% at approximately 80% of rating.

# GE Combined-Cycle Product Line and Performance



**Figure 34.** Combined-cycle, ambient air temperature effect curve

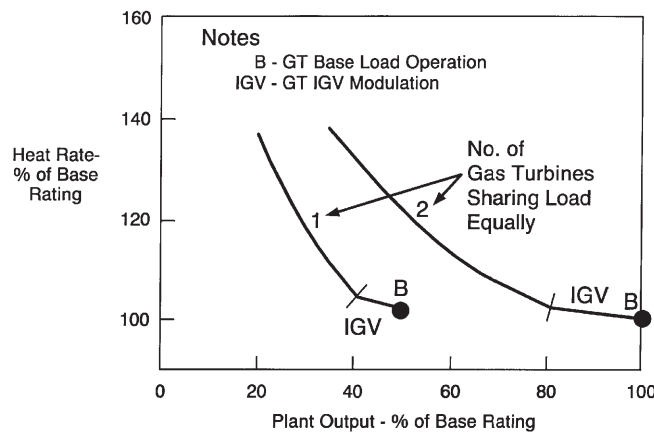
The modulated, inlet guide vanes (IGV) on the gas turbine compressor contribute significantly to the excellent part-load performance. The inlet guide vanes are modulated to control air flow in the power plant between the “hash mark” and the point marked “B.” Varying the air flow maintains nearly constant gas turbine firing temperature so that the thermodynamic quality of the cycle remains essentially constant. The stack and condenser losses vary almost proportionally with output, so that the heat rate remains almost constant. At loads below the hash mark, the gas turbine operates with con-

stant air flow, and firing temperature is reduced as load is reduced.

Fast starting and loading is characteristic of STAG combined-cycle generation systems. This enables them to operate in mid-range, with daily start peaking service as well as baseload. Typically, STAG systems can achieve full load within one hour during a hot start and within approximately three hours for a cold start. Multi-shaft STAG systems allow the gas turbines to start independently of the steam cycle and provide about 65% of the plant capability within 15–25 minutes, depending on the size of the gas turbine, for hot, warm, and cold starts, as illustrated in *Figure 36*. Single-shaft STAG systems are started and loaded to full capacity in about the same time period as the multi-shaft STAG systems. The startup sequence and load profile for the single-shaft systems differ because the gas and steam turbines are started as a single integrated unit and not as two separate units. Single-shaft STAG startup is illustrated in *Figure 37*.

## Plant Arrangements

The STAG combined-cycle equipment can be adapted to installation requirements demanded by varying climactic conditions, system configu-

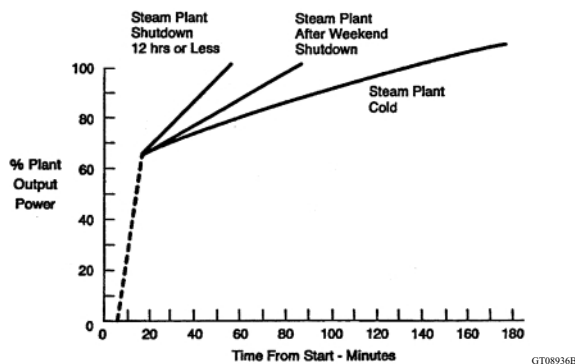


**Figure 35.** STAG 200 part-load performance

rations and owner/operator preferences. The equipment is suitable for outdoor installations, semi-outdoor installations, or fully-enclosed installations. Plant arrangements have been designed for each STAG system.

Plan views of STAG combined-cycle arrangements are shown in *Figure 38* (multi-shaft, S406B), *Figure 39* (multi-shaft, S207EA), *Figure 40* (single-shaft S109E), *Figure 41* (multi-shaft, S207FA), and *Figure 42* (single-shaft, S107FA). An elevation of the single-shaft S107FA is shown in *Figure 43*. *Figure 44* shows the S107H and S109H plan and elevation views. The S107H provides about 58% increase in combined-cycle power output with only about 10% increase in footprint area.

A 220 MW STAG 207E installation is shown in *Figure 45*. *Figure 46* presents a STAG 109FA combined cycle installation. *Figure 47* shows a 4000 MW installation with eight STAG 107F and four STAG 207FA systems at one site. These arrangements have indoor turbine-generator



**Figure 36.** Multi-shaft STAG starting times

equipment and outdoor HRSGs. *Figure 48* shows a plant with two STAG multi-shaft combined-cycle units in an indoor installation. For outdoor installations, the standard gas turbine enclosures are weatherproof, and weatherproof lagging is available for the steam turbines.

### Installation

The short installation time and low installation cost of STAG combined-cycle systems are key features contributing to economical power generation. This is due to factory packaging of all major components and containerized shipment of small parts. In addition to low direct construction cost, the short installation time reduces interest payments during construction. The standard factory modules and standardized designs also reduce plant engineering time and cost.

The time from order to commercial operation for pre-engineered, standardized STAG designs is typically 24 months, not including permitting time. The multi-shaft STAG systems can be installed in two phases to reduce the time between order and initial power production. The gas turbines contribute 65% of the plant capacity. Typically, the gas turbine can be installed in less than 18 months to provide power generation while the steam system is being installed. *Figure 49* is a typical two-phase multi-shaft STAG combined-cycle installation schedule.

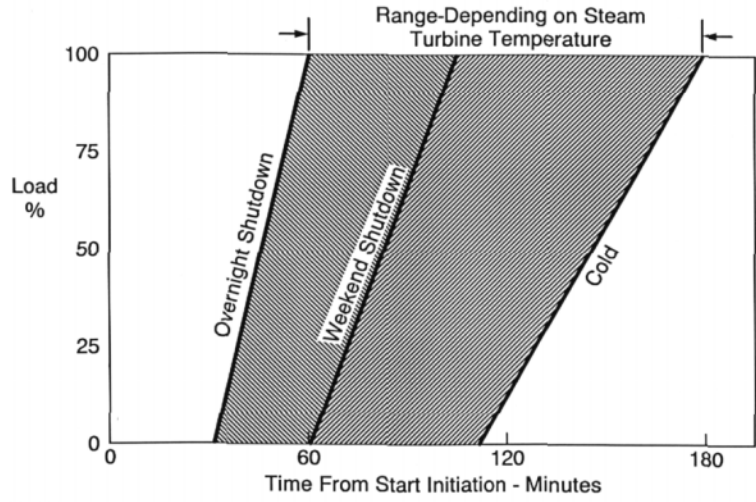
### Utility Load Growth

Power generation economics can be enhanced by the installation of generation capacity in small increments as utility load grows. STAG combined-cycle plants fit this economical pattern because efficient, low-cost plants are available in small blocks of generating capacity.

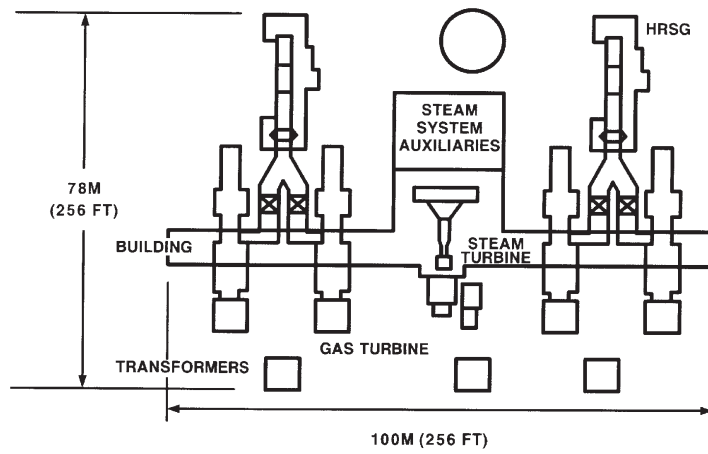
Flexibility is also available with the pro-generation approach to capacity addition. Initial natural gas/distillate oil-fired, simple-cycle gas turbine installations can be converted to combined cycle later, when power demands require capacity increases. Plot plan area for the steam cycle equipment and transmission line capability are the main considerations during the initial com-



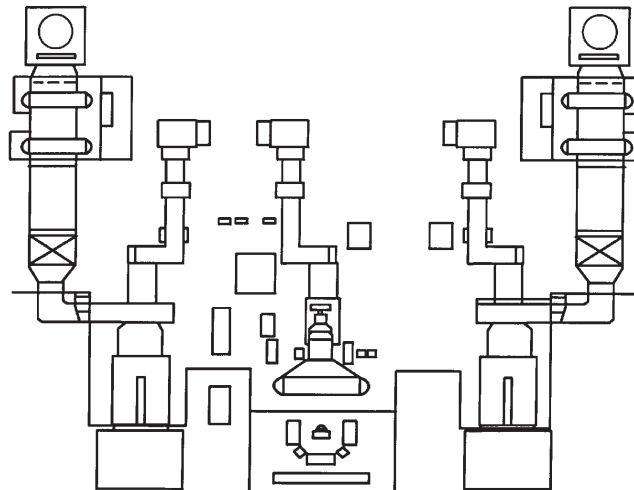
# GE Combined-Cycle Product Line and Performance



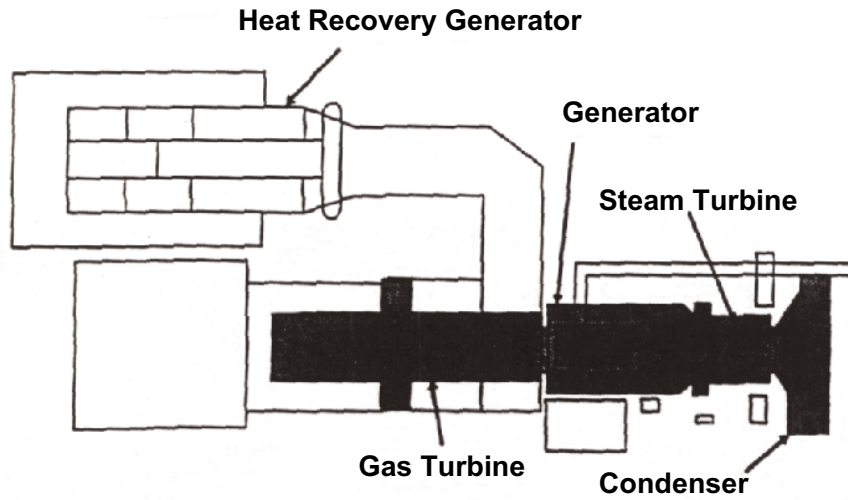
**Figure 37.** Single-shaft STAG starting times



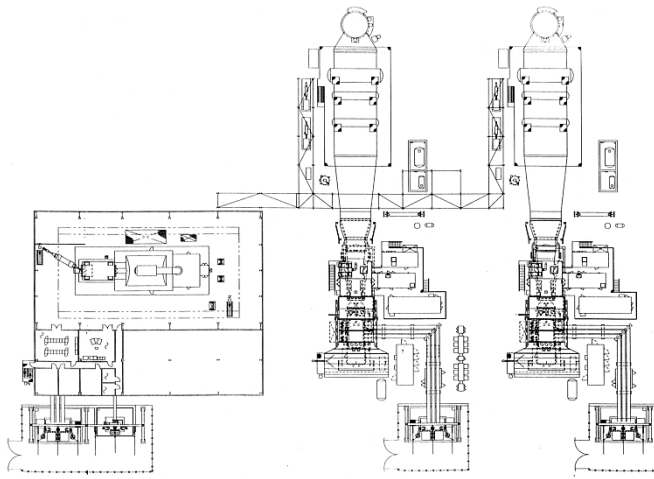
**Figure 38.** STAG 406B combined-cycle plan



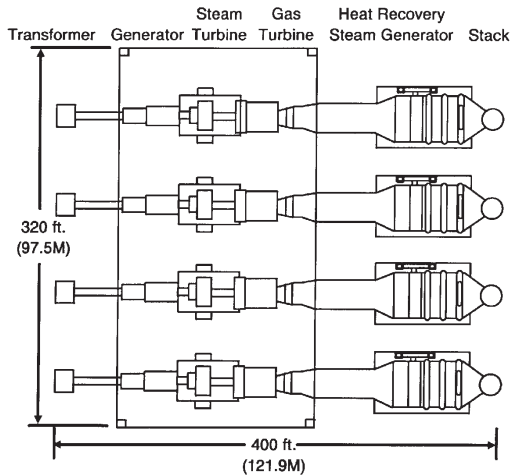
**Figure 39.** STAG 207EA combined-cycle plan



**Figure 40.** STAG 109E combined-cycle plan

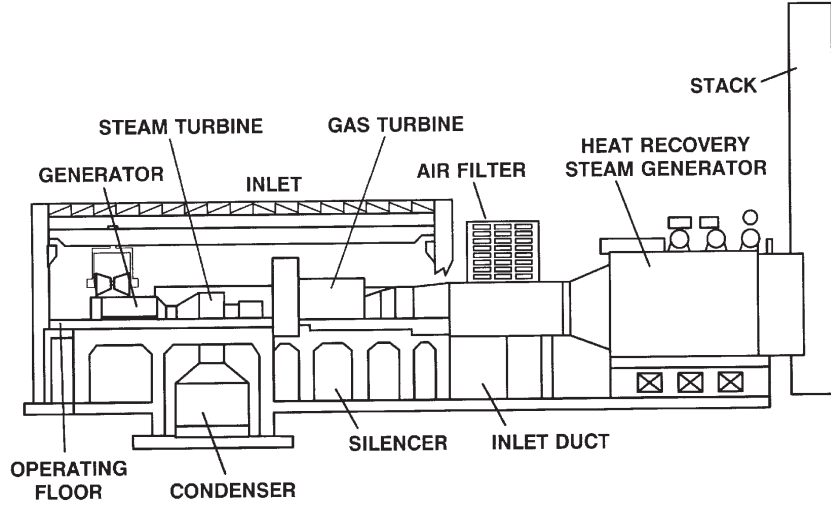


**Figure 41.** STAG 207FA multi-shaft combined-cycle plan

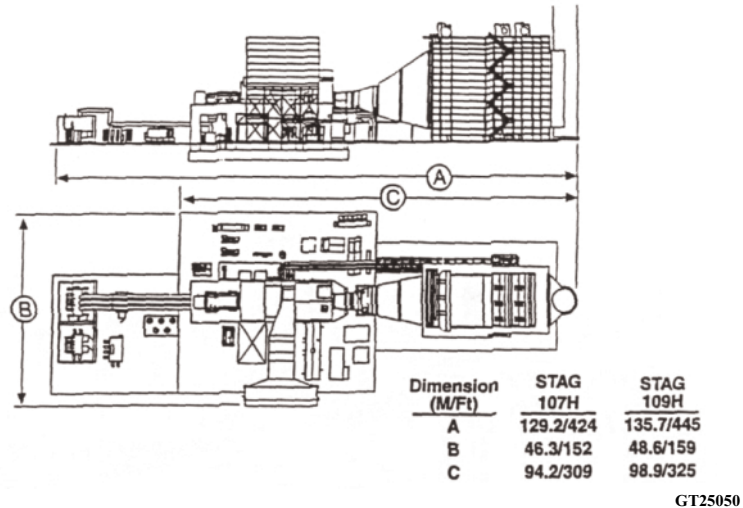


**Figure 42.** Four-unit STAG 107FA combined-cycle plan

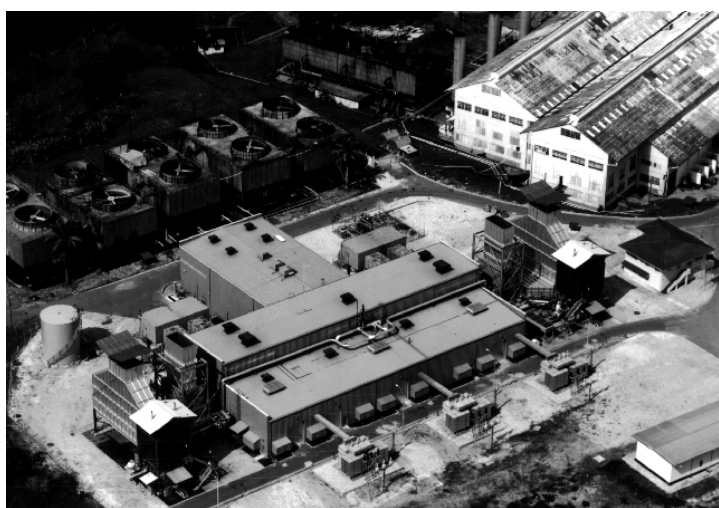
# GE Combined-Cycle Product Line and Performance



**Figure 43.** STAG 107FA single-shaft combined-cycle elevation



**Figure 44.** Single-shaft S107H and S109H plan and elevation



**Figure 45.** STAG 207E installation



**Figure 46.** Indoor S109FA installation

mitment for simple-cycle gas turbines. Future conversion to coal-derived fuels also is an option for dealing with the long-range uncertainties of conventional fuel availability and price.

### ***Thermal Energy and Power System Product Line***

The product line of thermal energy and power combined-cycle systems (cogeneration and district heating systems) are designed with structured flexibility to provide a wide range of

power and thermal energy capacities to suit varied application requirements. The most commonly supplied systems are:

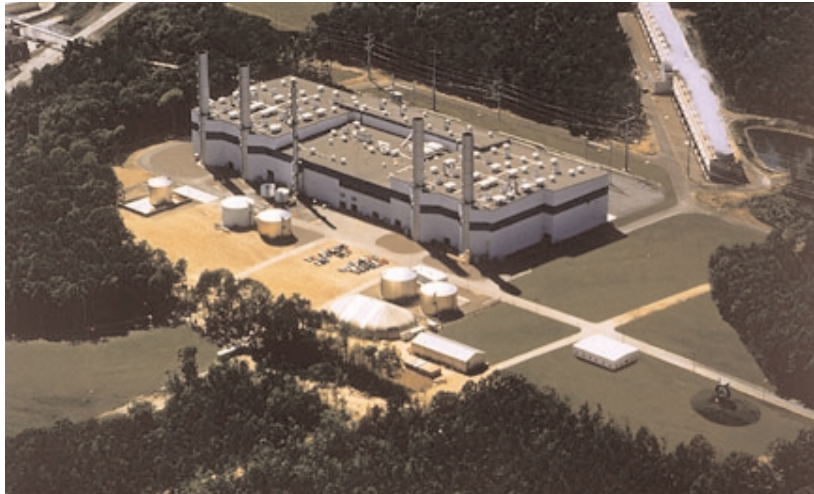
- Steam generation at process conditions with HRSG (no steam turbine)
  - Unfired HRSG
  - Supplemental-fired HRSG
- HRSG and non-condensing steam turbine exhausting to process
  - Unfired, one-pressure HRSG
  - Unfired, two-pressure HRSG
  - Supplemental-fired, one-pressure HRSG
- HRSG with extraction/condensing steam turbine
  - Unfired, one-pressure HRSG
  - Unfired, two-pressure HRSG
  - Supplemental-fired, one-pressure HRSG

The capabilities of the thermal energy and power systems are unique for each gas turbine frame size, as well as each set of process steam conditions for systems with both unfired process HRSGs and unfired HRSGs that have non-condensing steam turbines. The systems

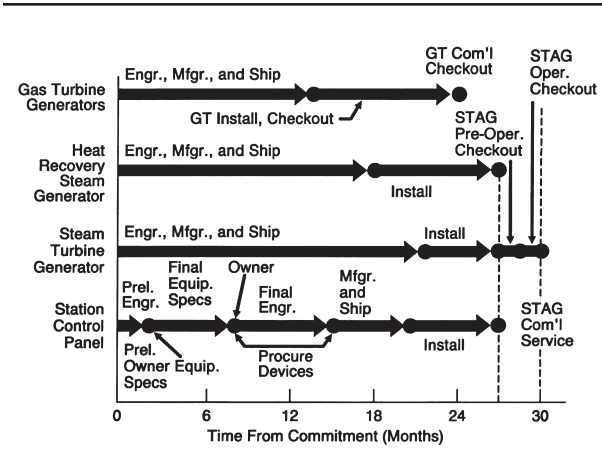


**Figure 47.** 4000 MW multi-shaft STAG installation

# GE Combined-Cycle Product Line and Performance



**Figure 48.** Two 207FA multi-shaft combined-cycle installation



**Figure 49.** Typical multi-shaft, combined-cycle project schedule

with fired HRSGs and condensing steam turbines provide extraordinary flexibility in both thermal energy and power generation capacity for each gas turbine frame size.

The performance characteristics include the net plant power, LHV heat content in fuel consumed, thermal energy in steam to process, and thermal efficiency and fuel charged to power (FCP). The thermal efficiency for these systems is calculated by the following equation:

$$\eta_{TH} = 100 \times \frac{(Q_p + Q_{TE})}{Q_F}$$

**Symbols:**

- $\eta_{TH}$  = Thermal efficiency - LHV (%)
- $Q_F$  = LHV heat content of fuel consumption (Btu/hr, kJ/hr)
- $Q_p$  = Net power output (Btu/hr, kJ/hr)
- $Q_{TE}$  = Thermal energy in process steam (Btu/hr, kJ/hr)

The fuel charged to power (FCP) is a useful parameter for comparing an integrated thermal energy and power system with separate systems generating the same power and thermal energy. For this comparison, the LHV heat content of fuel that would be consumed by a conventional fired boiler in producing the same thermal energy is subtracted from the LHV heat consumption of the integrated thermal energy and power system. The resulting FCP can then be compared with the heat rate of a separate power generation facility. This will assess the relative performance of the integrated thermal energy and power system with separate thermal energy and power generation systems. FCP is calculated by the following equation:

$$FCP = 100 \times \frac{(Q_p - [Q_{TE}/\eta_B])}{p}$$

**Symbols:**

**FCP** = Fuel charged to power = LHV

## GE Combined-Cycle Product Line and Performance

	(Btu/kWh, kJ/hr)
$Q_F$	= LHV heat content of fuel consumption (Btu/hr, kJ/hr)
$Q_{TE}$	= Thermal energy in process steam (Btu/hr, kJ/hr)
$\eta_B$	= LHV efficiency of fired boiler producing equivalent thermal energy (%)
$P$	= Net electrical output (kW)

Cycle diagrams for thermal energy and power combined cycle with steam generation at process conditions is presented in *Figure 50*.

These systems include generation of steam at process conditions. *Figure 50* shows combined-cycle cogeneration systems that produce process steam with an unfired or supplementary-fired HRSG. HRSG design for supplementary firing provides the maximum process steam energy supply. *Figure 51* shows combined-cycle cogeneration systems that are equipped with non-condensing steam turbines.

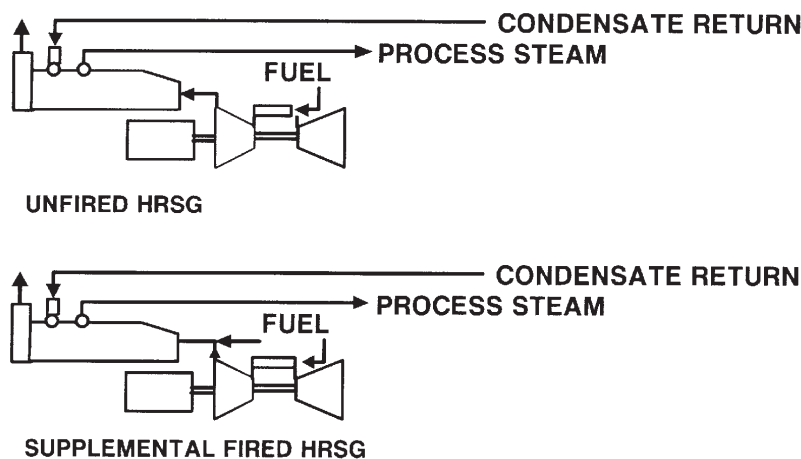
Many variations of these systems can be furnished to satisfy specific process plant energy requirements, including:

- Single automatic-extraction steam turbines to efficiently supply steam at two or three pressures.
- Multi-pressure HRSGs to supply steam

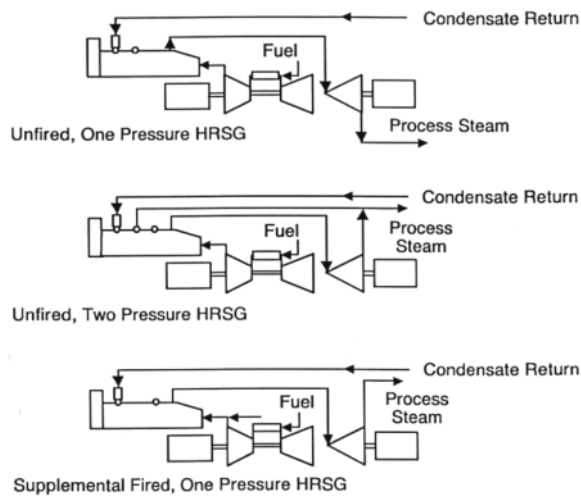
at multiple-pressure and temperature conditions. The most flexible thermal energy and power systems are those that include extraction condensing steam turbines. Simplified cycle diagrams for typical systems with single automatic extraction are shown in *Figure 52*. This system has the capability to operate at lower process steam demands while using the excess steam generation to produce power in the condensing section of the steam turbine. These systems can be furnished with double automatic extraction steam turbines and multiple-pressure HRSGs to satisfy specific process steam requirements.

### Engineered Equipment Package

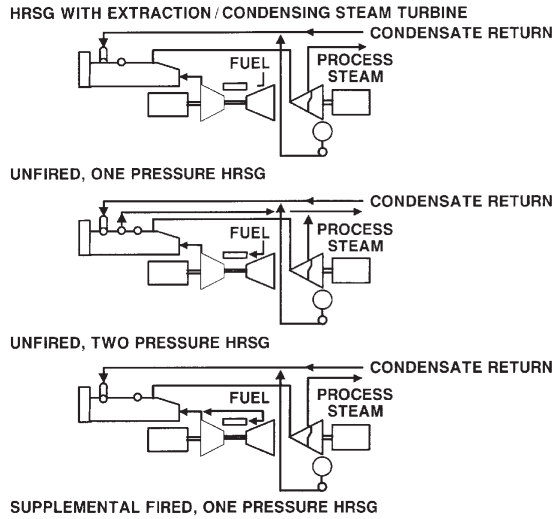
The GE Combined-Cycle Engineered Equipment Package (EEP) is a unique combination of equipment and services. It provides the owner with a plant performance guarantee and warranty of operation, and the ability to service the complete power generation system, as well as the capability to customize the plant design, auxiliaries, and structures. This is achieved by including in the GE scope the major combined-



**Figure 50.** Cycle diagrams – thermal energy and power combined cycle with steam generation at process conditions



**Figure 51.** Cycle diagrams – thermal energy and power combined cycle with non-condensing steam turbine



**Figure 52.** Cycle diagrams – thermal energy and power combined cycle with extraction/condensing steam turbines

cycle equipment that requires close coordination for assurance of meeting the performance and operating objectives. The equipment scope split between GE and the owner is shown in *Table 16*.

The services and software scope split is presented in *Table 17*. Key elements in the GE EEP scope are the combined-cycle system design and the interface definition that enable the owner

, or the owner’s architect-engineer or engineer-constructor, to design the plant to meet project specific requirements.

## Conclusion

The STAG combined-cycle product line, including power generation systems and thermal energy and power systems ranging from 60 MW to 750 MW, are efficient, low-cost systems that meet the environmental requirements of all countries. The GE combined cycle EEP provides assurance of satisfying performance and operating objectives while allowing a customized plant that incorporates the owner's practices and preferences. The attractive eco-

### GENERAL ELECTRIC

- GAS TURBINE(S)
- STEAM TURBINE(S)
- GENERATOR(S)
- HEAT RECOVERY STEAM GENERATOR(S)
- PLANT CONTROLS

### OWNER

- MECHANICAL AUXILIARIES
- ELECTRICAL AUXILIARIES
- MAIN ELECTRICAL CONNECTIONS
- BALANCE OF PLANT
  - FOUNDATIONS AND STRUCTURES
  - SWITCHYARD
  - FUEL HANDLING AND STORAGE
  - PLANT COOLING SYSTEM
  - CONSTRUCTION MATERIALS
  - SITE PREPARATION MATERIALS

**Table 16.** Equipment scope split with engineered equipment package

### **General Electric**

- Plant performance and environmental guarantee
- Combined cycle system design and warranty
- Balance of plant equipment functional specifications
- Equipment interface drawings
- Steady state and dynamic interface definition
- Equipment operation and maintenance
- Operation and maintenance training
- Construction and operation permit support
- Performance and environmental test support

### **Owner**

- Construction and operation permits
- Plant design
- Plant construction
- Plant start-up, commissioning and operation
- Performance and environmental testing
- Site preparation
- Project administration

**Table 17.** Services and software split with engineered equipment package

nomics, reliability, and operating flexibility of these systems recommend their consideration for all power generation applications.



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